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Unmanned Air Systems – a Capability and Research Landscape Review

A. Sóbester, D. J. J. Toal, J. P. Scanlan, S. Ramchurn[1]
M. Quinlan[2], H. M. Figueiredo, M. O'Dell, P. Kent, D. Coe[3]

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[1]University of Southampton
[2]Thales UK Limited
[3]QinetiQ

The technology behind the next generation of unmanned aircraft systems lies at the confluence of numerous research disciplines. These cover areas conventionally associated with aircraft engineering, such as airframe design, internal combustion engine optimisation, radar systems, autopilots, communications and so on. Modern unmanned aircraft systems engineering, however, also relies on areas that the aircraft engineers of yesteryear will have seldom associated with their craft or even have heard of, such as battery and fuel cell chemistry, autonomy, human-machine teaming, micro-technologies, global positioning systems and much else.

This report aims to provide a snapshot of this underpinning technology, with a particular focus on the low TRL (Technology Readiness Level) ideas being explored in research labs around the world. Some of these ideas will turn out to be dead ends. Others will only be enabled by other technologies whose time is yet to come. But some will be key enablers of the unmanned aircraft technology of the coming decades and a few may bring about revolutions that will open up up whole new areas of applications or lead to step changes in the 'real world' usability of drones. Like all such reviews, this report makes no claims of completeness, nor does it devote exactly the same level of attention to all of the areas listed above. It does, however, aim to be a tool that will enable researchers and decision makers to gain an understanding of the directions in which this industry is headed and where some of the key roadblocks and opportunities may lie.

A few important notes and caveats.

The first one is to do with terminology. We use terms like unmanned aircraft, drone, and UAV (unmanned air vehicle) interchangeably, to mean a remotely piloted/autonomous air vehicle, without implying any further details about the aircraft (e.g., fixed wing or rotary), and without loading any of these terms with distinctive meanings.

The second important note about this document is that it is entirely based on public domain information. In compiling this report we consulted over 850 public domain documents; they are listed at the back of the report.

Third, this document makes occasional references to commercial products related to the world of unmanned aircraft systems. These are meant simply as illustrative examples. This document is not a comprehensive review or comparative survey of the commercial landscape. Readers approaching this report from a procurement perspective should treat it simply as a review of the technical background and some of the research directions and trends in the field and they are invited to perform their own due diligence in selecting a product suitable for their needs.

The following is the work of a team of researchers from the University of Southampton, Thales UK and QinetiQ. We are all grateful to the UK's Defence Science and Technology Laboratory [dstl] for their support of and guidance in the compilation of this work.

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UNIVERSITY OF Southampton

Contents

Nomenclature

ABSAA Airborne Sense and Avoid

AC Alternating Current

ACM Automated Celestial Navigation

AESA Active Electronically Scanned Array

AI Artificial Intelligence

Al Aluminium

Al(OH)3 Aluminium Hydroxide

ALM Additive Layer Manufacture

AM Additive Manufacturing

ANS Adaptable Navigation Systems

AR Augmented Reality

AROD Airborne Remotely Operated Device

ARRL American Radio Relay League

ASPN All Source Positioning and Navigation

ASTM American Society of Testing and Materials

ATM Air Traffic Management

ATR Automatic Target Recognition

BBC British Broadcasting Corporation

BBQ Barbecue

BCI Brain-Computer Interface

BEA Bureau Enquêtes-Accidents (France)

BER Bit Error Rate

BLOS Beyond Line-of-Sight

BMEP Brake Mean Effective Pressure

BSFC Brake Specific Fuel Consumption

BVLOS Beyond Visual Line-of-Sight

C2 Command and Control

CAMPS Civil Aircraft Missile Protection System

CAPTEAM Collaborative Airborne Planning, Task Evaluation and Authorisation Manager

CCD Charge Coupled Device

CDMA Code Division Multiple Access

CFA Colour Filter Array

CFD Computational Fluid Dynamics

CFF Cross-Flow Fan

CNN Convolutional Neural Network

COMINT Communications Intelligence

COMPACT Configurable Operating Model for Automated Control of Tasks

CPRA Controlled Radiation Pattern Antennas

CPU Central Processing Unit

DAL Design Assurance Level

DARPA Defense Advanced Research Projects Agency

DC Direct Current

DoD Department of Defence

DOF Degrees of Freedom

DSSS Direct sequence spread spectrum

dstl Defence Science and Technology Laboratory

DVB-T Digital Video Broadcasting - Terrestrial

EAD Electroaerodynamics

EFI Electronic Fuel Injection

EKF Extended Kalman Filter

eLORAN Enhanced Long Range Navigation

EM Electromagnetic

EMI Electromagnetic Interference

EMP Electromagnetic Pulse

EO Earth Observation

EO/IR Electro-Optical / Infrared

EPSRC Engineering & Physical Sciences Research Council

ESM Electronic Sensor Measures

ETH Zurich Eidgenössische Technische Hochschule Zürich

EU European Union

FAST Future Advanced SATCOM Technology

FIAC Fast Inshore Attack Craft

FIRE Fully Integrated Robotised Engine

FKFS Research Institute of Automotive Engineering and Vehicle Engines Stuttgart

FNIRS Functional Near-Infrared Spectroscopy

FOG Fibre Optic Gyroscope

FOPEN Foliage Penetration

FSO Free-Space Optical

GA General Aviation

GaAs Gallium Arsenide

GAN Generative Adversarial Networks

GaN Gallium Nitride

GCS Ground Control Station

GLONASS Globalnaya Navigatsionnaya Sputnikovaya Sistema

Glossary

GMTI Ground Moving Target Indicator

GNSS Global Navigation Satellite System

GPS Global Positioning System

GPU Graphics Processing Unit

H2O Water

HACs Human-Agent Collectives

HALE High Altitude Long Endurance

HCCI Homogeneous Charge Compression Ignition

HF High Frequency (RF)

HFE High Fuel Economy

I/O Input / Output

IAI Israeli Aerospace Industries

ICAO International Civil Aviation Organisation

ICARUS Inbound, Controlled, Air-Releasable, Unrecoverable Systems

ICE Internal Combustion Engine

ICL Imperial College London

IEEE Institute of Electrical and Electronics Engineers

IF Intermediate Frequency

IMA Integrated Modular Avionics

IMU Inertial Measurement Unit

INS Inertial Navigation System

IR Infrared

IrDA Infrared Data Association

JCTD Joint Capability Technology Demonstration

JPL Jet Propulsion Laboratory

LAN Local Area Network

LCD Liquid Crystal Display

LCO Lithium Cobalt Oxide (LiCoO2)

LCTF Liquid Crystal Tunable Filters

LFP Lithium Iron Phosphate (LiFePO4)

LFV Luftfartsverket

Li Lithium

Li-S Lithium-Sulphur

LIDAR Light Detection and Ranging

LMO Lithium Manganese Oxide (LiMnO2)

LOI Levels of Interoperability

LORAN Long Range Navigation

LOS Line-of-Sight

LTE Long Term Evolution

LTO Lithium Titanate (Li2TiO3)

LVC Live Virtual Construction

MADCAT Mission Adaptive Digital Composite Aerostructure Technologies

MALE Medium Altitude Long Endurance

MAV Micro Air Vehicle

MAVIS Massive Atmospheric Volume Instrumentation System

MCP Multi-Core Processor

MDSET Multi-Domain Synchronized Effects Tool

MEMS Micro-Electro-Mechanical Systems

MIT Massachusetts Institute of Technology

ML Machine Learning

MOD Ministry of Defence

MP Mission planning

MRFS Multi-Function RF System

MTBF Mean Time Between Failures

MUM-T Manned, Unmanned-Teaming

MWR Microwave Radiometry

NaBH4 Sodium Borohydride

NASA National Aeronautics and Space Administration

NATO North Atlantic Treaty Organisation

NATS National Air Traffic Service

NCA Nickel Cobalt Aluminium Oxide (LiNiCoAlO2)

NCC National Coordinating Center for Communications

NCM Nickle Cobalt Manganese Oxide (LiNiCoMnO2)

NED North-East-Down

NH3 Ammonia

NiMH Nickel Metal Hydride

NIR Near Infrared

NLP Natural Language Processing

NOC National Oceanography Centre

NOTAR No-Tail-Rotor

NOx Nitrogen Oxides

NRL US Naval Research Laboratory

NWP Numerical Weather Prediction

O2 Oxygen (molecularH2O)

OMPS Onboard Mission Planning System

P3HB poly-3-hydroxybutyrate

P4HB poly-4-hydroxybutyrate

PACT Pilot Authority and Control of Tasks

PATS Personal Air Transportation System

PDF Pseudo-Derivative Feedback

PHA poly-hydroxyalkanoate

PHBV poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

PID Proportional Integral and Differential

PIV Particle Image Velocimetry

PLA Polylactic Acid

PNT Position, Navigation and Time

PRM Probabilistic Road Maps

PRS Public Regulated Service

QUARC QinetiQ UxV Autonomy Research Capability

QuASAR Quantum-Assisted Sensing and Readout

Radar Radio Detection and Ranging

RC Remote Control

RDE Rotating Detonation Engine

RF Radio Frequency

RGB Red Green Blue

RIBI Remote Intelligence for Building Interiors

RLG Ring Laser Gyroscope

RPM Revolutions per Minute

RRT Rapidly Exploring Random Trees

RTG Radioisotope Thermoelectric Generator

RTK Real-time kinematic

SACI Spark Assisted Compression Ignition

SAR Synthetic Aperture Radar

SATCOM Satellite Communications

SBAS Space Based Augmentation System

SCADE Safety-Critical Application Development Environment

SDR Software Defined Radio

SFC Specific Fuel Consumption

SHARP Stationary High-Altitude Relay Platform

SiGe Silicon-Germanium

SLAM Simultaneous Location and Mapping

SMART Smart Material Actuated Rotor Technology

SnCl2 Tin Chloride

SoOP Signals of Opportunity

SPCCI Spark Controlled Compression Ignition

STANAG Standardization Agreement (NATO)

STOL Short Take-off and Landing

SWAP Size, Weight and Power

TBC Thermal Barrier Coatings

TEF Task Execution Framework

TEL Tetraethyllead

THOR Transformable Hovering Rotorcraft

TRL Technology Readiness Level

TRM Transmit / Receive Module

TT&C Tracking, Telemetry & Control

TU Delft Technische Universiteit Delft

UAS Unmanned Air System

UAV Unmanned Air Vehicle

UEL UAV Engines Ltd.

UHF Ultra High Frequency (RF)

UK United Kingdom

UMTS Universal Mobile Telecommunications System

US United States

USA United States of America

USN US Navy

UV Ultraviolet

UxV Unmanned Vehicle (undefined environment)

VHF Very High Frequency (RF)

VO2 Vanadium Oxide

VR Virtual Reality

VTOL Vertical Take-off and Landing

WLAN Wireless Local Area Network

WPT Wireless Power Transfer

YSZ Yttria-Stabilized Zirconia

Chapter 1

Airborne Platform Design & Systems Integration

The definition of an unmanned air system (UAS) encompasses a huge variety of aircraft platform types and scales, from large HALE aircraft to pico scale rotorcraft weighing tens of grams, and sub-millimetre scale 'smart dust'. Each UAS platform is, by definition, a complex integration of multiple components and sub-systems which combine to make the system as light and efficient as possible. No aircraft platform concept can ever be successful without such tight integration and we observe this time and time again throughout the literature.

The following chapter considers the two primary categories of aircraft platform, fixed and rotary wing along with their various derivatives and also introduces the less familiar concept of 'smart dust'. The current state of the art of each platform is considered in turn and we identify researchers both developing completely new platforms and finessing and improving the performance of existing platforms through the adoption of new technologies.

1.1 Rotary Wing Platforms

The concept of a rotary wing aircraft is not a recent one and has, in fact, been around in one form or another as long as the concept of fixed wing flight. There are, however, a considerable number of platforms which fall within the rotary wing category. Here we define a rotorcraft, or a rotary wing platform, using the rather loose definition of an aircraft whose main source of lift is derived from some form of rotating wing. Based on this definition the majority of rotary wing aircraft are capable of VTOL or, at the very least, STOL.

The following review commences by considering what is probably the most familiar and longest serving rotary wing aircraft, the helicopter. We then consider a novel variant of the helicopter, the *ornicopter*, before moving on to discuss multirotor aircraft. Cyclocopters and their mechanically simpler cousins, crossflow fan based aircraft, are then considered before moving on to aircraft capable of transitioning between flight modes. Finally, given their potential as a future driver of rotorcraft technology, personal air transportation systems are considered.

1.1.1 Helicopters

Perhaps one of the most instantly recognisable aircraft configurations due to the plethora of manned variants used by air taxis, emergency services etc., the helicopter employs a single primary lift rotor usually mounted onto a fuselage with a secondary tail rotor used to cancel the torque of the main rotor and enable yaw control. Helicopters employ a relatively complex mechanical system to enable control of the aircraft with a swash plate used to translate pilot inputs from the non-rotating fuselage to control the pitch of the rotating blades. Most multi-rotor aircraft forego this complexity in favour of directly driven propellers. Nevertheless, there are a number of unmanned helicopter systems currently in operation.

Helicopters have been an integral part of manned flight operations in their current guise since the 1940s and take little introduction. Rather than focus on the underlying physics or operation of these aircraft, we instead focus on the research trends in helicopter design over the past 5-10 years.

Given the relative maturity of the underlying principles of helicopter design it is rather unsurprising that there have been very few step changes in helicopter performance in recent years. Instead the story is one of gradual incremental improvement from a variety of disciplines and, as is typically the case for a mature technology, improvements are aimed towards robustness with respect to uncertainty, emissions improvements, fault tolerance etc. As noted by Ormiston [606] the mission performance of conventional helicopters has essentially plateaued with future leaps in capability unlikely without a shift to derivatives of the traditional helicopter configuration.

The rotor blades of a helicopter have undergone a significant transformation from the 1940s as experimental investigations coupled with advances in computational fluid dynamics simulations have driven the development of novel blade tip shapes [245] in the pursuit of higher levels of efficiency. Despite these developments, and as noted by Brocklehurst and Barakos [245] this has not resulted in a single overriding 'best' blade design. With the slowing down in blade efficiency improvements research has begun to focus more on blade robustness to icing [798], impact damage [751] and interactions with complex flows e.g. those behind a ship [714] while the growing trend towards aircraft electrification has opened doors for improvements in lift and propulsive efficiency due to the ability to more effectively control rotor RPM [696].

The drive for electrification is perhaps more prominent in manned helicopter systems rather than unmanned systems which tend to be already electrified, particularly when one considers relatively small-scale unmanned helicopters. Never-the-less it is worth considering here as advances made in the electrification of manned systems flow down to improve unmanned systems and frequently the proof of concept prior to application in a manned system is development of an unmanned demonstrator. Electrification introduces a number of other advantages in the design and efficiency of helicopters, the need for highly contaminant oil is reduced, complexity and mass of the engine is reduced while efficiency is increased, part wear is reduced while reliability is increased due to removal of the gearbox [696]. The ability to easily and independently modify main and tail rotor rotational speeds could greatly improve overall performance and expand the flight envelope while the removal of the engine and transmission would almost eliminate internal noise and vibrations. Serafini et al. [696] suggest that by 2030 a Li-S based electric helicopter will have equivalent performance to an existing fuel powered aircraft, in terms of cruise speed, endurance etc.

The prevalence of electrification within unmanned helicopter systems coupled with the current low power densities of batteries has led a number of researchers to explore the development of autonomous docking, recharging and battery swapping [543, 746]. With increasing battery capacity one might expect research in this area to become redundant over time, however, requirements for autonomous delivery systems will still drive a need for docking and automated payload swapping (see Section 3.4 for more on automated recharging).

Helicopter control is a significant and ongoing area of research within the current literature which focuses on the development of control systems which are effective at coping with more extreme conditions and manoeuvres for both unmanned and manned systems. Hu and Gu [432] point out that the challenges facing the control of large-scale helicopters include dealing with system uncertainties e.g. ground effect, near ground wind gusts and atmospheric turbulence and development of control systems capable of stabilising a helicopter across all of the highly complex manoeuvres that it is capable of performing. When examining the literature on both manned and unmanned helicopter systems the major focus in recent years has been on finding solutions to these control problems compared to

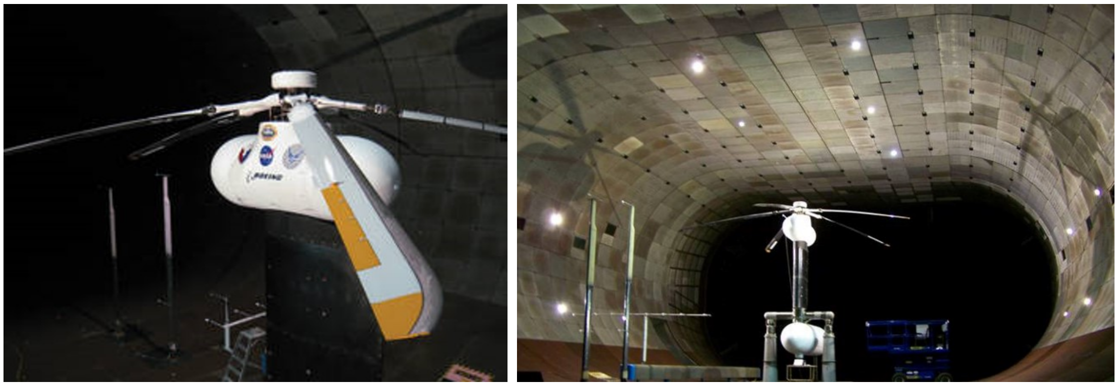

Figure 1.1: NASA wind tunnel test of the SMART rotor hub (image courtesy of NASA).

other areas of investigation. Significant effort, for example, has been expended investigating systems to dampen the response of underslung loads [231, 232], be more robust to uncertain operating conditions [194, 486, 334, 453] and operate at the optimal trim conditions [537]. Considerable research has also gone into methods for controlling helicopters when landing on moving or oscillating platforms in the presence of unfavourable flow conditions such as the deck of a ship [431, 801, 435]. Goulos and Bonesso [381] demonstrated that through optimal control of rotor speed and blade twist mission fuel consumption and therefore NOx production can be reduced by 5% and 8% respectively, compared to a fixed rotor.

Helicopters can face unexpected engine failure which can result in loss of the aircraft. Over recent years multiple researchers have developed approaches for control of helicopters during autorotation [510, 739, 491, 698]. Setu and Abhishek [698], in particular, have flight tested this capability using a Pixhawk 2.0 flight controller. Other efforts to develop robust control systems include those for actuator failures [629], obstacle avoidance [313, 794], operation in a degraded visual environment [727] and autonomous landing in cluttered previously unmapped terrain [685].

A further extension of helicopter control research encompasses the development rotor flaps with associated control loops [732]. The smart material actuated rotor technology (SMART) rotor, for example, includes a piezoelectric-actuated trailing-edge flap on each blade. The full scale rotor demonstrated that an 80% reduction in vibratory hub loads and up to 6dB noise reduction through active control of the flap.

Other recent research on improving the robustness of autonomous helicopter systems include intelligent algorithms to deal with windy conditions when flying long distances [321] and the optimal trajectory control within 'aggressive' manoeuvring [365].

As with all classes of aircraft there is a continual drive towards smaller and lighter airframes. The unmanned 100g micro helicopter developed by Bermes et al. [227] is a good example of developments within this area, however, in the past 3-4 years research into advanced helicopter configurations has been driven primarily by the need for an autonomous helicopter system to explore Mars [712, 392, 210]. Whilst the proposed Martian platform could not be classed as 'micro' in terms of its physical dimensions, the lower air density of the Martian atmosphere means that the rotors will be operating at extremely low Reynolds numbers [712] (<5000). Recent successful flights of helicopter systems designed for operation on Mars have therefore been forced to make advances in flap dynamics and rotor sensitivity to edgewise flows [392] which will naturally filter down over time to improve the performance of terrestrial micro helicopter designs. Of course Mars is also a GPS denied environment which necessitates advances in robust vision-based navigation systems [210], a capability which terrestrial micro helicopters, operating within buildings etc. can also take full advantage of in time.

Both Yeo [834] and Ormiston [606] have identified a requirement for an increase in cruise speed and

Figure 1.2: Sikorsky Rotor Systems Research Aircraft (RSRA) compound configuration (image courtesy of NASA).

range over that currently offered by a 'traditional' helicopter configuration and propose the compound helicopter as an alternative to a tiltrotor as a way in which these requirements could be fulfilled in the future. Originally investigated in the 1950s, compound helicopters have been largely ignored until recently due to the aeroelasticity issues associated with early prototypes which saw the tiltrotor overtake it as a preferred configuration to meet 'highspeed' mission requirements [606]. As the forward speed of a helicopter increases asymmetric flow conditions adversely affect the lifting and propulsive force capabilities of the rotor [834], a compound helicopter includes an additional fixed wing and/or propulsor which unload the main rotor in terms of the lift and propulsive force it is required to produce as forward speed increases. As the rotor is unloaded the pitch or RPM can be reduced reducing the level of asymmetric flow that the rotor sees and increasing the efficiency of the entire system in cruise. Hover performance can, however, be impacted due to the additional mass and, as with a tiltrotor, the level of performance advantage over a helicopter depends heavily upon the mission profile. Regardless of this, the compound helicopter configuration offers a considerable reduction in complexity over a tiltrotor configuration.

Research and development of compound helicopters has fallen far behind that of tiltrotors and helicopters with Ormiston [606] outlining the improvements required to realise their full potential. These include low-drag hub with a minimal frontal area, low-drag rotor design, advances in numerical simulation and control. Controller design is particularly important given the complex coupling between the rotor and propulsor in flight to ensure trim.

The future of helicopter development over the coming 5-10 years and beyond is therefore a mixed bag. With the exception of fundamental research into the aerodynamics and control of helicopters with rotors operating at low Reynolds numbers, improvements to 'traditional' helicopter configurations appear to be incremental and focused on robustness and control. Increased electrification in manned aircraft will demonstrate some advantages but the impact of this on unmanned systems will be less significant given that they are generally already electrified. The future, however, appears to be in developing hybrid concepts such a tiltrotors and compound helicopters which may be improved further still through the application of current and near term advances in helicopter technologies such as smart material rotors, greater electrification and control algorithms.

1.1.2 Ornicopters

As noted above, a conventional helicopter configuration requires some mechanism to cancel out the torque from the main rotor. Typically this is achieved through the use of a tail rotor or a similar system such as the Fenestron or NOTAR (no-tail-rotor) systems which employ, respectively, either a shrouded ducted fan within the tail fin or variable pitch fan within the tail boom to counter the main rotor torque and provide yaw control. The tail rotor, no matter the mechanism, consumes a substantial amount of the power generated by a helicopter, can suffer from control problems, is noisy and can be a significant cause of helicopter reliability issues [792]. Harris et al. [411], for example, state that 50% of US civil helicopter accidents between 1963 and 1997 are attributed to the tail rotor system. Removal of the rotor therefore has the potential of reducing maintenance and reliability issues and improving overall efficiency.

There are a number of other ways in which torque cancellation can be achieved. A counter rotating coaxial main rotor can be employed to cancel the torque as can a secondary offset rotor i.e. a bicopter or twincopter configuration such as on the Boeing Chinook. A pair of intermeshing blades, (a syncrocopter) can have a similar torque cancelling effect. An alternative approach is to design the operation of the main rotor such that no torque is imparted onto the fuselage in the first place. Inspired by flapping wing ornithopters which provide both propulsion and lift through the flapping of the aircraft's wings, Theo van Holten, proposed the concept of an aircraft with a set of rotating flapping wings, the Ornicopter [424]. This system consists of a single rotor helicopter that uses a set of flapping blades to propel the rotor thereby eliminating the reaction torque on the fuselage [772, 771].

Since its inception in 2002 the ornicopter concept has been almost exclusively developed by researchers at TU Delft. There are relatively few publications on the subject with the most recent in 2016 being an extension of the work carried out by Wan as part of his PhD thesis [792]. While perhaps currently being a relatively niche subject of investigation the ornicopter does offer some advantages over traditional helicopter systems although, as will be discussed below, these do currently come at a cost.

Wan's PhD thesis [792] represents the most extensive survey of the ornicopter literature and includes an investigation into the various aspects of the design, performance and operation of an ornicopter. By developing a series of ornicopter design and analysis tools Wan successfully demonstrated that compared to a conventional helicopter configuration (the BO-105), ornicopters have similar power requirements [791, 793], similar longitudinal and lateral stability but offer lower yaw stability [790], a smaller flight envelope [791] and suffer increased vibratory loads [792].

As noted above the removal of the tail rotor should remove a significant proportion of the power requirements for the rotorcraft. While this is indeed true, the main rotor of an ornicopter has been demonstrated to be less efficient than that of a traditional helicopter so that the overall power requirements are similar for both concepts [791]. Wan demonstrated that an ornicopter requires a larger rotor compared to a conventional helicopter configuration to reduce the induced power and keep the total increase in required power to a minimum [793].

Compared to the baseline BO-105 helicopter Wan demonstrated that an ornicopter with similar performance requirements suffered from poorer directional handling qualities. Removing the tail rotor impacts both the yaw stability and yaw damping [791] of the aircraft. However, Wan also demonstrated that implementing a simple stability and control augmentation system can improve performance somewhat [790].

Wan also demonstrated that ornicopters can suffer from a reduced flight envelope as they are more susceptible to rotor stall than a conventional helicopter configuration due to the larger variation in the angle of attack of the blades [792, 791]. However, stall performance has been demonstrated to be improved by reducing the mean blade element angle of attack.

Rather unsurprisingly, given the flapping mechanism through which an ornicopter achieves flight, these systems tend to generate significantly higher unfavourable vibratory loads than a conventional helicopter. These loads have been shown to be reduced significantly through the addition of more blades and/or through the modification of the blade flapping modes themselves [792].

As well as introducing additional vibrations into the system the flapping nature of the rotor coupled with the need to vary the level of flapping at different points around the circumference of the rotor requires a more complex mechanism than that of a traditional helicopter. However, whilst helicopters have generally converged around a mechanical configuration employing a swash plate to control blade pitch, there has been no convergence around a single solution to control of an ornicopter's rotor. Wan [792, 791] provides an interesting overview of the potential solutions to this particular mechanical problem which include a secondary swash plate, a gearwheel or some form of mechanism with an eccentricity. While a more complex rotor mechanism means an increase in maintenance and a potential reduction in reliability of the ornicopter the removal of the maintenance and reliability issues associated with the tail rotor may potentially outweigh this. However, the lack of convergence around a single mechanism and the lack of flying platforms and associated failure data makes this difficult to confirm. The unmanned demonstrator aircraft developed by TU Delft suffered from mechanism failures [792] during its operation although it was successful at illustrating the validity of the principle and that a torqueless state could be achieved.

While offering an attractive tailless single rotor configuration, the disadvantages associated with an ornicopter configuration currently limit it to an interesting research activity. However, this does not necessarily mean that the issues discussed above cannot be overcome in the coming 10-15 years making the ornicopter a viable alternative to other unmanned rotorcraft systems. Wan demonstrated [793] that if the design space for an ornicopter can be increased by introducing more freedom in terms of the number of rotors, flapping configuration, rotor size etc. such a system can approach the performance of an equivalent helicopter. Further improvements through, for example, the application of high harmonic control, individual blade control and variable RPM motors may also improve vibratory response of the system and performance in general [792]. But perhaps the immediate future of such a configurations lies in its hybridisation with other, more conventional configurations. A system whereby a fin compensates for torque in forward flight thereby enabling the flapping to be minimised and permitting the system to operated in a similar manner to a traditional helicopter has already been proposed by Wan [792].

1.1.3 Multirotors

We define a multirotor aircraft as any aircraft whose primary source of lift and propulsion is provided by one or more rotor. While helicopters can be considered within this classification we consider them separately due to their additional tail rotor and their ubiquity and familiarity within manned flight and, as shall be illustrated within this section, there are other single rotor platforms which cannot be classified as traditional helicopters.

Multirotor aircraft can come in a variety of configurations with different numbers of rotors and examples exist throughout the literature of almost all of them, these include monocopters, bicopters, tri-rotors, the familiar quadcopter, pentacopters, hexacopters, octocopters, decacopters, dodecacopters while the two seat Volocopter 2X has 18 rotors. Even within these broad classifications based on the number of rotors there exist sub-variants depending on whether or not the rotors are coaxial, for example, 'Y6' and 'X8' configurations of hexacopter and octocopter exist. Even within the relatively familiar quadrotor class there are a number of ways of arranging the rotors including, for example, 'X', '+', 'Y4' and even a four rotor V-tail. While a detailed taxonomy of each of these configurations and rotor arrangements is beyond the scope of this review it is worth noting that multirotors are highly configurable and flexible systems offering potential for considerable levels of redundancy with increasing numbers of rotors.

The past 5-10 years has seen a rapid growth of the unmanned multirotor sector fuelled by reductions

Figure 1.3: A NASA research & development quadrotor (image courtesy of NASA).

in flight controller cost and complexity, improvements in motor design and battery capacity [299]. The literature therefore contains many examples of these systems being applied throughout numerous walks of life to achieve mission objectives that would either have been impossible beforehand, required additional much more expensive equipment or a manned flight. Multirotors have been extensively deployed as a low cost platform for aerial imaging for a variety of purposes including, mapping for road design [864], rut and pothole identification [666], detection of pedestrians [298] and ground targets [422] including cattle [652]. Other example applications include the localisation of radio signals [317], inspection [702], wave and tidal measurement [437] and atmospheric sampling [384]. Multirotors have also seen a rapid rise in popularity within the hobbyist market due to the relative ease with which they can be flown by a novice compared to a fixed wing aircraft whilst providing a stable camera platform. The growth of drone racing activities in recent years has also helped catapult multirotors into the minds of the populous with drone racing leagues being set up around the world, races broadcast on television and large prize funds of over $100,000 on offer.

Naturally such a growth in the range of multirotor applications corresponds with a considerable increase in research effort. This research can be divided up into a number of distinct categories including, control, path planning, fundamental aerodynamics research, system design processes, novel multirotor configurations and nano (<0.1m and 50g) systems.

Despite the plethora of commercial off the shelf multirotor flight control systems developed over recent years, particularly for the hobby market, the development of novel multirotor control approaches continues to be an active research area. The development of novel rotor configurations naturally drives the development of novel control systems but beyond this there are fundamental control issues encountered by all unmanned systems which are also of interest in multirotor development e.g. controller robustness. Hori et al. [425] have explored the development of an adaptive control system capable of effectively controlling the altitude of a multirotor even if the dynamics of the aircraft change. Araar et al. [187] and Michieletto et al. [566] have explored control systems which enable a multirotor to remain in place at a fixed altitude upon failure of one or more propellers. Michieletto et al. [566], in particular, demonstrated the limitations of a number of existing multirotor configurations in this regard. Other researchers have investigated position and attitude control [471, 357, 262], control in the presence of a suspended payload [697, 482], autonomous landing onto a moving ground vehicle [394] and rejection of disturbances [279].

Moving beyond basic control the literature includes a number of examples of efforts to implement automated path planning and obstacle avoidance particularly within GPS denied environments. Such a capability has a number of applications including, for example, inspection, search and rescue, parcel delivery and surveillance. Pradeep et al. [626] and Dorling et al. [315] have investigated solutions to path planning problems for trajectory optimisation for, respectively, precision agriculture and drone delivery. However, a number of authors have developed systems for path planning within enclosed spaces where there are an unknown number of obstacles at unknown locations [247, 591, 197, 335]. Azevedo et al. [197], for example, developed a LIDAR-based real-time collision avoidance system while Brown and Rogers [247] developed a real-time probabilistic path planner for UAVs operating in cluttered environments. Drone racing has also been employed as a framework through which automated path planning and obstacle avoidance systems can be developed and tested due to the useful figure of merit, lap time. Jung et al. [456], for example, have developed a real-time system for an autonomous racing drone capable of quickly and reliably detecting race gates and avoiding collisions based on deep learning. Moon et al. [579] provides an interesting comparison of a number of University teams attempting to autonomously traverse a drone racing course using a variety of techniques. it is envisaged that this competition will be held annually and drive multirotor control and automation technologies in the same way that competitions such as the Large Scale Visual Recognition Challenge have driven the development of deep learning and neural networks in recent years.

Unlike fixed wing aircraft where there has been an established design methodology for a number of decades there is no agreed definitive approach to the design of a multirotor system. The recent literature therefore contains a number of examples of authors attempting to remedy this gap in knowledge by proposing different conceptual design and optimisation tools [359, 809, 476, 604, 292] each of which have been validated against a range of different aircraft sizes and configurations. Given the wealth of potential multirotor configurations possible a number of authors have wrapped their conceptual design systems up within a larger optimisation workflow to enable the optimal number of blades etc. to be automatically determined for a particular mission [541, 542, 213]. These efforts in developing optimal multirotor designs have been assisted by the efforts of other researchers to experimentally characterise multirotor propulsion systems [493] and quantify other figures of merit such as manoeuvrability and agility [778] or station-keeping [201].

The multirotor literature contains a number of examples of research into the fundamental aerodynamics of rotor blades all of which have important implications for the prediction of multirotor dynamics and therefore controller development and aircraft design. This includes performance characterisations of static rotors [307], studies into the impact of overlapping rotors [242, 713] and the influence of the rotor wash on wind speed measurements [576]. Models to predict the performance of multirotors in hover [379] and in ground effect [675, 648] have been developed. Other researchers have focused on the prediction of multirotor performance in forward flight determining, for example, that airframe drag is an important factor limiting multirotor performance [282] and that the performance of the rear rotor can be significantly impacted by the wake from the leading rotor in flight [590].

In addition to the above fundamental research into control, path planning, design and aerodynamics the literature also contains a number of interesting developments of the fundamental multirotor platform itself. Hockley and Butka [423], for example, have developed a biologically inspired autonomous monocopter. Inspired by the shape of a maple seed (similar to a sycamore seed with only one 'blade'), the aircraft consists of a single foam wing rotating around an axis located at one tip with a ducted fan on the opposite side of the axis of rotation. This configuration enables flight in any direction as well as hover, with any sensors on board the aircraft becoming scanning due to the rotation of the entire system. Whilst an automated flight of this system has been demonstrated the aircraft remains to be fully characterised and there is a considerable lack of experimental data going forward. Both Fujita et al. [346] and Tafreshi et al. [747] have taken the concept further and developed improved control systems for similar monocopter aircraft but currently this configuration remains somewhat of an oddity.

Shaiful et al. [699] have developed the monocopter concept a little further to create a unique transitioning aircraft. The Transformable Hovering Rotorcraft (THOR) concept consists of a wing which is able to rotate around a central axis and simultaneously effect changes to the pitch of either side. Similar to a monocopter, except the system is symmetric as opposed to asymmetric, the aircraft can take off and hover vertically when the entire aircraft rotates. As it moves forward the rate of rotation then slows until the aircraft transitions into a flying wing.

Traditionally multirotor systems employ a set of fixed pitch propellers with the RPM of the electric motor effecting control. As stated above this is mechanically a much simpler mechanism than the swash plate found on helicopters, however, the pitch control offered by a swash plate can bring aerodynamic benefits. Porter et al. [625] recently explored the application of variable pitch rotors in the context of a multirotor and found that compared to fixed pitch rotors the system was more efficient in terms of energy consumption under similar operating conditions.

Multirotor performance is naturally limited by the capacity of any on board power source. Jung et al. [457] developed a tethering system through which to power a multirotor and achieve considerable increases in endurance for low-altitude applications. Another option to reduce power consumption is to remove the loiter stage entirely from a mission and enable the aircraft to land, or perch, on buildings, lamp posts or similarly tall infrastructure in order to perform a surveillance mission. Lin et al. [518], for example, have developed an automated perching system to enable a multirotor to land onto, and remain attached to, a fence post.

Perching drones are an example of one of the ways researchers are beginning to explore alternative ways in which multirotors can more effectively interact with their environment. The work of Molina and Hirai [575] is an excellent illustration of the potential direction this kind of research may go in the coming years. Most aircraft are designed so that any payload carrying capability is focused around the aircraft's centre of gravity, this way any change in mass does not impact the stability of the system. Multirotors are no different in this regard, however, this constraint restricts the possible interactions that such an aircraft can have with the environment, a multirotor working in a warehouse for example cannot take packages off a shelf as the centre of gravity will shift considerably far forward. However, Molina and Hirai [575] employed the landing gear as a kind of 'tail' by which any shift in centre of gravity can be offset by moving the landing gear rearwards.

Continuing on the theme of environmental interaction Zhao et al. [854] developed an extremely novel transformable multirotor with the aim of passing through small spaces and wrapping itself around objects it is required to lift. The system consists of a set of six linked modules each with a shrouded propeller and a battery. Each of these modules are daisy-chained together using a set of actuators thereby enabling the modules to articulate in 2D. The entire system is capable of transforming in mid-air from a conventional hexagonal to a 'long thin' configuration on anything in between. This enables the system to navigate small passages and also 'wrap' around objects and lift them up.

Whilst multirotor systems can be relatively reliable due to the redundant rotors their reliability can be improved further through inbuilt health monitoring. Brown et al. [249] have developed an embedded structural health monitoring system capable of classifying propeller, motor, and structural hardware failures via an inbuilt sensor network. Such systems enable monitoring of future drone delivery systems, for example, thereby maximising in-air time and enabling maintenance planning and scheduling in a manner similar to that of modern aero engines.

The current limitations of multirotor endurance and forward flight speed has also led researchers to investigate cooperative missions with fixed wing aircraft. Jo et al. [454], for example, present experimental results from a number of tests whereby a multicopter is launched from a fixed-wing UAV involving automated waypoint navigation and landing. Advances in this area could see swarms of smaller multirotors launched from much larger unmanned or manned aircraft for rapid mapping or search and rescue missions.

As with all unmanned systems, multirotors have been the subject of continual efforts to miniaturise them. Nano quadcopter systems have been developed by a number of researchers in recent years. Zhang et al. [852] for example, developed a nano quadcopter weighing less than 45g with a diameter of under 0.15m which was capable of fully autonomous flight within a GPS-denied environment with the aid of an on-board vision system. More recently Garcia et al. [354] developed and successfully test flew an autonomous nano quadcopter smaller than that of Zhang et al., weighing only 27 g. The latest version of this aircraft, the Crazyflie 2.1, is available for purchase for approximately £200. With a maximum payload of 15 g and a flight time of 7 minutes with the stock battery, the platform is intended to be an open source development kit for swarming research.

The recent rapid rise of the multirotor has seen it achieve a ubiquity that other unmanned aircraft platforms can only dream of. it is not uncommon, for example, to find small quadcopters on sale on the high street or even in supermarkets, ASDA, for example, have sold nano quadcopters for as little as £29. Whilst perhaps not offering the performance of some of the cutting edge systems described below these 'toys' are indicative of the pace of multirotor development.

The above literature review points to a number of potential developments in multirotor design in the short to medium term. Improved predictive tools derived from a better understanding of the fundamental physics of multirotor flight combined with optimisation methods will help drive multirotor designs to be as efficient as possible using whatever components are available at the time. Controllability issues will continue to be addressed and drive towards a robust, fault tolerant control system capable of reacting seamlessly to changes in the dynamics of the system as it interacts with its environment. These improvements will also drive the development of novel mission specific systems or indeed systems which can exploit the flexibility of the multirotor platform to maximise multipoint operating performance through either in-flight adaptation/morphing or through hybridisation with other platforms e.g. transitioning aircraft. The continual investigation of applications for multirotors will see the development of further novel mechanisms through which multirotors can effectively interact with their environment again driving the need for an aircraft capable of adapting in real time.

1.1.4 Cyclocopters

A cyclocopter, otherwise known as a cyclorotor or cyclogyro, consists of an aircraft with a number of rotors each of which comprise of several blades rotating about a horizontal axis perpendicular to the direction of normal flight [844]. A pitch control mechanism within each rotor is used to vary the pitch of each blade relative to the tangent of the circle prescribing the blade's path. The pitch of each blade can be adjusted in both amplitude and phase angle thereby permitting a resultant thrust force in any direction perpendicular to the axis of the rotor. In operation the rotor is similar to that of a Voith Schneider propeller within the marine industry [615]. The cyclocopter is not a recent concept but has been around for over 100 years with early investigations into the feasibility of the concept dating back to 1909 [316, 663]. However, despite several attempts in the 1930s it is only in the past 15-20 years that a viable flying cyclocopter platform has been demonstrated. Failure of the early prototypes can be attributed to a number of factors including, available materials, the mass of contemporary engines and insufficient knowledge of the aerodynamics governing the operation of such rotors [695] all of which have advanced considerably in recent years.

There are predominantly two variants of the cyclocopter class of aircraft within the literature. The first is a dual rotor configuration with an additional conventional propeller used to counter the torque from both rotors and control pitch. The second is a quad rotor configuration which employs counter rotating rotors for torque cancellation and pitch control. While both of these quad rotor aircraft have two sets of parallel rotors other 'plus' configurations have been demonstrated within the literature [221].

Cyclocopter demonstrators within the literature vary hugely in their scale. Lee et al. [509] successfully demonstrated a large 110 kg cyclocopter with two cycloidal rotors and a single tail propeller for torque cancellation and pitch control in stable hover. Benedict et al. [221] successfully flight tested a 800g cyclocopter with a four rotor plus-shaped configuration. Benedict has also been heavily involved in the drive to produce cyclocopters of smaller and smaller scale. In 2014 Benedict et al. [222] demonstrated the successful flight of a 100g aircraft with a dual rotor and tail propeller configuration while in

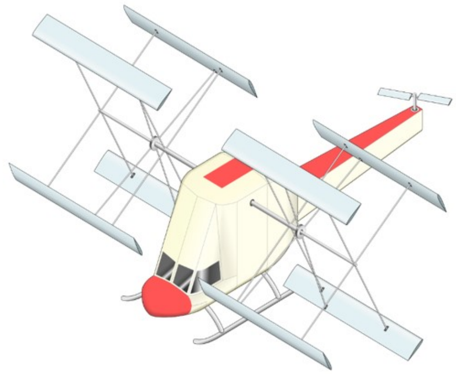

Figure 1.4: An example of a cyclocopter (courtesy Wikipedia Creative Commons)

2016 the Benedict was also involved in the development of a 29g aircraft [663]. Also a dual rotor plus tail propeller configuration but with no exposed rotor shaft, novel semi-elliptical blades and a custom built autopilot with PID controller weighing just 1.3g, this aircraft represents the smallest cyclocopter ever built.

Other variations of the cyclocopter concept include an all-terrain version developed by Shrestha et al. [708] which is capable of transition between aerial, terrestrial and aquatic locomotion. At just over 1 kg this aircraft employs four cycloidal rotors as a source of propulsion for all modes with terrestrial locomotion achieved using the outer 'rims' of the rotor and aquatic locomotion achieved with the aid of a set of floats with the rotors providing propulsion.

Schwaiger and Will's D-Dalus [695] concept employs four cyclorotors integrated within a lifting body to improve performance in forward flight while Ejaz et al. [328] have proposed the integration of dual cyclorotors within a novel autogyro concept.

The cyclocopter concept offers a number of considerable advantages over other rotary wing platforms. As already alluded to above the ability to change the pitch of the blades enables thrust to be vectored anywhere within the 360° parallel to the rotor's plane of rotation. The system therefore offers an almost instant variation in the magnitude and direction of thrust [578] which enables VTOL. Forward flight can also be achieved without the need to pitch the aircraft forward as with a more traditional multirotor concept or the need for a complex transition mechanism. The ability to instantaneously vector thrust may also offer enhanced manoeuvrability compared to conventional multirotor concepts which improves its utility in highly constrained and indoor operations [663]. A cyclocopter's rotors typically operate as a reduced RPM compared to conventional propellers which results in a lower noise level further enhancing their utility with respect to both indoor and general surveillance operations [663, 221, 578].

Unlike a traditional propeller the span of each blade within a cycloidal rotor experience broadly the same flow regime which makes the design and optimisation of these blades a much simpler operation compared to a propeller [663]. There are numerous examples throughout the literature that demonstrate that the power loading (thrust per unit power) of a cycloidal rotor can be considerably higher than that of a conventional rotor of a similar scale resulting in a much more efficient hover [844, 663, 221, 578, 219]. Some studies even suggest that the efficiency of a cycloidal rotor will improve with increasing forward flight speed [695]. Shrestha et al. [710], for example, state that the power to maintain a steady level flight drops by approximately 35% up to an advance ratio of 1.0 due to the associated increase in the lift producing efficiency of the rotor. Reed et al. [643] demonstrated a similar, 40% increase in efficiency for a rotor operating at low Reynold's numbers at advance ratios approaching unity.

A major advantage of a cyclocopter is its performance at small scales relative to that of a conventional multirotor. At low Reynold's numbers $O(10^4)$ conventional rotor blade designs suffer from a considerable reduction in their efficiency due to the large values of profile drag associated with thick boundary layer formations on the blades, large induced losses, and higher rotational and turbulent losses in the downstream wake of the rotating blades [663, 708]. This, coupled with the efficiency of the micro-motors necessary to power the propellers at this scale, can considerably limit the endurance of such an aircraft. The cycloidal rotors on a cyclocopter, however, have the potential to be much more efficient at small scale with some studies, particularly at the University of Maryland, demonstrating optimised cycloidal rotors with greater efficiencies than conventional propellers at these scales [221, 219].

The main disadvantage of the cyclocopter concept is relatively large fraction of the aircraft's empty weight taken up by the rotor when compared to other rotary wing concepts [222, 439]. Even though the rotor itself may be more efficient the additional mass of the rotor can put the system at a disadvantage. Rotor mass is directly related to the mass of the individual blades and the design of these blades to overcome the centrifugal loads on the system. Given that the stiffness of the blades directly impacts their performance it is only been with the advent of modern composite materials that the blade and rotor mass has been reduced enough to make the cyclocopter a viable system.

A considerable amount of work has carried out within the literature with regards to understanding and predicting the aerodynamic performance of cycloidal rotors. Analytical models have been developed which enable rapid preliminary design [844, 578] while 2D and 3D CFD simulations have been shown to correlate very well with experimental tests both in terms of overall performance prediction and the prediction of flow features [844, 509, 841, 434]. It should be noted though that the 'virtual camber' experienced by a blade section, whereby the rotation of the blade results in a curvilinear flow over the aerofoil, can introduce difficulties when using analytical techniques [578].

These investigations have highlighted the important design features for this class of aircraft. The number of blades has a direct impact on both the level of thrust [844] produced by the system and the systems vibratory response. However, there is a diminishing return with each additional blade and a clear optimal number of blades for maximum system efficiency has been reported by a number of authors [844, 615, 814]. With an increasing number of blades the level of interference between blades increases [749].

While the planform shape of the rotor blades has been shown to have some impact on performance (increasing aspect ratio can slightly improve efficiency) the blade aerofoil and pitching motion are generally agreed to be significantly more important [434]. Highly cambered aerofoils have been demonstrated to reduce performance while symmetric aerofoils, or aerofoils with a small amount of positive or negative camber (-5 - 1%) have been shown to be beneficial [814, 849, 750]. Aerofoil thickness has also been shown to have an impact on performance with thicker aerofoils impacting the level of variation in the side forces produced by the system, thereby reducing vibrations, delaying stall and also enabling a better structural design [814, 433]. Thicker aerofoils do, however, also increase drag which requires a compromise to ensure overall rotor performance is maximised [750, 814]. Blade tip vortices have been demonstrated to play an important role in determining the performance of a cycloidal rotor [841] with end plates often being added to reduce their impact [509]. Neglecting the cross flow caused by these vortices has been shown to impact the prediction of the force produced by a blade at each circumferential position [841].

As noted above control of the pitch of the blades as they rotate around the rotor axis is extremely important to effectively and efficiently control the aircraft. High levels of pitch can lead to blade stall and a dramatic increase in the required power [844] whilst the non-zero horizontal component of the resultant thrust force [749], caused by a combination of the Magnus effect, variations in the induced velocity on the advancing and retreating blades and the impact of virtual camber [509], requires the ability to offset the phase angle of the blade pitch to correct. To date the most common form of pitch control in flight proven aircraft is a four-bar linkage [221, 222, 578, 711] mechanism with the location of a secondary axis eccentric to the main rotor axis used to control the level and phase of blade pitch. it is been long recognised that in order to fully exploit the potential performance advantage of a cycloidal rotor, particularly at higher advance ratios [220], that a more effective control method of blade pitch is required. The literature contains few examples of research into the pitching mechanism itself with only the novel 3D cam designed by Adams et al. [167] considered a significant departure from the norm. This mechanism offers much more control over the blade kinematics and takes a significant step towards achieving the non-traditional pitching advocated by Siegel et al. [715] for improved forward flight performance.

As alluded to above the unsteadiness in the flow produced by the rotor causes oscillations to the sideways component of the thrust vector, although the time averaged resultant force and direction doesn't vary as a result of this it can introduce vibrations into the system. While these vibrations can reduce the mechanical efficiency of the rotor as a whole [433] there has currently been little research into ways in which these vibrations can be minimised apart from the inclusion of additional blades. Two bladed rotors, for example, are particularly impacted by unwanted vibrations [844].

The literature contains a number of examples of research into the structural design of individual rotor blades. Modern lightweight rotor blades tend to be the result of a combination of carbon or glass fibre composite materials, styrofoam, mylar film and balsa wood [844, 509, 440] to ensure they are as light and as stiff as possible. Experiments carried out by Halder and Benedict [401] into the impact of flexible blades on rotor performance demonstrated a clear correlation between an increase in blade flexibility and a simultaneous decrease in rotor thrust and increase in power consumption.

A number of studies have been performed into the control aspects of cyclocopters, however, these have primarily been carried out on the dual rotor plus tail propeller configuration [709, 430, 710]. Shrestha et al. [709], for example, developed a 6-DOF flight dynamics more of a cyclocopter from which it was discovered that there existed an inherent roll-yaw coupling in forward flight. Hrishikeshavan et al. [430], employed a series of infra red cameras and reflective markers to track a similar aircraft and determine the control derivatives. Again lateral and yaw modes were noted to be highly coupled but the longitudinal and heave degrees of freedom were found to be decoupled from remaining system dynamics. Hrishikeshavan et al. also estimated that the system was tolerant to gusts of 7.9 and 17 m/s in the longitudinal and lateral directions respectively, a significant increase over the 3 m/s tolerance of the shrouded MAV used to compare their cyclocopter to. Shrestha et al. [710] eventually implemented a control strategy based upon their earlier work on a dual rotor cyclocopter becoming the first to achieve stable forward flight using purely thrust vectoring i.e. without pitching the aircraft forward and maintaining a level attitude throughout.

Unlike more established rotary wing concepts the cyclocopter has undergone relatively little research and development and, as already noted, has only really become practical in the past 15-20 years. To date the focus of this research has been on miniaturisation, understanding the aerodynamics and control with little attempts made to date to serious optimise the system given the tools that have been developed. Some examples of the potential performance gains which are possible given time already exist within the literature. During the development of their D-Dalus concept Schwaiger and Wills almost doubled the thrust produced by their system whilst maintaining both the power consumption and the size of the rotor [695]. Tang et al. [750] demonstrated the potential for the application of modern design optimisation techniques to improving the performance of a cycloidal rotor with an 18% increase in rotor efficiency by modifying only four parameters controlling the aerofoil shape. Much more considerable improvements could be possible by optimising more parameters relating to the aerofoil shape and considering the pitching kinematics etc. There is considerable scope to investigate alternate mechanisms to control blade pitch which could potentially unlock huge improvements in performance be they from improved aerodynamic performance but by also removing losses from the mechanism itself. The incorporation of dielectric barrier discharge plasma actuators for active flow control has already been explored within the literature [815] and shows promise for the improving performance of the rotor blades under deep stall.

In terms of future applications. The suitability of the cyclocopter to small scale ‘micro’ aircraft operations is abundantly clear from the literature with relatively little optimisation an impressive figure of merit of 0.65 has already been demonstrated at a Reynold’s number of approximately 18,000 [643]. This is already on par with the most efficient multirotor system at that scale and with better understanding of the flow physics, better pitch control mechanism and a lighter design this performance could improve further in the coming 5-10 years. Applications to high altitude long endurance (HALE) aircraft which also operate at relatively low Reynolds numbers compared to conventional aircraft could also potentially benefit from improvements in cyclorotor technology [715]. Gaps in knowledge around the performance of such as system in forward flight at advance ratios greater than one currently exist but given the improvements in thrust ($\times$3.5 that in hover when travelling at 30m/s) in forward flight demonstrated by the D-Dalus [695] development program there is potential for the system to be more widely employed in higher speed aircraft designs. Regardless, advancements will need to be made in the design of the rotor in order to reduce the mass of the system to make it truly competitive.

1.1.5 Cross-flow Fan Based Aircraft

First proposed by Paul Mortier in 1893 [723] the cross-flow fan (CFF) could be considered as a distant cousin of the cycloidal rotor. Like the cycloidal rotor the fan consists of a series of blades rotating around an axis perpendicular to the main direction of air flow. However, unlike a cycloidal rotor there tends to be more blades in a CFF, the pitch of each blade is fixed as they spin around the axis and the fan is contained within a housing. A typical CFF consists of an inlet to the fan followed by an outlet to a diffuser. Unlike an axial fan the walls of the casing play a significant role in the overall performance and efficiency of the fan [609]. End walls are present to remove tip losses from the system which results in a broadly two dimensional flow [294], although some recent evidence suggests some 3D features close to the end walls when the fan has a relatively short span [264]. As with a cycloidal rotor the flow through a CFF passes over the blades twice, however, as the pitch of the blades remains constant a pair of eccentric vortices are created on the walls on either side of the fan. This recirculating flow introduces a loss into the system which makes it difficult for a CFF to be as efficient as a more traditional axial fan or propeller. While adiabatic compression efficiencies of up to 80% can be achieved with a CFF this is lower than that for an axial fan [619]. However, what the CFF lacks in efficiency it makes up for in compactness with the large span to diameter ratio of the fan making it ideal for embedding within structures and removing blade strike hazards [294, 619, 498, 497].

CFFs are ubiquitous within the air conditioning industry with their large span to diameter ratio being extremely useful for generating ‘curtains’ of cooling or heating air. As their application within this industry is rather mature a great deal of research has gone into optimising both the blades and casing for maximum efficiency. However, despite interest in CFF based STOL/VTOL aircraft as part of a US research programme in the 1980s [294] it is only in the past 20 years that CFFs are beginning to be investigated seriously for aerospace applications. As a result the knowledge and understanding of CFFs as a source of propulsion, lift augmentation, vectored thrust and for boundary layer ingestion is relatively immature.

CFF based concepts explored in the 1980s tended to employ the CFF as a high lift device or a way to ingest the boundary layer along a wing or fuselage, see the review by Dang and Bushnell [294]] for details. However, none of these concepts found their way onto a flight demonstrator aircraft. It wasn’t until the late 1990s, early 2000s, when Patrick Peebles[1] took a different approach to cross-flow fan technology that a CFF based aircraft was successfully flown. Rather than embedding a small fan within the wing or fuselage the ‘fanwing’ concept employed a large fan along the entire leading edge of a wing with an unusually thick triangular aerofoil profile. Here the fan generates and maintains a vortex

[1] http://www.fanwing.com/

at its center, the low pressure from which ‘sucks’ the wing forward. Simultaneously the fan accelerates air over the top of the wing which increases the lift generated and gives the concept its impressive STOL performance. Whilst not a true CFF, as there is no throughflow, it remains an interesting concept in its own right with considerable potential for further development. Recently, for example, Siliang and Zhengfei [716] developed a tandem variant of the fanwing concept with a combination of CFD and wind tunnel experiments used to optimally place the wings relative to each other.

Apart from the fanwing concept the majority of CFF based fixed wing aircraft concepts employ a fan embedded within the wing. The work of Kummer and Dang [498, 497] on their ‘propulsive wing’ concept is an excellent example of this particular configuration. Here a CFF is embedded within the trailing edge of the wing with the inlet to the fan on the wings upper surface and the fan exhaust along the trailing edge of the wing. Here the CFF is used to augment lift, maintain flow attachment at high angles of attack and provide propulsion. Kummer and Dang successfully demonstrated an aerofoil with the CFF in this configuration to be capable of maintaining attached flow up to 40° while simultaneously generating a lift coefficient of over 6.4 and a drag coefficient of -0.98 i.e. significant amounts of lift and thrust. Compared to other embedded CFF concepts Kummer and Dang chose to base their concept upon an unusually thick aerofoil. This enables the aircraft to be structurally more efficient and, coupled with the enhance lift capability, carry larger (×10 volume) and heavier (×3 mass) loads compared to similarly sized aircraft [723].

More recent fixed wing applications reported within the literature have focused on CFFs for lift augmentation and boundary layer ingestion. Kerho et al. [469] performed a series of experimental tests to determine the performance of a transonic aerofoil with an embedded CFF. The results of this study found that an aircraft crusing at Mach 0.7 would see a 62% reduction in drag and an 11.8% reduction in fuel burn. Karpuk et al. [462] and Raush et al. [642] have also explored the potential for CFF integrated within a wing as, respectively, a high lift device and for simultaneous thrust and lift enhancement with Karpuk et al. considering the CFF within the conceptual design of a medium range ‘multi-purpose’ aircraft. Perry and Ansell [619] explored the use of CFFs for distributed propulsion and boundary layer ingestion in transonic aircraft and noted that unlike axial fans CFFs are relatively insensitive to inlet distortion issues.

The literature contains a number of examples of CFFs being employed within VTOL aircraft. Explored primarily by the Naval Postgraduate School, Monterey, California over the past 20 years, a number of CFF VTOL concepts have been successfully flight tested. Mainly the work of masters students studying at the school there are no peer reviewed publications on this concept within the academic literature.

Gossett [380] initially investigated the application of a CFF within a hypothetical single seat VTOL aircraft and determined that the concept was viable but only with further investigation of power plant technology and fan design parameters and relationships. These finds inspired a number of masters projects to further understand CFF performance and driving parameters. Cordero [286] investigated the impact of a set of inlet guide vanes, however, a notable improvement in performance was not demonstrated. Delagrange [302] investigated a CFF propulsion system experimentally and demonstrated that reliable computational simulations could be performed. Kwek [499] performed a set of numerical and physical experiments comparing straight and helical CFF blades which suggested that helical blades offered a potential 40% increase in thrust, less variation in torque and a reduction in noise compared to straight blades. Martin [550] demonstrated, once again through a combination of numerical and experimental studies, that an optimal number of blades exists in order to maximise thrust and isentropic efficiency. This work was instrumental in demonstrating that a thrust to weight ratio of greater than 1.0 could be achieved. Yeo [835] assessed the feasibility of combining two CFFs in a back-to-back configuration and whether or not thrust could be augmented. Yeo found that air is indeed drawn between the CFF housing and the degree of this is dependent on the separation between the fans. However, it was also discovered that when close to the ground such a configuration can suffer from a degraded performance due to the being drawn back up between the fans.

In 2015, Smitley [723], exploited all of the prior research at the Naval Postgraduate School to successfully fly, untethered, the worlds first CFF VTOL. The aircraft consisted of a quad rotor configuration and was capable of a maximum thrust to weight ratio of 2.57. Fulton took the concept a stage further and combined the concept of Kummer and Dang [498] with Smitley's quad rotor to produce a quad rotor configuration where the fans are embedded within aerofoils. This aircraft was developed with the view to enable transition from vertical to horizontal flight but was only demonstrated in hover.

As noted above, CFFs are relatively immature within the aerospace sector and, in addition to, the aircraft concepts described above the literature contains numerous examples of more fundamental research being carried out in recent years on CFFs. Considerable work has been carried out to understand the impact of each of the CFF design features on system performance. Govardhan and Sampat [382] investigated the impact of blade number using 3D CFD and confirmed a change in performance with blade number. Toffolo [759] carried out a campaign of numerical simulations on different fan configurations and noted that the fan performance depends on the complex non-axisymmetrical flow within the fan which is heavily influenced by the design of both the casing and geometry. In particular the radial width of rear wall followed by the position and the thickness of the vortex wall were deemed to be the most important parameters. Fukutomi and Nakamura [347] studied the effect of angle and length of the inlet guide wall and noted an improved efficiency was possible by suppressing the circulating flow. As part of his PhD thesis, Kummer [497] performed a series of extensive validation studies of his numerical models and used these to study the impact of CFF parameters. He found that the vortex cavity, reducing the blade-wall clearance and moving to blades described by double circular arcs all have positive impact on efficiency. Kim et al. [480] reinforced the importance of the rear wall shape and noted that an Archimedes spiral raised the pressure coefficient of the CFF and improved efficiency. Similar to the later work of Cordero [286], Chen and Choi [278] investigated the impact of an inlet guide vane on CFF performance, however, they employed only a single vane compared to the cascade of inlet vanes studied by Cordero. Chen and Choi also noted that inlet angle will impact efficiency but unlike Coredo suggest that there is an optimal angle. The study carried out by Ozer and Kumluta [609] represents the single most exhaustive experimental study of the impact of CFF design parameters. Carrying out over 480 PIV experiments, they quantified the relative impact of a number of important design parameters on flow rate and determined that the vortex wall and curvature of the volute have a significant effect on flow rate. Noise production from CFFs has also been recently studied by Yang and Wu [831] and Li [517].

In addition to investigating a tandem fanwing, Siliang et al. [717] also investigated the CFF as a helicopter anti-torque device. Embedded along the length of the helicopter tail boom the CFF would provide a lateral thrust and therefore an opposing torque to that from the main rotor. The concept was demonstrated to be successful during wind tunnel tests.

Despite this recent research there remain a number of areas less understood. The influence of CFF design on noise production in aerospace applications is very immature. Little has been done on high speed flight either in an embedded configuration or within a multirotor configuration. The influence of the CFF within any configuration on aircraft flight dynamics has not been explored to date neither has the application of such a propulsion system to low Reynolds number systems i.e. micro unmanned aerial vehicles. The immediate future of CFF based aircraft concepts over the coming 5-10 years is one of continual development, proof of concept and research into the fundamentals of the fluid flow.

1.1.6 Transitioning Rotorcraft

The definition of a transitioning aircraft can encompass both fixed and rotary wing configurations. In the following section we consider only rotary wing aircraft capable of transitioning between vertical and horizontal flight but we extend our definition to include transitioning between mediums i.e. water

Figure 1.5: V-22 Osprey transitioned into cruise and landing vertically (courtesy US DoD and US Airforce)

and air.

The tiltrotor could be considered as the ‘classical’ transitioning rotorcraft configuration. Typically employing a pair of proprotors installed on the tips of a fixed wing the engine nacelle is capable of rotating through 90° from a vertical to a horizontal position. The aircraft will take-off or land with the nacelles vertical with the rotors then tilting around into the horizontal position during a transition phase into forward flight. While there are relatively few manned examples of this configuration, the V-22 Osprey and the V-280 Valor being two notable exceptions, there are considerably more unmanned examples of this configuration due to the reduction in transmission complexity when moving to an electrically powered system. While a twin rotor system is relatively common, examples of tri [842] and quad [489, 836] rotor systems do exist within the literature where all or some of the rotors tilt with others remaining fixed. Such a configuration enables the propulsion system to be optimised more effectively for different parts of the flight envelope [839].

In a similar vain to the more established rotorcraft concepts discussed above, the majority of recent literature around tiltrotors is focused on the development of robust control strategies particularly when transitioning (with and without suspended loads). However, the transitioning flight manoeuvre has inspired a number of fundamental studies into the aerodynamics of the system in particular rotor-aircraft interactions during transition [458].

Optimal controllers for transitioning have been developed by a number of authors. Yang et al. [826] have developed alternative strategies for transition flight control while Chen et al. [270] have developed an optimal system for attitude control. Xiao et al. [813] went slightly further and proposed a novel control methodology with improved fault tolerance to improve aircraft safety. Almeida and Raffo [296] have developed a control strategy to solve the suspended load transportation problem for tiltrotor aircraft. Control of other configurations has also been addressed within the literature with Yu et al. [842] developing a control system for a tri-rotor configuration with two tilting front rotors and a fixed aft rotor. More recently a number of authors [583, 836, 489] have developed transition control systems for quad-tiltrotor configurations and in both cases demonstrated a successful transition. In this configuration two rotors are fixed and two rotate enabling the aircraft to move in six degrees of freedom while maintaining a level central body.

Other novel tiltrotor configurations have been explored within the literature to date. Raeisi and Alighanbari [633], for example, demonstrated a tiltrotor configuration which employed wing tip mounted ducted fans instead of proprotors while Ma et al. [536] took this concept further by combining a set of rotating ducted fans with a high aspect ratio box-wing.

A number of authors have investigated improvements to the design of the rotor blades within a tiltrotor configuration. Park et al. [613], for example, explored the performance advantages of variable-twist tiltrotor blades using shape memory alloy hybrid composites. This enabled different twist distributions to be built-in along the span of the blade thereby enabling the blade to operate more efficiently in different flight modes. Employing this design the authors noted a 5.35% reduction in rotor power coefficient at modest levels of thrust and a 2.44% reduction at high levels of thrust. Kim et al. [479] investigated the ability of a series of synthetic jets along the blade to control separation of the leading and trailing edges in both hover and transition. Whilst only performed computationally the study did demonstrate that a reduction in drag was possible. There is, of course, no reason why these concepts could not be implemented on other rotorcraft configurations.

With the exception of Sanchez et al. [674] very few recent papers have investigated improvements in the transmission or mechanisms enabling control. Sanchez et al. proposed a mechanically simpler alternative to the swashplate traditionally used on tiltrotors to enable control.

While traditional tiltrotor concepts install the proprotors on the tips of the wing, Burrage [254] discussed a novel configuration where a pair of inter-meshing rotors are mounted on the fuselage of the aircraft and act as pusher propellers during forward flight. In this configuration the design of the wings are unconstrained by requirements associated with bearing the rotors and any associated transmission or nacelles. While fuselage mounted tilting meshed rotors leads to a very compact design it introduces considerable complexity in terms of the control and mechanics associated with the tilting and transition flight phase. Young [839] presents an excellent overview of a number of other novel tiltrotor concepts noting that while these concepts increase both aircraft complexity and weight a future combination of advanced technologies will offset these current drawbacks and the improved mission capability will justify their selection. Examples of the configurations considered by Young include, pusher tiltrotors, tiltrotor oblique wings, quad rotor systems with heterogeneous rotors tailored for discrete operating conditions, twin hull aircraft with tilting rotors on the mid-span and variable sweep wings.

Closely related to the tiltrotor configuration, a tiltwing rotates both the rotor nacelle and the wing on which they are mounted. As with the tiltrotor configuration the majority of recent literature on tiltwings has focused on the development of flight control systems with a particular emphasis on the transition phase of flight [608, 797, 655]. Other authors have developed tiltwing preliminary design tools [693] and investigated the aerodynamic interference between propeller and wing during different flight phases [165].

An alternative approach to achieving transition using a rotorcraft without adjusting the orientation of the propulsion system relative to the aircraft's body is the tail-sitter configuration. In this configuration the aircraft sits on its tail with the axis of all of the rotors aligned with the vertical. The aircraft then takes-off with the rotors providing the only source of lift before the entire aircraft rotates to the horizontal for forward flight. In this mode, as with a tiltrotor, the wings provide lift with the rotors providing only propulsion. The layout of the rotors can vary with both dual [855, 795, 738, 784] and quadrotor [605, 535, 786, 741] configurations within the recent literature. The duel rotor configuration, in particular, brings a number of significant challenges compared to the quadrotor configuration in terms of achieving control [784].

As with tiltrotor and tiltwing configurations the majority of recent literature is concerned with transition control for either dual or quad configurations with both computational models and experiments used to demonstrate the effectiveness of the developed strategy. Transition for this aircraft configuration can be particularly challenging given that the wing is stalled for a significant proportion of the manoeuvre [605]. Zhong et al. [855] designed a controller to achieve hover control while Wang et al. [795] developed and successfully implemented a controller to achieve automated transition for a duel rotor aircraft. Lyu et al. [535], Oosedo et al. [605] and Vorsin and Arogeti [786] have all developed control systems to automate transition for a quadrotor configuration. Swarnkar et al. [741] have recently taken the tail-sitter concept further by developing a biplane-quadrotor aircraft including the flight dynamics and control.

The literature includes a number of other variants on the 'tilting' theme. An interesting departure from the above configurations is the tilting body [350]. While not strictly falling within our definition of a transitioning rotorcraft it is never-the-less worth mentioning here. Developed by Freewing Technology, the tilting body consists of a lifting fuselage with a tractor propeller which is free to rotate. Unlike a traditional fixed wing aircraft the angle of attack of the wings remains constant with respect to the freestream instead the fuselage is tilted to vector the thrust from the propeller and achieve STOL performance. Other than the aircraft developed by Freewing, no other systems have been demonstrated to employ this configuration, probably due to the inherent additional complexity, particularly within the aircraft structure and the mechanics of the movement of the fuselage and folding tail.

The ducted fan UAV is another popular transitioning rotorcraft configuration employing a single, relatively large, lift fan with a set of stators and control vanes to, respectively, counteract the torque generated by the fan and direct the high-speed exhaust flow to enable aircraft control [484]. There are a number of existing UAV systems based around this configuration including the Honeywell MAV, iSTAR and the Sandia National Labs AROD. As with most transitioning aircraft there is a great deal of research within the literature around the development of control systems [803, 451], however, recently there have been a number of researchers investigating the fundamental aerodynamic or mechanical operation of such aircraft. Hou et al. [429], for example, explored the replacement of the control vanes at the exit of the fan with a set of rotating cylinders which enabled direction of the flow by exploiting the Magnus effect. The operation of such aircraft tends to result in flow separation over the lipskin of the duct which reduces performance, Camci and Akturk [257], investigated a concept to reduce inlet separation significantly thereby improving performance and controllability.

Other authors have investigated the fundamental aerodynamics of these systems. Deng [304], for example, investigated the impact of ground effect on VTOL ducted fan performance while Minhyoung et al. [665] analysed the impact of tip clearance on a counter-rotating ducted fan finding that the clearance should be minimised to reduce losses.

Yang et al. [829] present an excellent review of aquatic UAV concepts with a particular focus on UAVs that are capable of transitioning between underwater and aerial operations. Such aircraft have a variety of military and civilian applications including, but not exclusive to, combat, reconnaissance, communications relay, search and rescue, inspection, marine patrol and ecosystem monitoring. Yang et al. [829] reviews a number of waterproof quadrotor systems including the Aquacopter, QuadH2o and Mariner Quadcopter. These systems are all capable of operating in both air and shallow water for a short period of time, however, their underwater capability is limited due to the inefficiencies of the propulsion system which is designed for aerial flight. While demonstrating the feasibility of such systems challenges remaining regarding the design of the propulsion system, pressure-resistant structures, system layout, weight in both air and water and communications before these systems become commonplace. Progress has been made with respect to some of these challenges recently with, for example, Ye and Marzocca [833] investigating a system capable of deployment from a torpedo tube with a novel hybrid propeller system to enable the vehicle to operate more efficiently in water and in air.

1.1.7 Personal Air Transportation Systems

The concept of a personal air transportation system (PATS) is not a particularly new or novel idea and has long been the go-to staple of the science fiction writer. Be it the personal 'jet pack' or the flying 'cars' in the Jetsons cartoons or Blade Runner the ability to jump into a vehicle and fly oneself as part of a daily commute has a considerable appeal. Whilst PATS have been developed on a very small scale for a number of decades, the Aerocar of the late 1940's being an early example, it is only recently that PATS have begun to be seriously explored by large aerospace and automotive companies. Aston Martin, Airbus, Boeing, Rolls-Royce, to name but a few, are all currently investigating PATS in addition to newer PATS specific start-ups such as Lilium, Volocopter, Ehang and Aeromobil etc., with many having already flown full size or scaled demonstrators.

Whilst the concept of a PATS may not be obviously applicable to the future of unmanned systems the two are in fact inextricably linked. The same developments in technology which have driven improvements in unmanned systems e.g. propulsion, control, materials, battery capacity etc. have enabled PATS to become a potential reality. Vice versa if infrastructure and regulatory issues can be overcome a sudden large market for PATS with a correspondingly impressive level of research funding may drive technological improvements which could filter down into the unmanned systems sector. One should also be aware that a considerable number of the PATS concepts do actually involve autonomous flight operations in order to remove the requirement for a qualified pilot. it is worth, therefore, briefly considering PATS within this review.

The work of Rehmatullah and Kelly [645] is a good example of the duality between PATS and 'pure' unmanned systems. As part of their research they developed a system to aid the operator of a PATS in avoiding obstacles. The system monitors the surroundings of the aircraft for obstacles and employs a repulsive potential field to define appropriate control inputs thus enabling the system to fly around an obstacle. Throughout this haptic feedback is provided to the pilot. Whilst developed for PATS this system has obvious applications in a purely unmanned system.

Liu et al. [526] provide an excellent overview of recent endeavours into the development of PATS noting that advances made in recent years in terms of distributed electric propulsion, V/STOL capabilities and automation have made the concept feasible. Distributed propulsion, for example, has enabled multicopters with 10s of rotors, such as the Volocopter, to become a reality. Such configurations offer a improved level of reliability of the propulsion system while a reduced tip speed offers reduced noise levels [700] compared to a helicopter. However, Liu et al. [526] point out that there are still considerable challenges remaining around the safety and reliability of such systems, the infrastructure necessary for them to be widely used and public acceptance.

Fleisher et al. [340] lay out the strong economic case for PATS in terms of congestion and discuss the main technological drivers for such systems including, lightweight materials, propulsion and battery technologies and control, communication and information processing. As with Liu et al. they highlight the considerable infrastructure issues related to battery charging and landing sites within cities which, along with public perception may limit widespread adoption.

1.2 Fixed Wing Platforms

The word 'drone' conjures up a multi-rotor platform in the minds of the general public, but the term carries no such layout-specific meaning. Nor does the advent of the now ubiquitous multi-rotor vertical take-off aircraft mark the beginning of the history of the drone (or unmanned aircraft concept). In fact, the very first drone, the *Hewitt-Sperry Automatic Airplane* (which first flew a century ago!) was a fixed wing biplane.

Fixed wing aircraft continue to dominate applications where range or endurance are of interest and this is unlikely to change. This is true of both manned and unmanned systems. An enormous amount of work is invested by research teams around the world into improving the speed, the aerodynamic and structural efficiency, the robustness (in the 'robust design' sense), etc. of fixed wing airframes; the interested reader may wish to consult the proceedings of numerous conferences – for example those of the Royal Aeronautical Society or the American Institute of Aeronautics and Astronautics – or the journals of these learned societies, to gain an insight into the numerous lines of enquiry associated with these research areas. In this report dedicated to unmanned air systems technology we shall limit ourselves to two selected areas of particular interest from the perspective of the future of drone design.

Figure 1.6: NASA distributed propulsion experiment – measuring lift at low speeds on a wing equipped with 18 electric motors (image by Tom Tschida, courtesy of NASA).

1.2.1 Fixed Wing Platforms With Distributed Propulsion

The generally smaller scale and shorter range of unmanned aircraft makes electric motors (see Section 2.3) a feasible propulsion design choice. They have numerous advantages, one of which is that they scale down quite efficiently. Thus, the engineer has the choice of one or two large motors to satisfy a given power requirement, or a large number of small motors, a so-called *distributed propulsion system*.

Fractionating the power in this way has multiple advantages. Careful layout design (in terms of the setting angles of the motors and their positioning around the airframe) can yield exceptional aerodynamic efficiency. Additionally, and perhaps more obviously, careful systems engineering has great benefits in redundancy (the failure of one motor has an entirely different impact on a twin than on an 18-motor aircraft!). Of course, reaping the greatest benefits from this architecture requires enormous attention to detail in terms understanding how the weight of the motors and their ancillary systems scales with distributing the task of thrust generation and in terms of understanding where any subsystems shared by multiple motors may cut into the theoretical redundancy gains of distribution. There are other, less obvious wins associated with breaking up large point masses into several small ones; for example, strategic placement of small propulsion units around the lifting surfaces can serve as a useful means of flow control, especially for slow flight.

One of the highest profile programmes aiming to answer the outstanding research questions around distributed propulsion is NASA's X-57 Maxwell, a demonstrator to feature a mix of 'cruise motors' (60kW each) and 'high-lift motors' (10.5kW each) mounted on the leading edge.

Kim et al. [477], reviewing the current state of the art in distributed propulsion, conclude that it is "a disruptive concept that can lead to unprecedented improvements in future aircraft designs", noting new opportunities (in addition to those mentioned above) in control (including reducing requirements on control surfaces through the use of differential thrust strategies), acoustic shielding (in the case of small electric ducted fans), and 'wake filling'.

While designing a distributed propulsion system is commonly achieved, reaping maximum benefits from the idea and a thorough understanding of the engineering trade-offs involved is still some way away, especially in terms of conclusions that can be integrated into systematic, evidence-based design processes.

1.2.2 Morphing Aircraft

The history of morphing aircraft goes back a very long way; indeed, the Wright Flyer already featured warping wings (see [452] for a historical review). The fundamental driver has remained the same through more than a century: a fixed geometry aircraft is unlikely to be optimal for all of its operating points – a solution is to design an aircraft with variable geometry. Hinged control surfaces, all-flying tail planes, etc. are generally not included under the 'morphing' heading.

Numerous (manned) morphing aircraft have reached maturity (mostly featuring variable sweep), but the world of unmanned aviation is now looking for bolder geometry changes as a possible means of mission optimization, enhanced control, gust alleviation, etc. An area of particular interest from the perspective of long endurance pseudo-satellites, on which distributed control loads along the wing span can be used to achieve the optimum wing geometry on a highly flexible very high aspect ratio wing at various flight conditions [406].

The EU FP7-funded CHANGE (Combined morphing assessment software using flight envelope data and mission based morphing prototype wing development) project [824, 1] explored a range of mechanical means of achieving morphing geometries. Wind tunnel tests of a morphing leading edge [632] and investigations into a morphing wing with span extension and camber morphing [214] resulted in mixed success.

The scale of the structure supporting the morphing of the outer mould line of the aircraft is one of the interesting questions being examined in research labs, with fine scale lattice scaffolds showing promise some promise of late [289].

Exotic means of morphing bring about exotic control and autopilot tuning challenges too and this is likely to be an active research area, with some unconventional approaches (e.g., machine learning based) needed. An example is the investigation by Xu et al. of the morphing control of a new bionic morphing drone with deep reinforcement learning [816].

1.3 'Vanishing' Drones

The desire for a drone to 'vanish' after completing its mission may be driven by environmental considerations (the avoidance of harm to wildlife ingesting a single-use vehicle that landed away from any 'home base') or by the strategic goal of not leaving a landed (or crash-landed) vehicle in enemy hands. Some technologies that could facilitate this may be useful in either case.

In 2015 DARPA launched its Inbound, Controlled, Air-Releasable, Unrecoverable Systems (ICARUS) call for proposals for the development of a balloon-launched glider capable of precision landing 150km away from its 35,000ft high balloon launch point, carrying a three pound payload, followed by its real 'party trick', the requirement to "fully vanish within four hours of payload delivery or within 30 minutes of morning civil twilight (assuming a night drop), whichever is earlier". 'Vanishing' is defined in this context by the "full and complete physical disappearance (to the naked eye) of a complete system and its constituent materials – independent of the surrounding environment", with no remaining parts of the aircraft (save for a tennis ball sized container carrying guidance and control equipment) exceeding 100μm on its longest dimension [295, 2]. To date, no details have been released on the outcome of the competition, but the call, as well as the results of an earlier DARPA call aimed at developing sublimating polymers, indicated that the mission is plausible, though a very significant materials science challenge at this stage.

Biodegradability, which means 'vanishing' over somewhat longer timescales, is also on the horizon. Take, for example, the cardboard flying wing developed by San Francisco robotics company *Otherlab*, developed (also with DARPA funding) as a single-use delivery vehicle for emergency scenarios [3]. At a smaller scale, a team at the University of Southampton developed a family of paper sensorcraft designed to be launched from balloons, forming large sensor clouds capable of transmitting environmental data

Figure 1.7: MAVIS paper sensorcraft built with conductive inkjet printing (CIP) technology.

via 433MHz telemetry, before landing and decomposing (with the exception of some of their small electronic components). The MAVIS (Massive Atmospheric Volume Instrumentation System) aircraft carry their avionics on the surface, upon which the circuitry is printed using an off-the-shelf inkjet printer [481] (Figure 1.7).

In addition to paper, the emerging field of biodegradable drones is likely to be looking towards new materials, some even suitable for additive manufacturing. PLA (polylactic acid, most often derived from corn starch) seems to be emerging as an early leader on the biodegradable thermoplastic polymer market, scoring highly from a mechanical design point of view through its good strength to weight ratio and compatibility with a range of fused deposition modelling printers. Its biodegradation performance is less attractive, however, with larger components likely to retain their structural integrity for over a year, even in a marine environment. A 12-month long test conducted by Greene [385] against the standard set by the American Society of Testing and Materials (ASTM) showed that only 8% of a PLA sample exposed to sea water biodegraded into carbon dioxide, which was only marginally more than the 6% measured on the low-density polyethylene plastic bag used as a control. PHA (poly-hydroxy-alkanoate), another family of materials (including plastics such as P3HB, P4HB PHBV) with good mechanical properties and suitable for fused deposition modelling, performed far better in the Greene study. Two PHA sample parts were tested, with 12-month degradations of 52% and 82% (38% and 45% recorded after six months).

1.4 Smart Dust

Whether it be a need to reduce cost, improve stealth or explore smaller areas for scientific reasons, as with all engineering systems there is a continual drive to miniaturise unmanned systems. The above review of rotorcraft, fixed wing and hybrid unmanned air systems graphically illustrates the reduction in platform size from large HALE systems to ‘pico’ size quadcopters and flapping wing systems of the order of 10s of millimetres in size. If one were to continue this trend of minimisation of autonomous systems one naturally arrives at sub-millimetre scale systems commonly referred to as ’smart dust’.

The smart dust concept, first developed by Warneke et al. [799], revolves around a single sub-millimetre scale ‘chip’ comprising of multiple micro-electro-mechanical systems (MEMS) often including some sort of wireless communication system, some sensors, a programmable microprocessor and some sort of energy harvesting and storage system. While seemingly not directly related to unmanned air systems the uses for such devices within the literature are often accompanied by a deployment process involving a much larger unmanned system [412] whilst smart dust systems can even propel themselves [703], float or be carried on the wind [412, 656]. Coupled with the ability to sense and communicate with each other or a base station and potentially act as a swarm [558] this puts smart dust systems squarely into the category of an unmanned air system.

1.4.1 Examples of Existing Smart Dust Systems

Since the seminal work by Warneke et al. [799] there have been a considerable number of advances in both the underpinning technology and the applications of this technology with smart dust systems whose dimensions are of the order of 100μm being produced.

Lee et al. [512] developed a 1mm^3 sensing platform constructed from five interconnected layers comprising of two processors, a temperature sensor, a low-power imaging system and an energy harvesting system. The system included a novel low power I^{2}C (Inter-Integrated Circuit) interface to facilitate communication between the layers of components whilst the system is capable of harvesting energy from solar, thermal and microbial fuel cells. Overall the system uses 20μW of power when operating.

The smart dust concept relies on a combination of perpetual energy harvesting and extremely efficient low power components, of the order of 10nW per component, in order to be practical [512]. In 2010, Chen et al. [271, 272] demonstrated a 8.75mm^3 sensor platform capable of near perpetual operation thanks to an inbuilt 1mm^2 solar cell and a thin film solid state battery. The system was equipped with a pressure sensor and was designed for intraocular pressure monitoring.

Kim et al. [475] developed an energy autonomous system with an embedded 160×160 pixel image sensor, optics and wireless communications within a $2 \times 4 \times 4$mm platform. The system is capable of motion detection and remote wake-up via an optical receiver. While an inbuilt RF transmitter is used to transmit image data to an associated receiver, the system requires the receiver to be positioned 15mm away. This highlights one of the current limitations of such smart dust systems, the wireless transmission of data, with the power requirements for RF communications still posing a considerable challenge.

Early smart dust systems, such as those developed by Warneke et al. [799], disregarded RF communications in favour of an optical solution with embedded active or passive reflectors or micro-mirrors for data transmission. Whilst undoubtedly more efficient such optical communication systems are limited by a requirement for line of sight to other dust motes or a base station and can struggle with intense ambient lighting conditions. Whilst RF communication has improved since the development of these early systems it still poses a considerable challenge, a more recent system by Chen et al. [276], for example, has only managed to achieve RF communication over distances of 15m indoors.

There exist a number of other extensions or variations of the general smart dust concept throughout the literature, including ‘Claytronics’ [372], smart surfaces [212] and ‘lablets’ [559]. Each of these proposed systems involves a large number of small MEMS-like devices, similar to smart dust, operating in tandem through a distributed intelligence [238] to achieve a goal.

The Claytronics project, proposed by Goldstein et al. [372], aimed to explore how programmable matter could change the computing experience with the goal of developing a material whose shape, motion, appearance etc. can be controlled arbitrarily by a computer. This was to be achieved by harnessing millions of millimetre sized spherical robots which could stick together and move around each other like a fluid. To date this vision is yet to be fully realised but it’s considered not a case of ‘if’ but rather ‘when’ the technology develops sufficiently to enable such a system to be realised. Bourgeois & Goldstein [238], who provide an excellent review of all such distributed intelligence systems, present a number of technological advances that have already been made towards the realisation of this vision in terms of manufacture and self-assembly [646, 461], motion of the spheres [238, 658, 308] and programming languages [659, 191].

Smart surfaces [212] consist of surfaces with a series of micro-manipulators built into them which work together to enable automated positioning. Each micro-manipulator contains a micro-actuator, a micro-sensor, a processor and some form of communication capability. Examples of this type of system can create an airflow from each micro-actuator in four directions which enables the position of an object on top of the surface to be manipulated. Given that each node of the surface communicates only with its immediate neighbours the system is an interesting proving ground for distributed intelligence control systems [211]. One can clearly observe parallels between this technology and that which may potentially develop within larger systems such as the MADCAT intelligent wing [387, 289] which includes a considerable number of small modular units which permit the entire wing structure to morph in order to affect flight manoeuvres or maintain the most efficient aerodynamic shape.

Lablets, first proposed by McCaskill et al. [559], are similar in a number of ways to the smart dust concept of Warneke et al. except that they operate within a chemical solution, are significantly smaller, O(100μm), aiming to operate at a scale similar to that of living cells and aim to 'load or dose chemicals, modify surfaces, initiate reactions within complex chemical environments' [559]. Other applications include, remote sensing, experimentation with chemical and biochemical systems, epidemic monitoring with lablets ultimately mooted as an important stepping stone on the path to artificial life [558]. Despite their ultimate purpose and scale being different they exhibit a number of the aspects of the distributed intelligence systems discussed by Bourgeois & Goldstein [238] and yet are not considered within their review. Funke et al. [348] actively compare the lablet concept to that of smart dust and note both include sensors, some form of communication and perhaps locomotion and must operate collaboratively within swarms to achieve a goal. However, some of the issues with smart dust systems are more profound within a lablet, such a RF communication which is penalised even further by the highly-damped transmission within solution and the even smaller antenna footprint.

The lablet system developed by Funke et al. [348] is a recent example which illustrates the capabilities of such systems. The lablet in this case is approximately 200μm $\times$ 100μm $\times$ 35μm in size and contains a pH sensor, actor electrodes which allow the system to interact with its chemical environment. Recognising the limitations of RF communications within solution, Funke et al., present a novel communication system via local contact between lablet or a docking station in the base of the vessel containing the solution. Such base station and inter-lablet communication is reminiscent of the work on distributed intelligence control systems in other smart dust-like systems.

Sharma and McCaskill [703] demonstrated how a lablet of a 100μm scale can be propelled by an electroosmotic drive with sufficient force to overcome viscous drag acting on the lablet. They then demonstrated, via simulation, that such lablets can dock and self-assemble to form compartments and perform chemical operations.

McCaskill [558] provides an excellent overview of the recent advances in the field of lablets. A key component within the overall lablet architecture, Straczek et al. [731] developed a microelectrode array system as a docking platform to enable both charging and communication with lablets. Liu et al. [524] presented protocols for controlling the patterning of conducting polymers on surfaces which has direct applications to the reversible self-assembly of lablets [558]. While Sarvašová et al. [678] demonstrated the dispersion and aggregation of micro-particles 'remotely' via RF signals in addition to the remote release of encapsulated payloads enabling future swarm like behaviour and interactions with other soft-matter. Finally, Zhirnov and Cavin [783] discuss the development of lablets beyond the 10μm scale.

1.4.2 Smart Dust Development & Challenges

Distributed intelligent systems such as smart dust, or more recent incarnations of lablets, claytronics and smart surfaces, are currently limited in very similar ways and will require advances in a number of different areas for these to become feasible on the kinds of scales first proposed by Warneke et al. [799].

For smart dust systems to become useful requires the production of millions of individual motes. The majority of smart dust systems demonstrated within the literature, particularly those based on

MEMS, include only a single mote which has been fabricated, rather laboriously, by hand with each mote including many individual wire bonds between each of the sub-systems. Clearly this method of manufacture does not lend itself well to the production of millions of systems and new manufacturing techniques are required [238]. 3D-silicon processing techniques, to which there is currently limited access to, could be employed to improve the scalability of such systems [558]. Hardware scalability is also somewhat hampered by the requirement for the logic and MEMS actuation on such devices to operate at different voltages which can lead to integration issues. The MEMS onboard each mote will be operating exposed to the environment but currently such systems are sensitive to dust or air quality which could change the response of the system.

Whilst scalability is limited by manufacturing issues it is also limited by software issues that are yet to be overcome. Programming languages are yet to be developed which hide the overall complexity of a system comprising of millions of elements and enable the system architect to programming the overall ensemble and not have to programme individual motes.

With an increasing number of motes within the dust cloud, short comings with the control and communication both to and within such an ensemble become apparent. Communication within such a system becomes an order of magnitude more complex that current systems or communication protocols can cope with and this becomes more complicated still when one factors in the mobility of individual motes and the freedom they have to make or break connections with each other as they move around. Communication and coordination of actuators to affect not only movement, but collaborative operation [558] is also a considerable challenge. While inter-mote and mote base station communications have been demonstrated [348], the scale is much smaller than that would be required to be useful and other systems currently struggle with irregular or dynamic networks [238] and significant research is required to enable effective control. The overall software architecture must also be tolerant of uncertainty due to faults within the system or as a result of the operating environment.

As demonstrated above through the work of Chen et al. [271] we are rapidly approaching perpetual powering of systems on the 1-10mm scale but moving to the smaller lablet scale, encapsulated power will remain a difficult challenge to overcome but it is within reach in the next few years [558].

While lablets suffer from the same hardware and software challenges list above, the focus of their application within the chemistry field leads to a number of other, more specific, challenges, namely the encoding of chemical functionality within each lablet which will require further advances in the fields of electrochemistry and neuro-electronics [558]. However, while there are challenges Lablets are viewed as potentially realising a 'pourable' digital platform capable of interacting with biological cells and complex chemicals within the next 10 years [558].

Of course, the production and dispersion of millions of small micrometer scale electronic devices, whilst technically possible, within the next 10 years, will have its considerable critics and opponents. The scale of smart dust systems places them squarely in the definition of microplastics and regulation may prevent their application outside of a controlled environment unless safeguards are in place, such as ensuring the biodegradability of each mote.

Chapter 2

Propulsion Systems

In order to fly and overcome drag (or gravity, in the case of a VTOL aircraft), UAS require some form of propulsion system, which ultimately results in the acceleration of air behind the aircraft, propelling it forward. In the majority of cases this is achieved through a propeller or fan driven by a motor or turbine of some description. Propeller technology is relatively mature and current research trends in this area have already been discussed in the context of rotary wing platforms in Section 1.1. The following chapter therefore concentrates on the state of the art with respect to the piston engines and electric motors used to drive a propeller along with gas turbines and recent advances in hybrid electric systems which combine an electric motor with some form of internal combustion engine. Also considered within this chapter are the recent advances in solid state electric propulsion, which results in a virtually silent aircraft.

2.1 Gas Turbines

Gas turbines have been around for several decades and within that time have undergone continual development and improvement, the gas turbine literature is therefore extremely extensive and as a result the following review shall be restricted to the previous 5-10 years. In addition to this, while gas turbines have power generation, marine as well as aerospace applications the following review is restricted to aerospace applications, although there is significant cross-over in a number of the technologies under development. As will be made clear below, there is relatively little research within the literature that has been undertaken on gas turbines specifically for unmanned system applications, before addressing these applications let us consider general developments to gas turbines for manned applications.

Current state-of-the art in gas turbine research and development falls distinctly into two camps. The first represents incremental improvements to existing gas turbine technologies where through, for example, the application of optimisation, robust design or uncertainty quantification, the goal is to incrementally improve performance of compressor and turbine blades, combustion systems, cooling schemes [511] etc. so that reliability and value can be maximised. The second category represents research into lower TRL technologies which are approaching a level of technical maturity which may see them implemented on a real engine but which represent a fairly substantial architectural shift. The following review therefore neglects incremental improvements to gas turbine performance in favour of focusing on these more substantial changes.

The inclusion of intercoolers and recuperators within gas turbine engines is widely seen as a way in which engine performance can be improved [672, 516, 562]. Zhang and Gummer [847] note that the incorporation of recuperators shows considerable potential to lower both emissions and fuel consumption. However, this does not currently hold true for short range aircraft where the fuel consumption reduction is not enough to offset the increased mass of the recuperator. However, they point to the potential of future novel compact, low mass, highly effective heat exchangers to remedy this. Schmidt and Staudacher [687] point to realistic efficiency improvements of 10% when intercooling, recuperation and other technologies are incorporated into a gas turbine, with intercooling being identified as a driving technology towards higher efficiency systems. Kyprianidis and Rolt [500] present improvements in overall SFC when intercooling is combined with a geared fan.

The gas turbine combustion system continues to be a source of considerable research and development, not least because the accurate numerical prediction of combustion chamber performance and emissions is still an incredibly challenging task. Combustor development continues to struggle with the competing objectives of low NOx and soot emissions through the arrangement of dilution and mixing ports [851], management of air fuel ratios and combustor geometry. The performance and therefore size of the combustion chamber has a significant impact on the overall engine driving its length and therefore overall mass. Enabling fuel injection, mixing and combustion to occur in the smallest volume possible is therefore a continual objective of the combustion sub-system designer. The fuel injection system is critical to the combustion process and there are a number of novel injection approaches considered within the literature. The review of future fuel atomisation technologies by Alajmi et al. [173], for example, considers four competing technologies, air-assisted, plasma-assisted, ultrasonic-assisted and supercritical fluid-assisted atomisation. Plasma and ultrasonic atomisation were found to result in the finest droplets but ultrasonic was found to be cheaper and easier to adopt.

An alternative approach to improving combustion efficiency is to better control the combustion process itself. Delaat et al. [301] present an active combustion control system for gas turbine engines which suppresses combustion instabilities. Operating at engine pressures, temperatures and flows the system employs a high-frequency fuel valve to perturb the fuel flow into the combustor thereby acheiving control.

An alternative to the annular combustion systems found in most modern gas turbines is to replace this with the combustion chamber found within a rotating detonation engine (RDE) [413]. The RDE combustion process offers a number of advantages, the process requires a relatively simple structure but offers high thermal efficiencies [859]. Consisting of a coaxial cylinder with a series of fuel injecting nozzles at one end together with a slit to permit the entry of an oxidant into the chamber, a detonation wave propagates in a circumferential direction around the chamber with combustion products of high temperature and pressure being produced behind the wave. These burnt products are ejected at high temperature and pressure axially out of the chamber thereby providing thrust. Compared to a traditional combustion system the effective thrust produced is relatively large at a lower pressure ratio which reduces the required number of compressor stages compared to a traditional gas turbine thereby reducing both mass and the demands on the turbine. While the RDE is still very much in the research and development stage, stable and continuous detonation waves for a long duration have been achieved using a variety of fuels [859]. Significant challenges still exist around the injection and mixing mechanisms, for example, before this technology will find its way onto an aircraft.

Somewhat related to combustion technologies, there is a growing body of research within the literature over the past 5-10 years focused on the consideration of alternative fuels for gas turbine engines. Biodiesel [653, 521], synthetic paraffinic kerosene [233], ammonia [770, 485], n-octane, methanol, methane and hydrogen [371] have all been the subject of investigation within the literature. This investigation is driven by a number of objectives including, for example, the reduction of carbon emissions and improved fuel security.

Biodiesels are an attractive option as either a drop-in replacement for jet-A or as part of a fuel blend. Blakey et al. [233], Litt et al. [521] and Rochelle and Najafi [653] all point out the advantages of biodiesels including reduced exhaust emissions, improved biodegradability and a higher flash point. Whilst temperatures, pressures and power production are not negatively affected by biodiesel usage fuel flow rates do tend to be higher than jet-A only. However, they point out that there are significant developmental hurdles including oxidative stability and cold flow properties.

Ammonia combustion has also gained some traction within the literature as it is completely carbon free (NH_3) and offers a hydrogen storage vector without the additional complexity associated with pressurised containers. Valera-Medina et al. [770], Goldmann et al. [371] and Kobayashi et al.[485] have all performed studies on ammonia based combustion within gas turbines. Whilst being carbon neutral (during combustion), they point out that ammonia demonstrates very slow reaction speeds, requires higher ignition temperatures, produces considerably high NOx emissions and produces less heat. Valera-Medina et al.[770] discuss countering some of these issues by doping the ammonia with another molecule. Both they and Goldmann et al.[371] suggest that a 50:50 mix of hydrogen and ammonia shows potential with the hydrogen being obtained by cracking the ammonia.

The drive to increase gas turbine efficiency has been accompanied by an increase in turbine entry temperatures. This has lead to a considerable amount of research into the development of cooling technologies. These advances have seen an overall increase in component cooling effectiveness from 0.1 to 0.7 over the past 50 years[252]. Cooling within a gas turbine engine continues to be an area of active research with new cooling schemes, materials etc. all being developed[821]. Thermal barrier coatings (TBC) are often applied on high-temperature surfaces within a gas turbine in order to extend component life, increase performance and durability[368]. Ghosh[366] describes possible future ceramic, glass-ceramic, and composite TBC materials which may offer improved performance over existing materials while Yoon et al.[837] describe the development of a yttria-stabilized zirconia (YSZ) aerogel which offers a thermal conductivity 30-40 times less than that of the YSZ coating used in commercial gas turbines.

Bunker[252] describes technologies that may have a transformative effect on gas turbine cooling and chief amongst these is the ability to include micro cooling or transpiration thanks to the capabilities offered by additive manufacturing (AM). Beyond just efficient cooling schemes AM is widely recognised as enabling the manufacture of complex organic, cellular or lattice structures which may result in a simultaneous reduction in overall mass, part count and complexity and an improvement in structural performance[362, 540].

Other areas of recent gas turbine development include advanced sealing technologies to reduce oil and air leakages, the development of high temperature resistant materials and abradables in order to prevent fast degradation at high temperatures and health monitoring systems to anticipate sub-system degradation and failure[718].

As already noted above gas turbine engines have not been widely adopted for unmanned aircraft applications primarily due to their lower efficiency at smaller scales compared to internal combustion engines which means they suffer from significantly increased fuel consumption[383]. Never-the-less gas turbines have a higher reliability and power density and also remove the vibration issues associated with piston engines[661] and these advantages have driven researchers within the recent literature to improve the performance of gas turbines for UAS applications.

Hybridisation is an obvious method by which the benefits of a gas turbine can be leveraged within UAS. Bryner et al.[251] present the design of a small scale gas turbine based hybrid propulsion system where the gas turbine provides power for a hybrid electric aircraft. Rouser et al.[661] present a similar hybridised system where the electric power produced by a gas turbine is utilised within a distributed propulsion system. Powered by a 1.8kg turboshaft engine producing 5.2kW of power the system has a significantly longer range and endurance compared to a battery only system. Aguiar et al.[168] have also considered employing gas turbines and solid oxide fuel cells to improve the performance of high altitude long endurance (HALE) unmanned aircraft.

Another method of hybridisation considered within the recent literature is to use the gas turbine to drive a propeller as part of a turboprop configuration. Such a configuration offers improved cycle efficiency thereby increasing its competitiveness compared to a pistol engine powered propeller system[654, 185, 547]. Such turboprop configurations have also been demonstrated to offer significantly lower noise levels (17 dB lower) than an equivalent turbojet[323].

Vick et al.[781] developed a 3kW recuperative ceramic turboshaft engine which offered improved reliability, life, noise and vibration characteristics compared to an internal combustion engine. Citing a need to improve the efficiency of miniature gas turbines to make them competitive when integrated within long range unmanned systems, Vick et al. developed a novel, cost-effective ceramic turbine rotor, heat exchanger and turbine stator. The resultant system was demonstrated to have a reduced sensitivity to internal flaws, creep, and foreign object damage. More recently Large and Pesyridis[505] demonstrated the conversion of a micro turbojet into a turbofan with the aid of a continuously variable gearbox. This system demonstrated a 65.8% improvement in thrust specific fuel consumption and a 38.46% increase in thrust at maximum engine RPM.

Gas turbines are evident in other aircraft configurations within the literature. Jafari et al.[447], demonstrated an aircraft employing four gas turbines in a quad configuration capable of VTOL performance. This was treated as more of an interesting control problem than a viable efficient aircraft concept.

While gas turbine development will no doubt go on unabated for the foreseeable future this development will be primarily focused towards manned systems rather than unmanned systems. The technical challenges and cost associated with shrinking these technologies down to a scale where they can be widely adopted within unmanned systems may be so significant that by the time they are addressed other technologies e.g. batteries, fuel cells, electric motors etc. have been improved so much in parallel that gas turbines (an also internal combustion engines) become redundant even for long range missions. One should, however, point out that large scale unmanned systems can benefit directly from gas turbine technologies developed for manned applications. In this instance, perhaps value for money becomes more of a critical factor where, depending on the mission, a systems architect may be reluctant to install a expensive propulsion system on an aircraft with a significantly lower level of reliability than a manned system.

2.2 Piston Engines

Developments in piston engine technology have largely been led by the automotive industry. Largely as a result of emissions concerns, automotive companies are diverting development resources away from traditional internal combustion research towards electric and hybrid propulsion. The trend in the automotive industry is towards smaller, lighter turbocharged engines as part of a hybrid powertrain. Considerable efficiency gains are achieved by the ability to run such engines at a single design point by avoiding idle and part load conditions [419].

A notable development in the pursuit of higher efficiency is the homogeneous charge compression ignition (HCCI) engine. HCCI combines characteristics of conventional petrol engine and diesel engines [446]. The challenge in this technology is to be able to get the timing of combustion right. A further development of HCCI pioneered by Mazda is the Spark Controlled Compression Ignition (SPCCI) engine which solves many of the problems associated with HCCI. The Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS) is developing a similar technology that they call Spark Assisted Compression Ignition (SACI).

Other engine developments underway in research labs around the world include work towards engines with increased compression ratios, lean combustion, reduced pumping losses (use of deactivated cylinders) and optimal combustion timing control.

BACKGROUND NOTES

PISTON ENGINES

Propulsion systems for unmanned aircraft are dominated by three types of internal combustion engines: four stroke engines, two stroke engines and Wankel engines (more on the latter below). These types may be naturally aspirated or utilise fuel injection. Furthermore the fuel injection might be direct (into the combustion chamber) of indirect (into the intake manifold).

The attraction of internal combustion engines is the relatively **high energy density** of the overall system. Whilst the efficiency of an internal combustion engine is low at around between 25-40%, a single litre of petrol contains approximately 34 megajoules of energy. By comparison the latest battery technology achieves a typical volumetric energy density of 0.7-1.27 MJ/L. In other words, internal combustion engines continue to have an order of magnitude of energy density advantage compared with battery powertrains.

An important measure of engine efficiency is **Brake Specific Fuel Consumption (BSFC)**, defined as $\mathrm{BSFC} = \frac{r}{P}$, where r is the fuel consumption rate in grams per second (g/s), P is the power produced in Watts where $P = \tau\omega$, τ is the engine torque in Newton meters and ω is the engine speed in radians per second. The resulting units of BSFC are grams per joule (g/J). A typical efficiency figure for a Rotax 914 engine is 29% [660].

Another important measure of engine performance is the **Brake Mean Effective Pressure (BMEP)**, the mean effective pressure calculated from a measured dynamometer power (torque). This is the actual output of the internal combustion engine, at the crankshaft. Brake mean effective pressure takes into account the engine efficiency and is defined as $P_{\mathrm{me}} = W/V_{\mathrm{d}}$, where P_{me} is the mean effective pressure (Pa), W is the work performed in a complete engine cycle and V_{d} is the engine (cylinder) displacement [418].

Aircraft internal combustion engines generally lag behind automotive technology for reasons of conservatism and certification requirements. Typical General Aviation engines have, for decades, been dominated by petrol fuelled engines. These require high octane 100LL avgas. Most commonly used grades of avgas still contain *tetraethyllead (TEL)*, a toxic substance used to prevent engine knocking (detonation), with ongoing experiments aimed at eventually reducing or eliminating the use of TEL in aviation gasoline. Avgas is widely available in the USA, but in many areas of the world it is difficult to source.

Many unmanned aircraft engines have started life as General Aviation petrol engines. These tend to be of a **two, four and six cylinder horizontally opposed layout** with dual redundant magneto-based ignition systems and twin spark plugs. The main advantage of these engines lies in their simplicity and the fact that they have well known life and reliability characteristics.

Wankel rotary engines are receiving increasing amounts of attention in the unmanned aircraft world. They are typically smaller than a reciprocating engine of similar power rating because they have three work-generating expansion events per rotation of the rotor, as opposed to a standard four-stroke engine, which only has one per 720°rotation of the crankshaft. However, the shaft turns at triple the rate of the rotor in a Wankel rotary engine, which results in the engine having about twice the power output compared to a four-stroke reciprocating engine for the same combustion volume [390]. All this amounts to a number of potential advantages over reciprocating piston engines: higher power output and lower mass for similar displacement, lower noise, lower vibration levels and lower part count. Moreover, having an iron rotor in an aluminium housing reduces the likelihood of engine seizure. Contrasting these advantages, the mean time between overhauls and the reliability of some commercial Wankel engines has been questionable (see, for example, the accident report on the recent loss of Watchkeeper aircraft [300], a platform powered by a petrol engine with a total loss lubrication system).

2.2.1 Engines Derived From Manned Aviation Designs

Very few unmanned aircraft are powered by traditional aviation petrol engines. The one exception is the Rotax family of four stroke aircraft engines, which differ from conventional GA aircraft engines in that they have air-cooled cylinders with liquid-cooled heads. Rotax 912/914 engines now constitute more than 80% of the whole piston engine powered aerial vehicle fleet. They use a reduction gearbox to reduce the engine's relatively high 5,800 rpm shaft speed to a more conventional 2,400 rpm for the propeller. For example, the General Atomics MQ-1 Predator, and the IAI Heron unmanned aircraft use Rotax 914 turbo-charged engines in a pusher configuration.

There is an increasing trend in General Aviation to adopt Diesel engines (typically running on Jet A1). This is particularly the case in Europe where, in many areas, avgas is becoming difficult to obtain.

In the late 1990s a promising Diesel based aviation engine was developed by *Thielert* in Germany. These are based on heavily modified Mercedes-Benz automotive engines. Initial applications included the highly successful Diamond aircraft range of light aircraft. After a promising start, incidents started to occur. Between 2003 and the end of August 2011, the French air accident investigations bureau (BEA) launched 44 investigations into Thielert engine related incidents. These incidents demonstrated the complexity of taking proven automotive technology and trying to apply it in the aviation domain. Problems included issues with clutches (seven incidents), low pressure fuel pumps (three incidents), high pressure fuel pumps (four incidents) and electrical failures (eight incidents) [4].

As a result of these incidents, in May 2008, Thielert went bankrupt. Although it was resurrected from insolvency in January 2009, by then Cessna had dropped plans to install their engines, and Diamond Aircraft had now developed its own in-house diesel engine: the Austro Engine E4.

Austro Engine now produce engines for unmanned aircraft, including, for example, the Schiebel Camcopter S-100, which uses the AE50R heavy fuel engine. Similarly, the Austro Engine AE300 is used in the Aurora Flight Sciences developed Orion very long range platform.

Several hundred Thielert-powered manned airplanes are still flying, however, and Continental have now bought the rights to the Thielert engines and have developed the technology. Piper Aircraft delivered its first Diesel jet-A-powered Archer DX in June 2015. Following considerable testing and evaluation, the company chose Continental's CD-155 power plant. However, the engine has very strict life limits and must be replaced every 2,100 hours, the gearbox has to be replaced for an inspection at 900 hours, the high-pressure pump has a life limit of 600 hours, the alternator 600 hours, friction disk 900 hours, V-ribbed belt 1,200 hours.

The Thielert Centurion 1.7 engine was used in the General Atomics MQ-1C Gray Eagle. However poor system reliability [5] led to the development of the improved Gray Eagle (IGE) equipped with the Lycoming DEL-120 Heavy Fuel Engine (HFE) [341].

In June 2017 Textron's Cessna Aircraft division announced a jet-A version of the 172 powered by a Diesel Continental CD-155 jet-A engine installed in-house. Textron however dropped this offering in May 2018. It has also dropped the diesel 182 that suffered from poor sales.

2.2.2 Engines Derived From Automotive Designs

According to a report by the Australian Transport Safety Bureau piston engines have a failure rate of one every 3200 flight hours [657]. Compared with a typical aircraft turboshaft engine such as the P&W PT6, which has an in-flight shutdown rate of one per 651,126 flight hours, this internal combustion engine reliability is extremely poor [622].

The RQ-2B Pioneer drone attributed over 50% of systems failures to engine/propulsion failures [765]. The UAV exhibited a MTBF (Mean Time Between Failures) of 28.6h. A typical (very inexpensive) automotive engine has an MTBF of over 4000 hours based on actual data retrieved from car black boxes by an Italian insurance company [621].

The advantage that the automotive industry has is twofold: economies of scale and considerable in-service data. As an example, between 1989 and 2018, approximately 50,000 Rotax 912/914 series aircraft engines were delivered, which have accumulated approximately 45 million flight hours. By comparison, in the same period, over eight million Fiat FIRE (Fully Integrated Robotised Engine) engines were produced, which have accumulated approximately 20 billion hours [621].

The IAI RQ-5 Hunter uses the Mercedes HFE Diesel, inline 3 cylinder, 800CC, 56 HP engine that was originally developed for the Daimler AG Smart car. This engine features a single-overhead camshaft with two valves per cylinder and an aluminium alloy cylinder block and head. It is turbocharged and has an exhaust gas recirculation system. The engine was updated in 2007 and received increased performance due to a new common rail fuel system with increased boost pressure.

The most prominent internal combustion engine research is largely being carried out by automotive companies. Arguably the most advanced engine with mass production potential is the Mazda Spark Controlled Compression Ignition (SPCCI) engine. Mazda plan to release this engine into production as the Skyactiv-X. Essentially, this engine will combine the advantages of Diesel (efficiency) and petrol engines (low emissions). This is a specific implementation of the Homogeneous Charge Compression Ignition (HCCI) technology that many automotive companies are working on.

It is likely that automotive derived high efficiency engines will be attractive to the unmanned aircraft market, although the automotive trend away from heavy fuels is an issue for military usage. Certainly, for naval drones the ability to run on heavy fuels is mandatory. The US military, for example, has made a considerable effort to convert all of its petrol-powered equipment to operate on a single fuel under the One Fuel Forward initiative. The largely kerosene based JP8 is one of the primary fuels used for this initiative. The reason for using this fuel over gasoline is that it is very hard to ignite, and it can sit in storage containers for a very long time without degrading. This makes it relatively safe and reduces the risk of fire on a ship or base [507].

2.2.3 Case study: An Academic Research Team's Experience With Low Cost Piston Engines

Beyond engine designs adapted from aviation and from the automotive industry, many small drones use engines that have been derived from or sourced from the model aircraft 'hobby' industry. Several manufacturers that had been focused on the hobby market are now specifically addressing the UAV market (3W, RCV, Rotomotor), providing low cost solutions that open up opportunities for rapid prototyping and research activities, as well as some commercial and defence related applications. This raises interesting research questions in terms of engineering trade-offs; in particular one that is alien to most propulsion system engineers in the (manned, traditional) aerospace industry: how do our design processes accommodate large uncertainties around life and reliability for the reward of cost savings of an order or magnitude or greater. Let us consider a brief example of the integration of such designs into research drones from the perspective of a university research team.

The University of Southampton has developed a small twin-engine aircraft (SPOTTER). As part of this research work, an extensive survey of available engines was carried out. The conclusions of

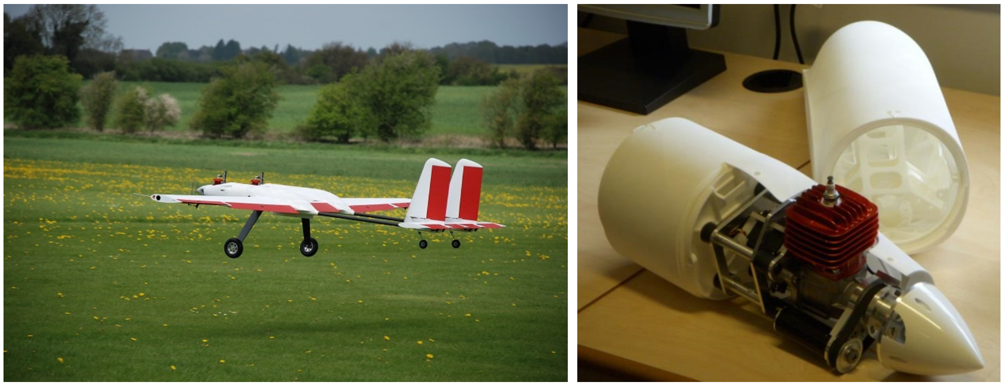

Figure 2.1: SPOTTER prototype platform and its 3W engine installation.

this survey have been documented by Keane et al. [468]. The original prototype SPOTTER aircraft (Figure 2.1) used 2-stroke engines: 3W 28iCSs that can develop 2.65 Kw (3.6 HP) from a capacity of 28.5cc.

The 3W 28iCS engine is relatively cheap (around EUR800). It has unknown reliability and life, but researchers at Southampton flew this platform for many tens of hours. The fuel consumption of the engine is poor, with an overall burn rate on SPOTTER of two litres per hour per engine at cruise conditions. The right-hand panel of Figure 2.1 shows a photograph of the 3W engine installation with a belt-driven brushed electrical generator integrated to power the aircraft avionics. The SPOTTER platform has been enhanced over recent years; a major improvement was the fitment of O.S. GF40 four-stroke engines. The GF40 engine has a slightly higher power to weight ratio compared to the 3W 28i. More importantly, it has a fuel burn of approximately half that of the 3W engine at an overall one litre per hour of mission per engine. The standard engine costs approximately the same as the 3W engine.

A major concern in operating cheap 'hobby'- derived engines is, of course, reliability. As a result of extensive test flying it was revealed that the valve gear on the GF40 engine needed adjustment approximately once every ten hours of operation. Following discussions with Ripmax (the UK distributor of this engine), O.S. provided the researchers at Southampton with a modified version of this engine, which has upgraded valve-gear. The team put one of these modified O.S. engines in an engine test cell to establish a better understanding of the life characteristics of this product. A typical engine flight cycle was programmed into the engine test cell, consisting of: start, high power climb (100% throttle), cruise power (75% power), descent (20% power), idle, shutdown. The engine was put through this cycle continuously whilst monitoring 'health' parameters such as power (torque), cylinder head temperature, and exhaust gas temperature. After a total of over 40 hours of such operation no significant performance degradation was observed. The engine was subsequently stripped down and inspected, and no significant wear was detected, particularly within the valve-gear. From this testing it was concluded that this modified version of the O.S. engine shows a substantial improvement in durability and can achieve at least 50 hours before any adjustment is required.

The unmanned aircraft prototyping team at the University of Southampton has also purchased and tested a large number of other small engines such as the ROTO 85 FS-NG, NGH four stroke, and the OS49 Wankel. These 'model aircraft' engines are all significantly inferior to the 3W and OS GF40 in either power to weight ratio or/and fuel consumption. Of note is the Wankel engine shown in the right of Figure 2.2 (O.S. Engines 49-PI Type II 0.30in^3). This was evaluated for a platform which required very low level of vibration. Although the Wankel engine did indeed have lower vibration levels and a reasonable power to weight ratio (2.7 kW/kg), the fuel consumption was extremely high.

In order to achieve high levels of fuel economy, fuel injection is desirable. However, in small engines

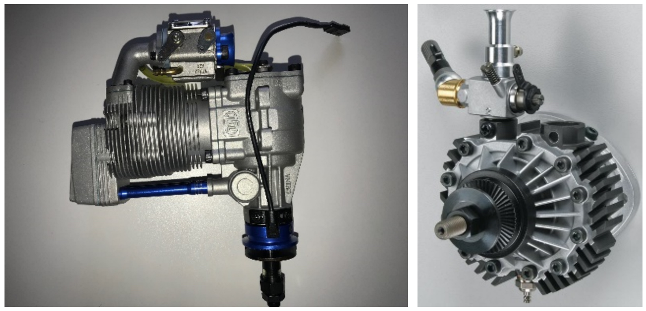

Figure 2.2: A selection of alternative engines for small unmanned aircraft.

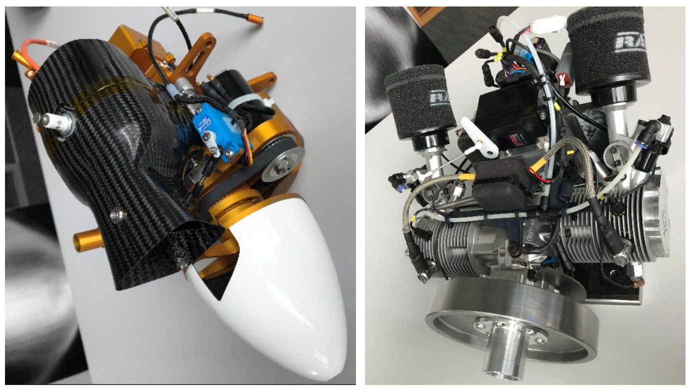

Figure 2.3: Fuel injected 2 stroke engine (UAV Factory, left) and RCV DF70 twin cylinder engine.

(<5kw) the fuel injection system is relatively bulky, heavy and consumes a significant amount of electrical power. The left-hand panel of Figure 2.3 shows the UAV factory UAV28-EFI engine that the team purchased for evaluation. Whilst this engine is very fuel efficient (400 g/kWh in cruise) it is heavy (weighing nearly 2.5kg). It is also relatively expensive at over £15k. The life of this engine is not published, and little is known about the required servicing intervals. However, the engine is supplied with a maintenance kit for a target 300 hours, which includes: five spark plugs, coarse fuel filter, two muffler packaging material kits, two exhaust gaskets, two-cylinder head gaskets, two modified cylinder head kits, two piston assemblies. This implies that the spark plug must be changed every 60 hours and the engine must be fully rebuilt with new pistons and gaskets every 150 hours.

The university also evaluated a single and twin cylinder engine from Dorset-based manufacturer RCV. The RCV DF70 twin cylinder engine (Figure 2.3, right hand panel), for example, has the advantage of being able to run on heavy fuel. This engine is a similar price to the UAV28-EFI engine, has a power output of 4Kw but has a lower fuel consumption of 330 g/kW.hr for a weight of 2.7 kg. The great advantage of the RCV engine is the use of rotary valves which leads to manufacturing simplicity and significant improvements in reliability. A particular advantage of the RCV DF70 is the ability to run on a wide variety of fuel types including heavy fuels (JP8). The RCV engines have been fitted in a range of US military funded UAV programmes.

2.2.4 Recent Developments

The unmanned aircraft piston power research agenda is driven, to a large extent, by power to weight ratio as an objective. Wankel engines (see also Background Notes panel) offer advantages in this regard. Drone applications include the Textron Shadow, the IAI Malat Searcher, the Elbit Hermes 450, the Leonardo Falco, the IAI MBT Harpy and Harop, Schiebel's Camcopter and the UK's Watchkeeper aircraft. Wankel engines have amassed over a million flight hours in service. One of the leading manufacturers is UAV Engines Ltd. (UEL), who produce air cooled and water cooled rotary engines from 38hp to 95hp. Their engines are used on the AAI Shadow 200 and several other global UAV platforms, including the Watchkeeper vehicle.

A number of heavy fuel Wankel engines are presently being developed. A DARPA funded initiative concerns the LiquidPiston 30kW X4 engine, which is expected to weigh just 30lbs and fit into a 10in box, while achieving 45% brake thermal efficiency [200].

Another important recent development is the use of thermal barrier coatings, particularly for piston crowns. Efficiency and reliability improvements have been reported in trials of this technology [464].

Engines with Continuously Variable Compression Ratio show promise for increased thermodynamic efficiency. Such an engine is indifferent to operation on full or part load; hence its efficiency gain. However, these engines are more complex, heavier and more costly [193].

2.3 Electric Propulsion

The continual growth of air traffic coupled with the competing demands for increased performance, reliability and availability, reduced maintenance, operating costs and emissions are gradually pushing the civil airliner industry towards more electric aircraft [261, 538]. This is driving research into electric motors, magnetic and electrical materials, advanced manufacturing processes, thermal management techniques and an improved understanding of the failure mechanisms of these systems [538]. The general consensus, however, is that hybrid aircraft architectures, for example, turbo-electric systems, provide a realistic near-term pathway to improved performance while other key enabling technologies are refined [204].

The following section considers the current state of the art within the literature with respect to electric propulsion. The term, electric propulsion, could be considered to cover all aspects of the electric powertrain of any vehicle including automobiles, trains, ships as well as aircraft. Given the higher demands of reduced mass and increased reliability within the aerospace sector the following section will focus on cutting edge electric propulsion in only aerospace.

The electric power train of an aircraft can be further decomposed into a number of individual sub-systems including, for example, battery storage or any other form of power generation, control systems, electric motors and the propulsor. As a number of these sub-systems are considered elsewhere within this overall literature review the following section will primarily focus on electric motors and the technology driving their improvement, some of the multidisciplinary considerations of electric powertrains and recent developments in solid state electric propulsion.

2.3.1 Traditional Electric Motors

A 'traditional' electric motor is defined within this document as any motor other than a superconducting electric motor. This includes, for example, inductance, switch reluctance, brushed and brushless AC/DC motors etc. Henke et al. [414] provide an excellent overview of each of these motor types along with the pros and cons of each from the point of view of their suitability as part of an electric aircraft. Electrically excited synchronous machines are normally ruled out of aerospace applications as their brushes and slip rings require regular maintenance. Reluctance machines have no permanent magnet or rotor winding, are cheap to produce and offer lower losses compared to inductance machines. However, they tend to be 50% larger than equivalent power permanent magnet synchronous machines which makes them generally unsuitable for aerospace propulsion applications. Induction machines tend to be robust, low cost, have no permanent magnets but suffer issues with mechanical stresses within the squirrel cage. Permanent magnet electric motors are widely thought of as being the most feasible system for use in electric aircraft [414, 236] due to their higher efficiency, higher power density, lower levels of heat production and lower maintenance requirements. The use of permanent magnets, however, does increase their cost relative to other motors. Currently the commercial electric motor with the highest rated power and power density is the Siemens SP260D, a permanent magnet motor capable of 260kW and with a power density of 5.2kw/kg. Weighing a total of 50kg it powers the propulsor of the Extra 330LE.

The current literature around such electric motors tends to present incremental improvements in performance through a combination of improved understanding and/or the application of optimisation techniques. Hannan et al. [408], for example, employed design optimisation approaches to develop better control algorithms for induction motors while Chiu et al. [283] optimised the phase shift angles of a motor and demonstrated a reduction in motor noise, vibration and an improvement in overall motor efficiency.

As with any mature system, electric motors are seeing increasing attempts to explore the uncertainties driving variations in motor performance. Al-Timimy et al. [171] explored the influence of permeable rotor end caps on magnetic end leakage and demonstrated that this should be taken into account in order to accurately predict motor performance computationally. Al-Timimy et al. [172] also explored the impact that incorrect assumptions of material properties after manufacture have on the numerical prediction of motor performance finding that efficiency predictions can be off by over 1% if ignored.

The high reliabilities expected within aerospace applications naturally drive research into understanding motor failure mechanisms and improving fault tolerance. Barater et al. [203] employed a thermal vacuum chamber through which temperature and pressure were cycled to mimic the operation of an aircraft in order to develop models to predict the degradation of motor insulation. While Cao et al. [261] have developed an electric motor tolerant to the occurrence of a single electrical fault.

2.3.2 Superconducting Electric Motors

As noted above the latest ‘traditional’ electric motor literature presents incremental performance improvements, significant step changes in motor efficiency and power density only really come about when one considers superconducting electric motors. Superconductors encompass a class of materials which offer almost zero electrical resistance below a critical temperature with a sub-class of high temperature superconductors defined as any material exhibiting this characteristic where the critical temperature is greater than 20K. Motors employing this material therefore replace copper within any windings with a superconducting material which results in a significant improvement in performance, as described above, and/or a reduction in mass [370, 414]. ‘Traditional’ electric motors can offer a power rating of the order of 5kW/kg [754] whereas superconducting motors can offer >40kW/kg [416, 737] and efficiencies of over 99% [236]. Schiferl et al. [686] compare a 6000hp induction motor to its superconducting equivalent and note that efficiency increases from 96.6% to 98.5%, the motor is 58% smaller and weighs 73% less. An aircraft employing such motors has the potential of reducing fuel burn by between 12% and 70% depending on the configuration of the aircraft [740].

The majority of superconducting electric motors tend to have only the rotor constructed from a superconducting material with a conventional copper stator used [610, 677, 616]. Fully superconducting motors, where both stator and rotor are made from these materials have been built once or twice but there is relatively little literature on them. Applications of superconducting motors have primarily been within the marine sector [596] where system performance is less sensitive to mass and there is ample space for cryogenic cooling. Marine generators operating at >98.7% efficiency and motors operating at over >97.3% efficiency have all been demonstrated [610, 740].

A number of theoretical superconducting motors have been designed by various authors throughout the literature with a view to employing them within an aircraft. Terao et al. [754] designed both a 3MW and 5MW motors with power densities of 19.4kW/kg and 25.2kW/kg respectively with a view to installing them within a 180 passenger civil airliner. Similar studies into theoretical superconducting motors have been perfromed by Luk [530], Kong et al. [488] and Manolopoulos et al. [546]. Liu et al. [522] have designed and manufactured a 500kW, 12,000 rpm motor but it is not for use in aerospace applications and is yet to be tested.

To date a practical superconducting motor for aerospace applications remains to be demonstrated and there are considerable issues which remain to be addressed [740]. Sarlioglu and Morris [677] outline a number of opportunities and challenges that exist including, the development of new motor topologies, new high energy density magnets, improved redundancy, reductions in mass and volume, the use of novel lightweight composite materials, new cooling techniques, advances in structural design and better insulating materials. The pace of development, however, has been relatively slow with regards to these technologies despite early proponents of superconducting motors stating that they were already mature enough for use in aircraft in 2007 [554].

2.3.3 Role of ALM in Motor Design

Electric motors, as with almost all aspects of aircraft design, can benefit considerably from the application of additive layer manufacture (ALM). The recent literature reflects this with a number of papers actively exploring the application of ALM within both traditional electric motor architectures as well as superconducting electric motors. Garibaldi et al. [355] note that ALM offers a route for the creation of innovative three-dimensional designs for magnetic core structures otherwise impossible with traditional manufacturing techniques. Goll et al. [373] present three novel topologies of a soft magnetic core including internal slits and multiple material layers to reduce eddy-current losses which can only be produced by ALM. Henke et al. [414] note that ALM offers a number of opportunities to implement new more efficient cooling technologies.

However, as with any new technology the application of ALM comes with a note of caution. Rassolkin et al. [641] note that significant challenges still exist within the ALM process which can introduce issues regarding the reliability and strength of the manufactured part. This is particularly important when one considers the application of ALM within high speed rotating components such a the rotor within an electric motor.

2.3.4 The Wider Electric Powertrain

Progression towards a more electric aircraft has also seen a number of researchers study the wider system level implications. The introduction of electric motors on board an aircraft can introduce issues associated with cooling, the mass of additional wiring, generator and propulsor placement and integration of power storage within the aircraft. Naturally this further complicates what is already a heavily coupled design problem before electrification is even considered. The literature therefore includes a number of examples where researchers have attempted to address these problems.

The work of Gur and Rosen [398] represents an early attempt to solve this complex design problem and produce an optimal aircraft configuration by employing multidisciplinary optimisation techniques to design the complete electrical power train of an unmanned aircraft. This process simultaneously considered battery, motor and propeller sizing in order to define an optimal system. Gnadt et al. [369] went a step further, assuming a number of different motor topologies and aircraft configurations, they performed a multidisciplinary sizing optimisation for a 180 passenger commercial aircraft.

State of the art non-superconducting electric motors and generators typically have peak efficiencies of 95%, a 0.55 MW electric motor therefore produces a similar level of heat to a BBQ [344]. Thermal management therefore becomes a critical issue in the design of more electric aircraft and one which is further exacerbated if superconducting motors requiring cryogenic cooling are employed [344]. A number of researchers within the recent literature have considered motor thermal management either directly or as part of a motor design study. McCluskey et al. [560], for example, discuss an approach for the thermal management of a smart electric motor for hybrid electric aircraft propulsion via indirect liquid cooling. Patel et al. [616] explored the integration of novel cryogenic cooling techniques within the restricted space between stator teeth.

2.3.5 Solid State Electric Propulsion

The traditional view of aircraft electric propulsion is that of an electric motor driving some sort of propulsor, a propeller or a fan, for example. However, recently, significant steps have been made towards solid state electric propulsion where an 'ionic wind' generated by the aircraft provides the main source of thrust.

The field of electroaerodynamics (EAD) is not a new one and has been studied extensively to provide local flow control but prior to the seminal work of Xu et al. [818] it was widely accepted that the limitations in thrust-to-power ratio and thrust density associated with this form of propulsion would make it infeasible to propel a heavier than air aeroplane. Xu et al. [818] achieved this feat through a combination of the application of cutting edge design processes and the development of an ultralight high-voltage power converter. The aircraft and powertrain were considered within a multidisciplinary design optimisation employing genetic programming which sought the most viable size and power for the prototype aircraft design. The power converter, capable of stepping up battery voltage to 40 kV achieved a specific power 5-10 times higher than conventional systems for the voltage and power used. This reduction in mass was therefore a significant factor in developing an aircraft capable of sustained flight. The prototype aircraft generated a thrust-to-power ratio of 5N/kW which is of a similar to conventional propulsion methods but the thrust density of the system (3N/m^2), is significantly lower than that of a conventional UAV (10N/m^2) or an civil airliner (1000N/m^2). Despite an overall efficiency of 2.56% the aircraft was capable of sustained steady level flight for approximately 10s. The authors suggested that with a few modifications to the aircraft an efficiency of 5% is readily achievable with existing technology and that electroaerodynamics theory for an idealised system suggests that the efficiency of the thrust could be as high as 50%. Within their more recent paper, Xu et al. [817] successfully demonstrated that through optimisation of the voltage and frequency of the dielectric-barrier-discharge the thrust to power ratio can be increased to 6.7N/kW from the 5.N/kW recorded for their prototype aircraft.

Naturally the success of Xu et al. has spurred a recent flurry of activity into solid state electric propulsion for aircraft. Sato et al. [679] proposed a method of generating an ionic wind through surface dielectric-barrier-discharge which does not require a high-voltage power supply that may be suitable for application on small unmanned systems. Chen et al. [274] have used a combination of experiments and numerical models to explore the influence of electrical and flight parameters as well as power storage on the performance of an EAD aircraft. Orriere et al. [607] successfully demonstrated the generation of an ionic wind using nanosecond repetitively pulsed microplasmas. While not implemented on an aircraft the experimental study using particle image velocimetry (PIV) demonstrated that the approach could produce a flow velocity of 2m/s using 1W of power.

Applications of this technology are not restricted to fixed wing aircraft and efforts are already underway to investigate rotorcraft applications. Ieta and Chirita [441], for example, have successfully demonstrated the first rotational ionic device to fly. In this case a propeller has been modified to include a strip of copper tape along the blade. When power was applied the generated ionic wind was found to be capable of rotating the propeller around a shaft and generating enough lift to overcome the mass of the propeller.

2.4 Electric – Internal Combustion Hybrid Powertrains

The simple idea of an internal combustion engine (ICE) and one or more electric motors working in tandem, as part of the same powertrain, in a way that allows each to play to its strengths and plug the gaps in the capabilities of the other, has seen immense success in the automotive world. The uptake is broad, ranging from mass market family hatchbacks (pioneered by Toyota) through high performance supercars, to Formula 1. While the tendency in that sector is towards full electrification (with ICE bans looming in the distance in several countries), systems with varying levels of hybridisation are likely to be around for a while yet. Such powertrains range from systems with a dominant ICE supported at low speeds and in high power demand situations by a small electric propulsion system that runs largely on energy it harvests through regenerative braking, to electrically dominated systems powered through most of the mission by a powerful electric motor, assisted by a small range extender ICE designed to alleviate the driver's range anxiety.

We have already seen in the case of pure piston engine powered systems that the aviation industry in general and unmanned aircraft powerplant engineering in particular, tend to be, to an extent, slaves to and late adopters of the technologies of the automotive world; so, is this the case with hybrids?

To an extent, the answer is 'yes', but there are two major differences between the two applications. First, the ease with which excess kinetic energy can be recovered (through regenerative braking, effectively reversing the polarity of the drive motor, with the battery as the load) makes cars prime candidates for such hybridisation. Second, the energy required to propel a car in cruise (say, on the motorway) is largely independent of its mass (save for a small rolling resistance penalty), but this is far from being the case in aviation, where the lift-induced drag of a cruising fixed wing aircraft will be heavily mass-dependant. This is why the automotive world's unwillingness, at the moment, to fully ditch the ICE with its tremendously energy-dense fossil fuel, in favour of poorer energy density battery electric vehicles is largely due to non-technical reasons (and, even with all economic and political roadblocks, the ICE, as automotive powertrain technology, is heading towards an inexorable demise), while, in contrast, aviation has very strong technical reasons to hang on to ICEs for a while longer (at least for long range applications). Weight is still the number one driver of all aircraft design discussions!

All this adds up to the conclusion that hybrid systems have a different role and potentially different drivers, constraints, pressures and design rationales in unmanned aircraft design. It is also more likely in aviation for the best design solution (for example, in terms of the balance between electric and ICE power) to be very mission dependent and methodologies for developing bespoke solutions are a likely emerging area of research.

Indeed, this is an exciting time from a research and technology development perspective, as the foundations of a new field are having to be laid down in this area. The German aviation think tank *Bauhaus Luftfahrt* are among the pioneers from this point of view, having started to set out the key metrics we may use to analyse proposed hybrid systems [444]. Fundamental questions going back to appropriate alterations of the Breguet range equation [363] and an understanding of related scaling effects [243] (are optimal solutions not just mission-sensitive, but also heavily scale-dependant?) and optimal topologies (parallel/serial layouts) are being debated in the research community.

There is a slowly increasing number of manned prototypes emerging too, potentially paving the way towards applications in larger drones – notable examples include the Cambridge SOUL [345] and the Wankel – battery electric hybrid *Diamond DA36 E-Star* [111].

Chapter 3

On-board Energy Storage & Power Supply Systems

The conceptual design process of a new unmanned aircraft system is likely to have the future platform's energy source at the forefront of the designers' thought processes. Preliminary decisions on this aspect are taken even before the first curve of the tentative geometry of the vehicle is drawn and the choices made on energy storage and power supply and intimately interlinked with every aspect of the design of the platform.

The design problem is generally three-fold: how do we supply the propulsive energy required by the flight mission, how do we power the on-board systems of the aircraft and how do we power the payload? A secondary question is do we store the required energy on board, and, if so, how? If not, how do we capture it? Does it require some sort of conversion process and, if so, what are the mass, volume, cost, efficiency, observability, and performance implications of this process (an example might be the conversion of the chemical energy stored in a hydrocarbon fuel into the electrical power required by a camera or some other payload).

There are many factors at play that drive the latest research and the future of unmanned aircraft energy and power, and we shall discuss some of these in what follows. The general trend is one of diversification, with most future vehicles and their payloads and on-board systems (especially in the case of larger, more complex platforms) likely to be powered by increasingly sophisticated mixes of chemical and electrical components.

3.1 Batteries

3.1.1 Lithium Batteries

Lithium-based chemistries dominate unmanned aircraft on-board energy storage today and this is unlikely to change in the foreseeable future (Lithium is the lightest metal and has the lowest reduction potential of any element, which leads to high gravimetric and volumetric capacity and power density and the highest possible cell voltage [595] – neither fact is likely to change!). We therefore focus here on the current research landscape around Lithium batteries.

The theoretical limits of Lithium battery energy densities and specific capacities are a somewhat contentious topic (see [326] for a discussion of some of the reasons). There is also some debate over what 'real-life' impact further improvements in chemistry can make, considering that the weight of current collectors and structural components accounts for a significant fraction of the overall mass budget and any significant changes to these components without an impact on safety are relatively unlikely. That said, there is some agreement that whatever gains *can* be made at this point, will require major changes, such as new electrode materials, new cell architectures, and/or transitioning from intercalation to conversion chemistry [820] or hybrids of the two.

BACKGROUND NOTES

BATTERIES

Capacity is the amount of charge the battery is able to receive, store and discharge. On the assumption that the discharge occurs at a constant current I over a time period t (after which the *cut-off voltage* is reached and the battery is considered discharged), the capacity is calculated as $I \cdot t$ and typically measured in Ah (ampere-hours) or mAh. The value typically quoted is the *nominal capacity*, which assumes a certain constant discharge current. High discharge currents may reduce the effective capacity available (*capacity offset*) due to thermal losses. The greater the *internal impedance* of the battery, the greater such losses are and the less capable it is of meeting spikes in demand. A related performance metric of relevance in UAV design is the maximum safe current draw of the battery (typically expressed as a *C-rating* in the case of Lithium-polymer batteries).

The **energy storage capability** of a battery is the product of its capacity and the differential potential (voltage) it is able to maintain between its cathode and anode.

Lithium-ion batteries are dominating applications where high energy density is critical. While the previously ubiquitous Nickel metal hydride (NiMH) cell chemistry offered higher peak discharge rates, Li-ion batteries offer not only significantly higher energy density, but have greater cell voltage (by a factor of three), low self-discharge rates and withstand a large number of charge cycles. The term covers a range of cathode chemistries, characterised by their intercalation materials. Typically, layered transition metal oxides are used: *NCA* ($LiNiCoAlO_2$, found in the Tesla/Panasonic 18650/2170 electric vehicle battery cells), *LCO* ($LiCoO_2$, commonly used in mobile phones), *NCM* ($LiNiCoMnO_2$), *LFP* ($LiFePO_4$), *LMO* ($LiMnO_2$) and *LTO* (Li_2TiO_3).

Intercalation or conversion? Lithium-ion batteries feature one of two fundamental types of chemistries. In batteries with *intercalation* cathodes a solid host network stores guest ions (Li^+), which can be inserted into and removed from the host network (reversibly, in rechargeable batteries). The host network compounds are usually the transition metal oxides listed above, or metal chalcogenides, or polyanion compounds. Conversely, *conversion* electrodes undergo a solid-state redox reaction during lithiation/delithiation (discharging/charging), in which there is a change in their crystalline structure, accompanied by the breaking and recombining of chemical bonds [595].

Solid state batteries have a solid electrolyte (not to be confused with dry electrolyte batteries). The overwhelming majority of current Lithium-ion batteries have chemistries based on liquid organic electrolytes, because they have high conductivity and wettability on the surfaces of the anode and the cathode. But they do have familiar drawbacks compared to solids, mainly related to safety; for example, they do not prevent thermal runaway on impact (no solid barrier to separate the anode and the cathode in case of deformation) [832]. This, as well as the possibility of higher energy densities and better cycle performance motivate much current research into solid state batteries.

Caveat emptor... The performance figures quoted in relation to batteries must always be studied with great care, as different research teams may use different definitions of seemingly simple quantities. For example, there are energy density values published in some research papers that are calculated with respect to a dry cell, that is, the overall mass does not include the mass of the electrolyte! It is also worth considering the practical implications of what is claimed in relation to a new chemistry or a new cell architecture. For example, some performance figures are only maintainable on a practical battery pack given a sophisticated battery management system (capable of balancing temperatures, charge levels, voltages, etc. across the pack) and the mass of such systems is rarely included in the claimed energy density figures. Along similar lines, certain cycle numbers may only be achievable if a battery is hardly ever discharged below, say, 20%, and is rarely fully charged, so it is worth checking that the energy density quoted alongside the cycle number does not actually refer to a full charge (it almost always does!). When reading about a quoted cell energy density of, say, 250Wh/kg, it is worth bearing in mind that, for purposes of conceptual design calculations (that is, accounting for all of the above), a realistic overall on-board energy storage figure might be around 150Wh/kg.

An active area of development is that of *Li-S chemistries*. Consider, for example, the work of Zhou et al [857], who propose the combination of intercalation and conversion reactions to improve the volumetric capacity of the cathode in Li–S batteries. Their proposed cathode consists of hollow VO2@S microspheres, which achieves greater volumetric capacity (1084 mAh/cm^3 at 0.1C) by combining the intercalation and conversion mechanisms. They also report good rate capability and cycling performance (440 mAh/g at 1.0C after 200 cycles) (see also the work of an MIT team recently reporting on a cell featuring a hybrid cathode delivering an energy density of 366 Wh/kg when assembled into a pouch cell [822]).

Commercially available Li-S packs with performance metrics (energy density and cycle number) that may make them viable as propulsion system batteries for unmanned aircraft are on the horizon; for example, Oxis Energy claim to have achieved 400Wh/kg at the cell level with a goal, by 2021, of 500 cycles, and the added bonus of a 100% available depth of discharge[1].

The use of *aqueous ('water-in-salt') electrolytes* is another active area of research interest in battery chemistry (has been for over a decade, see, for example, work by Nobel laureate John Goodenough [529]). A recent contribution that has garnered much attention is the work of a large team bringing together researchers from the University of Maryland, the US Army Research Laboratory, the Chinese Center for High Pressure Science and Technology, Argonne National Laboratory and City University of Hong Kong [825]. They report impressive energy densities (304Wh/kg with the electrolyte mass included and 460Wh/kg calculated with the mass of the anode and the cathode alone), demonstrated thus far over 150 charge cycles. This is a low number in the context of consumer electronics or electric road vehicles, but 150 flights is comparable to the mean time between overhauls of certain combustion engines used on aircraft; in particular, in the case of small to medium sized unmanned air vehicles, very high energy density at the expense of low charge cycle counts may be an attractive proposition.

Other efforts underway in this area include the development of aqueous lithium rechargeable batteries with a lithium anode and an aqueous $SnCl_2$ solution cathode separated by a lithium-ion conducting solid electrolyte, by a Japanese team (see Watanabe et al. [800]), who report theoretical energy densities of 681Wh/kg.

Focusing on cell degradation and cycle performance in near-100% depth of discharge operations[2], Harlow et al. [410] present the results of three years of testing on $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NCM) 40mm x 20mm x 3.5mm pouch cells (with a moderate specific energy of 200Wh/kg) with a range of electrodes and at a range of temperatures. The benchmark chemistry they propose uses a single crystal NCM

[1]These claims are made on `https://oxisenergy.com/technology`, as of September 2019.

[2]This is of relevance to unmanned aircraft in cases where the decision to attempt to land at, say, 80% depth of discharge, in marginal conditions, may be coloured by the knowledge that a diversion involving close to 100% depth of discharge might have a significant cost in remaining charge cycles. Similarly, a battery with good tolerance of 100% state-of-charge storage has the potential to improve the operational readiness of an unmanned aircraft.

electrode in which, in their tests, no micro-cracking can be observed after 5,300 cycles. Their test protocols included simulating storage followed by daily discharge cycles to 100% depth of discharge (over a period of 6 hours) was designed to be representative of electric lorry operations (the work is part of a long-standing research partnership with Tesla, Inc.), but these are also features of some unmanned aircraft operations. From this point of view, 200Wh/kg maintained over in excess of ten years of daily, deep discharge operations, appears to be a useful data point representing the state of the art going into the 2020s.

Increasing volumetric charge capacities, energy densities and cycle life are not the only active areas of battery research of relevance to unmanned air systems design. Faster charging (see [828] for some recent work), low leakage currents, increased safety (reduced flammability), better shaping (different form factors), and good temperature performance are other areas being targeted.

Solid state batteries (that is, batteries featuring a solid electrolyte) show some indications of answering much of this wish-list. While high capacity solid state batteries are currently in development, the higher levels of the readiness level range of the research landscape (demonstrations in the 'real' environment) are populated by low capacity, extremely light batteries, suitable for powering, for example, sensors with modest energy needs. An example of research results on the cusp of making into industrial applications is the Ilika Stereax® family of micro-batteries[3] designed for Internet-of-Things applications (the researchers predict wearable device scale batteries by 2022). Instead of the polymer electrolyte of the ubiquitous Li-Po batteries that dominate unmanned aircraft applications, the Stereax batteries have a ceramic ion conductor. For now, this category of batteries shows the most promise, from an unmanned aircraft point of view, in applications such as structural health monitoring (sensors and batteries powered by small solar cells or using energy harvesting technologies). Larger, unmanned aircraft powerplant scale batteries are estimated to arrive in the next decade.

Solid state batteries also feature on the research horizons of areas such as flexible batteries (see [856] for a review into progress in flexible lithium batteries). Like many other developments in battery technology, this is primarily driven by the needs of the consumer electronics industry (roll-up devices, wearable electronics) or the biomedical sector (e.g., implantable devices), but they could play an interesting role in unmanned aircraft design too, for example in fixed wing platforms with warping wings.

There is thus a great deal of interest in solid state batteries and there are key chemistry questions yet to be answered (including the best choice of solid polymer matrix, with polyether, polyester, polyacrylonitrile, and polysiloxane among the contenders [850]). A recent review by Yao et al. [832] discusses the current state of the art in polymer-based composite electrolytes for Lithium batteries.

3.1.2 Primary Batteries

Primary (non-rechargeable) batteries generally have greater energy densities than rechargeable batteries, which makes them potential candidates for unmanned aircraft applications. From an operational perspective, they certainly make sense in the case of aircraft designed for one-way missions (e.g., sensor platforms designed to return telemetry data from harsh environments, such as an area affected by nuclear contamination), but logistical, cost and disposal considerations generally make them impractical for more conventional operations.

A future exception might be metal-air batteries, in particular, aluminium-air batteries which would make practical sense in a greater variety of concepts of operations if they could be 'mechanically recharged' in an affordable and environmentally responsible manner (effectively replacing the consumed aluminium anodes with aluminium reclaimed from the electrolyte of the spent battery). An aluminium-air battery (perhaps it would be more apt to call it an air-breathing fuel cell), uses oxygen from the

[3] For more details see `https://www.ilika.com/battery-technology`.

air and water (in addition to the aluminium anode) and converts it into aluminium hydroxide while maintaining a cell voltage of 2.71V:

$$4\,\mathrm{Al} + 3\,\mathrm{O_2} + 6\,\mathrm{H_2O} \longrightarrow 4\,\mathrm{Al(OH)_3} + 2.71\,\mathrm{V}\,\cdot$$

Their practical energy density is generally estimated to be an order of magnitude greater than that of rechargeable lithium batteries, though power densities tend to be lower (see Vegh and Alonso's recent analysis [776] of the technology from an aircraft design point of view).

Research into aluminium-air chemistries goes back several decades (see, for example, Zaromb's work [845] from the 1960s) and is continuing with generally far lower funding levels than lithium-ion battery development (see [527] for a recent review). Research mainly focuses on reducing costs (most cells require high purity aluminium [327])and increasing power densities, as well as solving the practical obstacles around 'recharging' (minimising the amount of water required and converting the $4\,\mathrm{Al(OH)_3}$ back into Al). Israeli start-up *Phinergy*, as well as UK-based *MAL Research and Development Limited* (makers of the *Métalectrique* cell) are reported to be working on commercially viable solutions [6].

3.1.3 Structural Batteries & Capacitors

Conventional electric propulsion aircraft design treats the battery pack as a self-contained, modular object, whose only function is to provide energy for flight and for on-board systems and payloads. An emerging school of thought sees the battery as a component that could take on additional functions, as a means of reducing overall system mass; crucially, as a structural member in itself, or part thereof, such that, in addition to its energy storage role, the battery also carries stresses that would otherwise be carried by structural members of the airframe, thus allowing weight savings on the latter.

Combining structural and energy storage functions is being considered in several research labs around the world, at several different scales. Till et al [166] offer a helpful classification of structural batteries from this point of view, from complete separation to micro/nano-level integration (e.g., energy carrying fibres).

It is clear that adding structural duties to those of a battery will reduce its energy (and power) density, and, of course, there comes a point where the sacrifice is such that the structural battery will no longer be earning its keep. Scholz et al. [689] estimate this break-even point to be 51.8Wh/kg and 103.3W/kg (in terms of specific energy and power respectively) for a particular architecture, though clearly this is very much a function of the actual design. It does, however, offer a ballpark number to target by researchers. Their case study predicts possible endurance gains of 31%. State of the art values appear to be falling short of this at present, with designs around the 25Wh/kg mark being reported [455] (contrast this to the state of the art Lithium battery energy density values reported elsewhere in this section).

An alternative route is represented by structural super-capacitors, which have the main advantage of charging more rapidly than batteries; this is, however, a very low TRL area at present, with power densities of 34W/kg, and energy densities of 0.12Wh/kg reported [448].

This is clearly another area where a systems level view is likely to pay dividends. On stark energy density numbers alone, structural batteries are a long way away from practical use, but clever engineering might bring benefits by reducing the amount of wiring required (if the airframe structure can be 'tapped into' anywhere), as well as offering natural cooling to the cells. It is also likely that the numbers will make sense at specific scales (e.g., very small or very large vehicles), depending on the type of integration.

3.2 Hydrogen

Hydrogen has always been of great interest, as a fuel, in aeronautical engineering research, due to the simple physical fact that it has the highest specific energy of all non-nuclear fuels [733].

Research into fuel cells (systems capable of generating electrical power using hydrogen stored on board and atmospheric oxygen) as aircraft power sources has intensified over the last two decades, driven by the fundamental observation that such systems have the potential to achieve some of the advantages of electric motors (low noise and vibration, low environmental impact, low cost, low maintenance) with the specific energies typical of internal combustion engines. A typical system would be powered by a polymer electrolyte membrane (PEM) fuel cell, receiving its fuel supply from a gaseous or liquefied hydrogen tank integrated into the airframe (though on-board hydrogen generation is another option being considered).

The downside of fuel cell powered aircraft propulsion systems (other than the obvious issues related to safety and the absence of a Hydrogen infrastructure that have so far also limited the uptake of fuel cells in the automotive industry to a small number of low production number designs) is that, while they shine on specific energy, they tend to be poor on specific power. Fuel cell powered aircraft concepts therefore tend to have highly constrained performance envelopes and low payloads [239], which pushes them into the high persistence, moderate payload niche of the design space.

Indeed, this is the type of mission the highest profile such vehicle, the AeroVironment Stratospheric Global Observer was designed for. It first flew in 2010, under the Joint Capability Technology Demonstration (JCTD) programme [7], with a stated endurance target of 5-7 days. The aircraft suffered a 'mishap' later in the flight test programme [8] (which later led to the cancellation of the demonstrator programme) and AeroVironment's current efforts in the ultra-persistent aircraft domain appear to be focused on solar powered platforms [118].

Interestingly, Boeing's answer to the GlobalObserver, the PhantomEye high altitude pseudo-satellite first flown in 2012 [139], also used hydrogen, but in an entirely different type of propulsion system: it used turbocharged piston engines supplied by Ford.

We are, it seems, into a second wave of development, driven by the conclusions of these early attempts, which have proven the basic principle and highlighted a number of research needs.

The Ion Tiger program at the US Naval Research Laboratory [126] (see Figure 3.1 showing the 16kg gross take-off weight, low altitude platform) has tackled two of these. First, efficient hydrogen storage: the 48-hour endurance of the Ion Tiger vehicle is partly thanks to the NRL's in-house developed cryogenic liquid hydrogen storage tank and delivery system [4]. Their lightweight dewar has an internal volume of 20.46 litres, capable of storing 500g of gaseous hydrogen at 35MPa (this is how the vehicle was fuelled early in its flight test programme). The novel cryogenic system allowed the storage of 1.3kg of liquid hydrogen, of which the aircraft was able to use 799g during a 48-hour test flight (the rest was vented to control the inner pressure). The remarkable achievement here was that the endurance of the vehicle was increased by around 85% compared to its earlier gaseous hydrogen flights, as a result of the increased volumetric efficiency of the hydrogen storage[733, 374]. Second: high fuel cell mass-efficiency drove the development of their 5kW system based on metal foil bipolar plates [126, 151, 374, 744, 745].

There are several other development efforts progressing in labs around the world, aiming to improve the gravimetric and volumetric efficiency of fuel cell propulsion systems. For example, researchers at Washington State University have developed the Genii unmanned air vehicle demonstrator [268], which also features a cryogenic liquid hydrogen tank, albeit of a different architecture. Some systems appear to have reached the higher end of the technology readiness scale, such as the *Hycopter* multi-rotor offered by *HES Energy Systems* [123], running on compressed hydrogen stored in a cylindrical tank, offering an endurance of up to 3.5 hours at sub-0.5kg payloads (the maximum take-off weight is 15kg).

[4] Unlike other gases, hydrogen does not liquefy under pressure; rather, it requires very low temperatures to form a cryogenic liquid [374].

Figure 3.1: The NRL Ion Tiger research aircraft and its fuel cell (inset). Images courtesy of the US Naval Research Laboratory.

As we mentioned earlier, there is an alternative to complex hydrogen storage systems: chemical storage methods that work either via *chemisorption (absorption)*, when hydrogen molecules are dissociated into atoms and integrated in the lattice of the host material or *physisorption (adsorption)*, where hydrogen molecules are attached to the surface of the host material. Absorption generally offers better gravimetric and volumetric efficiencies [374]. The advantages of chemical storage: good storage capacity at the same time as offering simpler systems and a much easier refuelling processes (involving liquids or solids at room temperature) [478].

Absorption-based systems use metal hydrides, borohydrides, amides, imides, and hydrocarbon fuels, with *sodium borohydride* ($NaBH_4$) perhaps the most popular choice for unmanned aircraft research applications (even some commercial systems are beginning to appear). Systems to date have relatively low power outputs, however, and some cells require the replacement of the catalyst (platinum, ruthenium, cobalt) [374].

An alternative material that has received much attention in the research community is ammonia borane. In particular, a technology developed by a team from Rutherford Appleton Laboratory spinoff *Cella Energy Limited*, University College London and *Chilton Tech*, involving the hydrogen storage in ammonia borane-polymer composite pellets [588] may be a promising avenue (with some early experiments involving a light unmanned aircraft having taken place at the Scottish Association for Marine Science [9]). An interesting related proposal was to integrate the pellets into the primary structure of the airframe [374]. Alas, with Cella Energy in administration at the time of writing, the future of this technology is uncertain.

Current commercial offerings in the solid hydride storage propulsion space include the *HES Aeropak-S* cartridge, capable of 250W standard output and storing 1,500Wh of energy, according to the manufacturer who also supply liquid hydride and compressed gas solutions [104].

While research into increasing the performance of various types of fuel cells continues, there is an increasingly influential school of thought, according to which the limited power density of fuel cells is likely to remain an issue, so the most productive direction appears to be the use of fuel cells as part of hybrid systems, for example combining fuel cell stacks with Li-ion battery packs [594]. The battery packs thus cover mission segments with peak demand (e.g., take-off), while the fuel cell provides the bulk of the cruise power. Verstraete et al. [780] report on the performance of one of the latest such systems, the *HES Aerostak*.

Much of the vehicle energy research landscape is generally driven by the automotive industry (far larger than the unmanned aircraft manufacturing sector) and unmanned aircraft are likely to benefit from this immensely, though at the cost of research directions and requirements being set by automotive design drivers. Lithium batteries are a good example of this. At the same time, another high value industry, that of commercial air transportation, has driven the agenda of cleaner, more efficient gas turbine propulsion. Hydrogen, in particular hydrogen fuel cells are in a curious, somewhat different place. Automotive applications appear to be very limited (largely due to issues around the absence of a hydrogen infrastructure) and scaling issues, as well as technological risk aversion, limit the appetite of the commercial aircraft sector. This leaves unmanned aircraft as a niche application, especially when it comes to ultra-persistent pseudo satellites. While there are some incipient commercial offerings out there (in terms of fuel cells suitable for unmanned aircraft) there are still many interesting areas of research to be pursued if hydrogen fuel cells are ever to hold a significant chunk of the long endurance patch:

- availability of the required fuel and infrastructure at the point of use (off-grid refuelling systems?)
- optimal liquid hydrogen tank design to resolve trade-offs around performance and mission flexibility
- high altitude (low ambient pressure) performance of hydrogen fuel cell systems – there is debate over the mechanisms that appear to be causing significant performance degradation with altitude [374]
- water management (membrane hydration is required to maintain conductivity) [374]
- meteorological robustness – hybrid systems are currently being designed for idealised conditions, but will weather variability dent the usability of such systems? (e.g., unexpected climbs or mission segments flown into strong headwinds exceeding the power capabilities of the system).

The above is merely a snapshot of the current unmanned aircraft hydrogen power research landscape – the interested reader may find the reviews by Gong and Verstraete [374] and Pan et al. [611] useful in further delving into the state of the art of this potentially promising technological area.

3.3 Solar Power

The advent of increasingly light and efficient photovoltaic cells has brought solar power into the mainstream of unmanned aircraft propulsion system design thinking, especially in the domain of high altitude, long endurance systems. It has been a challenging technological path from NASA's partially successful, but ultimately ill-fated Helios prototype (Figure 3.2) of the early 2000s to today's remarkable QinetiQ/Airbus Zephyr aircraft that measures its endurance in weeks or the *Solar Impulse* manned aircraft[5] that flew around the world on solar power alone. The key engineering challenge has always been to balance the need for sun-facing real estate (required for structurally inefficient photovoltaic panels) with demands for robustness, altitude and endurance targets and payload carrying capabilities.

Propulsion systems with photovoltaic cells as their main energy source do not scale down well, nor are they very practical at low altitudes where the availability of solar energy is very variable. Nonetheless, there is a small, but persistent stream of research looking at applications in small and micro-air vehicles (where the propulsion system and the payload receive at least some of their power from photovoltaic cells). One argument in favour of such platforms is that, while they do not have the payload capability of high altitude surveillance pseudo-satellites, nor do they need it, as, being closer to the ground, they can obtain similar quality images with lighter cameras. Of course, traffic and conspicuity issues push the balance in favour of the higher altitude platforms... All of this shows that there are no black and white answers and the optimum scale may be very much mission-dependent.

An example of small solar-powered research platform is the hand-launched *AtlantikSolar* (weighing in at 7.36kg without payload), developed at ETH Zurich with the ultimate goal of offering perpetual

[5] `https://aroundtheworld.solarimpulse.com`

Figure 3.2: The Helios aircraft during its June 2003 mishap when a turbulence encounter caused the aircraft to exceed its design dynamic pressure and this, in turn, led to its catastrophic structural failure. Image courtesy of NASA.

endurance for search and rescue type missions. The AtlantikSolar carries its batteries in the wing spars and the solar panels on the wing surfaces; these supply a peak power of 275W at the sunniest moment of its design mission. The ETH team showed that the batteries alone are capable of sustaining the aircraft for over 12 hours, which indicated that, in theory, it should be capable of staying airborne through the night [600]. Subsequently, AtlantikSolar would go on to achieve an 81-hour perpetual flight, which, according to the Swiss researchers, is currently the longest continuous flight of any aircraft in the sub-50kg category. The aircraft operated during its record-breaking flight in the 600-800m altitude band [601].

Going to smaller scales still requires clever use of the solar panels as structural and even aerodynamic components. An example of this thinking is the *Robo Raven III* flapping wing micro air vehicle, the compliant wing of which almost entirely consists of a flexible solar panel [618].

An interesting, relatively recent realisation in the aircraft design research community is that, when it comes to designing solar-powered aircraft, an entirely novel thought process may be required. In the case of more conventional power sources the problem is formulated as 'given this fixed mission, what is the optimum aircraft that is able to perform it?' Solar-powered unmanned aircraft may require a somewhat more flexible and slightly inverted design process, which asks 'which aspects of the mission would I have to alter slightly to make it significantly better suited to solar powered operations?' Examples include modifying a baseline mission profile to include altitude changes that allow the aircraft to store excess solar energy in the daytime in gravitational potential (to be relinquished subsequently by night-time gliding) [352], modifying the flight path and/or attitude of the aircraft to give better solar exposure to its photovoltaic cells [483, 796, 812] and considering the optimal design of a solar-powered aircraft in the context of the geographical locale of its intended operation [635].

Another shift in emphasis involves the higher level goals driving the missions of solar-powered aircraft – these could be applications that aircraft have not been considered for, such as the provision of 5G network coverage [106] or of persistent surveillance tasks that only satellites would have been capable of previously.

3.4 Automated Refuelling & Recharging

Automated airborne refuelling has attracted significant interest and funding since the beginning of the millennium, with a DARPA-contracted research programme in 2006 an early highlight of these efforts.

Using an optical tracking system and relative GPS/INS systems on both the tanker and the receiver, a pre-production McDonnell Douglas (now Boeing) F/A-18B flew a number of automated engagements (see Figures 3.3 and 3.4) [311]. While automated, this was not a true unmanned demonstration yet – another milestone in that direction would be reached a year later involving truly unmanned (RQ-4 Global Hawk) aircraft through another DARPA effort, but a human pilot was 'in the loop' to 'set conditions and monitor safety during autonomous refuelling operations' [10].

Figure 3.3: Look, no hands! In 2006 the Defense Advanced Research Projects Agency (DARPA), working with NASA's Dryden (now Armstrong) Flight Research Centre, demonstrated the first ever autonomous probe-and-drogue airborne refuelling operation over the Edwards Air Force Base test range. Image courtesy of NASA.

Research efforts involving Global Hawks (both in the tanker and receiver role) continued through to 2012 as part of the KQ-X Autonomous High-altitude Refueling project, with flight tests operated in an unusual configuration: the tanker flew behind and underneath the receiver [127]. Due to time pressures on the aircraft involved, the programme ended before actual fuel transfer could be demonstrated [122].

With the recent first flight of the carrier-launched Boeing MQ-25 Stingray unmanned tanker and a projected entry into service date of 2024 (to support F/A-18 Super Hornet, EA-18G Growler and F-35 operations) [134], the 'tanker side' automation of air-to-air refuelling appears to be reaching the top rungs of the TRL ladder, though the operational level of autonomy of the MQ-25 is unclear at this time. Meanwhile, full automation of drone to drone refuelling operations remains an area of active research interest.

An interesting field of enquiry at present is the optimal configuration of the refuelling system for automated operations. Consider the two main contenders: the flying boom (tanker) and receptacle (receiver) system and the probe (receiver) and passive drogue (tanker) method. There is an interesting tension here between the fact that the control system for the former may be more complicated due to the need for 'steering' both the receiver aircraft and the boom; conversely, the control system of the latter might pose the harder control problem of aiming to make contact with a passive drogue flying less predictably in potentially unsteady flow conditions [756]. The choice of the steered boom architecture raises another interesting research question – should the control system adopt a 'leader-follower' type model or is a collaborative architecture (as described by Thomas et al [757]) the better answer?

Figure 3.4: Camera tracking system image captured during the DARPA/NASA automated refuelling tests at Edwards Air Force Base in 2006. Image courtesy of NASA.

The pre-requisite of air-to-air refuelling, is, of course achieving rendezvous and holding formation in the first place and this is a hot research topic at present, whether with the end goal of achieving a refuelling capability (e.g., [533]) or other concepts of operations (such as aerial recovery of a drone by a 'mother ship' [755]) and whether the target is the leader or a cable/hose towed by it [592]. All these problems are made challenging by having to design control systems for dealing with operational uncertainties, such as actuator failures and wake turbulence [843]. Ultimately, the fundamental technologies underpinning the operation of autonomous systems in general, such as robust control algorithms and computer vision [551], are dictating the pace of developments on all of these fronts.

Recent successes include those of Briggs [244], who reports achieving infrared vision aided close (down to 4m) formation flight over extended periods in wind speeds in excess of 25 km/h. Their docking flight tests achieved 'numerous airborne connections over multiple flights, including five successful docking manoeuvres in seven minutes of a single flight'.

Most of the techniques developed for the in-flight refuelling of drones can also be applied to in-flight recharging of battery-powered aircraft. However, there are interesting alternatives here to a physical umbilical between the 'tanker' and the receiver (analogous to the refuelling hose). Short range wireless power transfer may ultimately prove to be an interesting way for a 'mother ship' tanker (electrical equivalent of) to recharge fleets of electric drones in flight and researchers at Imperial College have recently provided a very early, laboratory demonstration of the idea. As reported by Arteaga et al. [190], they were able to create an inductive coupling between a small, batteryless multi-rotor drone and a charging pad, with the power being sufficient to keep the small drone in the hover. At a larger scale, *Global Energy Transmission*[6] are offering a similar system that is said to recharge commercial grade drones while they are hovering inside a 'large area power hotspot'.

It is important to note that this type of short range inductive power transfer is highly efficient (>90%), unlike the much longer range radiative power transfer techniques we will be discussing in the section on *power beaming*.

Technologically far simpler, especially in the case of rotorcraft, is the automated recharging of aircraft on ground-based docking stations. The roughly decade and a half long history of such endeavours goes back to the work of Dale [293], who developed the first automated battery recharge landing station at MIT (as well as the first *mobile* recharge platform). The same lab went on to develop a battery *swap* platform, which would reduce the landing pad dwell time of the drone to the duration of

[6] www.getcorp.com

the automated removal of the spent battery and the insertion of a freshly charged one [760].

Such automated battery swapping technology remains, to date, on the low rungs of the technology readiness scale and public domain research in this area is currently very limited. There are indications that charging pads (including pads that can be operated outdoors) are beginning to become a practical reality [11], though they are a long way from becoming widespread (the authors are not aware of any 'real life' cases of operational use). This perhaps indicates certain technological roadblocks, or, more likely, the lack of obvious demand, associated with the lack of a clear use case/mission at the moment. A broader view would have charging pads as components of a more generic infrastructure consisting of docking stations that serve other functions too, such as navigational aids, package handling facilities, etc. A patent recently granted to *Amazon Technologies*[364] indicates that the company may be thinking along these lines.

Using existing infrastructure for charging is the impetus behind such ideas as using high voltage power lines. A US Air Force filed patent[548] describes such a system, noting that 'energy collection is by way of a parked vehicle engagement with the transmission line in a current flow dependent, magnetic field determined, rather than shunt, voltage dependent, conductor coupling'. The sketches illustrating the patent show a fixed wing platform. Another US Air Force patent application[581] also mentions 'power line scavenging circuitry'.

The scavenging process is, of course, only part of the challenge here. Another current area of research interest is around how the aircraft locates the power line, how it exploits its magnetic field for navigation (and, indeed, how it avoids its control systems being affected by the strong electromagnetic fields) and how it manoeuvres to a safe landing – a fruitful area of overlap with the increasingly active research area of perched landing dynamics [580]; and, speaking of overlaps, this is where we also come full circle, in terms of how to actually scavenge the power from the high voltage lines once landing has been accomplished, to the wireless charging methods mentioned earlier.

3.5 Thermal, Orographic, Dynamic & Regenerative Soaring

Human glider pilots apply a set of rules for maximising altitude gained in thermals. These range from the simple (if the starboard wing is lifted by a thermal, start flying right-hand orbits) to the complex, relying on vision and high level mission management thinking (use cumulus clouds, other gliders that appear to be climbing and certain ground features roughly aligned with the planned course, as waypoints).

Implementing machine intelligence that replicates some part of this continuum has long been a goal of unmanned aircraft engineers keen to use some of the 'free energy' available in thermal lift, with NASA's successful flight tests from 2005 [179] marking the first major milestone.

The current line of inquiry in this area appears to have shifted from replicating human glider pilot intelligence to using modern technology to exploit the sort of high level, strategic vision that humans pilots cannot achieve. One example of this is exploiting collaborative behaviour within a swarm of autonomous gliders, which, work together to chart the resources available (lift and solar irradiance) and maximise collective performance. Andersson et al. [184] claimed the first success (in flight tests conducted with two aircraft) in this area, though, clearly, routine operational use of collaborative soaring is still a long way away.

A single aircraft learning an increasingly accurate model of the environment the aircraft operates is another potentially fruitful direction in autonomous soaring. Perhaps the most impressive recent demonstration of autonomous soaring based on this principle is reported by Depenbush et al. [305, 306]. Their soaring algorithm includes thermal mapping, explore/exploit decision making, navigation, optimal airspeed computation, thermal centering control, and energy state estimation. Their approach highlights the importance of a data fusion approach to the automated soaring problem and the success of these early experiments indicates the approach being sufficiently feasible to warrant further research.

A related endurance stretching approach is autonomous dynamic soaring [503]. This, as well as the broader problem of exploiting wind fields for automated gliding [288], are largely at the numerical simulation level at present and the jury is still out on the feasibility of practical applications.

Finally, the idea of regenerative soaring (using propellers to harvest energy from updrafts through windmilling) has been simmering on the fringes of the unmanned aircraft energy research agenda for a long time, with Barnes [207] and de Carvalho [297] among recent proponents. The concept of operations typically involves the aircraft thermalling at constant height (as opposed to climbing in the thermal like a conventional glider), recharging its batteries as it does so, before flying on to the next thermal. The key argument (as formulated, for example, in [297]) is that the propeller and generator/motor plus battery combination can also serve as a self-launching powertrain. Once again, this is an idea that has been at the conceptual level for some time, with practical applications seemingly unlikely in the near future, largely due to question marks around the overall efficiency and complexity of the system.

BACKGROUND NOTES

POWER BEAMING

Far field **power beaming** or **wireless power transfer (WPT)** is the transmission of power via electromagnetic waves focused at the receiver, without any wires connecting the transmitter and the receiver. Power beaming is of enormous interest in many applications (e.g., transmitting energy from in-orbit photovoltaic cells to the ground or the opposite, beaming energy from the ground to spacecraft). From an unmanned aircraft systems perspective, such systems have the attraction of eliminating (or drastically reducing) the need to store energy on board the air vehicle.

The useful parts of the spectrum. The atmosphere is opaque to most of the the electromagnetic spectrum, leaving two possible band gaps for ground-to-air power beaming: the radio window and the optical window. The former is limited, from a practical point of view, to centimetre wavelengths (microwaves), as longer wavelengths would require very large antennae.

Rectenna. A contraction of 'rectifier-antenna', this is a key component of microwave power beaming systems. It is meant to convert the alternating current resulting from the captured microwave energy into direct current.

A century-old idea. In the 1920s Nikola Tesla predicted that *'houses will be lighted and powered by wireless, as will be airplanes and other vehicles on land and sea'* [188]. Anything approaching a practical flying vehicle had to wait for several decades due to the absence of the technology required for capturing and, if needed, rectifying the electromagnetic radiation beamed up from the ground (either a rectenna, in the case of microwaves, or suitable photovoltaic cells in the case of light). Raytheon's early rectennas and their experiments with a small beamed power helicopter in the 1960s [250] constituted the first proof of concept of Tesla's 'wireless power' aircraft. The next notable experiment was the 1987 flight of the Canadian SHARP (Stationary High-Altitude Relay Platform), a high aspect-ratio, hand-launched single motor fixed wing, microwave beam powered drone. The 150W required for loitering flight were supplied by a rectenna system fitted to the airframe, onto which a 15ft parabolic dish focused a 2.45GHz, 10kW microwave beam [338].

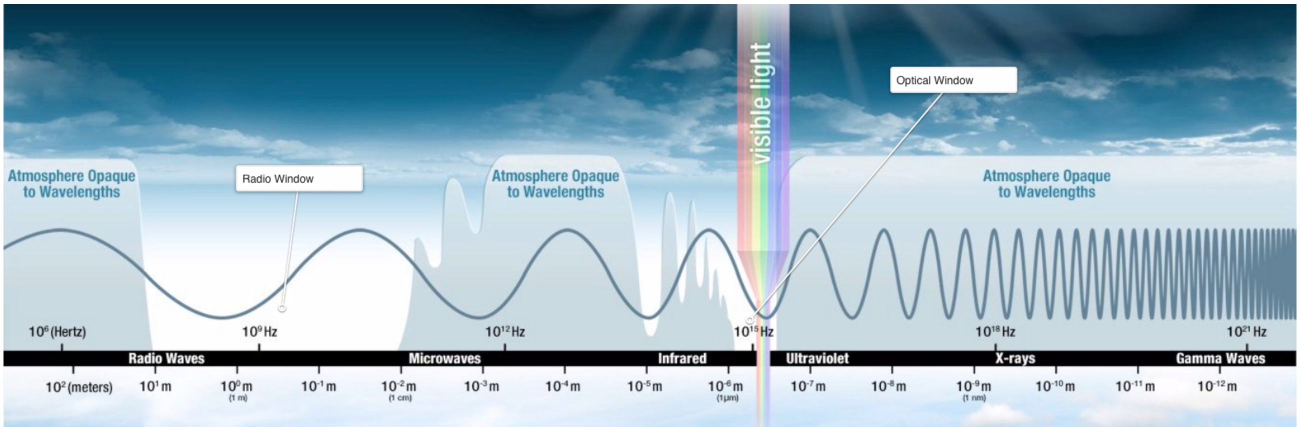

Figure 3.5: Atmospheric opacity across the electromagnetic spectrum. The candidates for unmanned aircraft power beaming are the two opacity gaps (atmospheric windows). Image courtesy of NASA [255].

3.6 Tethering & In-Flight Power Beaming

A solution to unmanned aircraft endurance limitations is to use a ground-based, practically infinite energy source. Conceptually, the simplest implementation of this idea is the use of a physical tether, a cable carrying the power required by the propulsion system and the payload of the drone (as well as, sometimes, data).

Immutable laws of physics will always limit the range (cable length) of such drones, as increasing cable length will demand an increase in drone payload capability and thus power, which, in turn, will demand more power and thus a heavier cable and so on. That said, there are a number of applications where range is of limited interest (e.g., persistent, local, overhead surveillance [144]) and the physical tether has the added benefit of constraining the drone to a hemispherical block of airspace even in the case of complete systems failure.

Powering drones through the targeted beaming of electromagnetic energy from the ground (see the *Background notes* on power beaming) has similar motivations to tethering: taking the primary energy source off the vehicle can extend its endurance, potentially to as long as the service interval of the vehicle. Unlike wired tethering though, power beaming does not physically constrain the vehicle to a hemispherical block of airspace (as one may desire, for example, to ensure airspace deconfliction, even in the case of complete systems failure), the energy efficiency may be lower than on wired systems and the operation of high energy beams may involve complicated safety considerations. On the plus side, the vehicle can be smaller, as the power capturing equipment on board may be smaller and lighter than the equivalent tethering cable.

The unmanned aircraft power beaming research landscape can currently be found around TRL 4, splitting into two distinct schools of thought: one focusing on the microwave 'window', the other on the light (laser) band gap.

The desire for microwave beaming to become a practical means of powering unmanned aircraft is currently driving two pivotal areas of research, one on the aircraft side and one on the ground side: *rectenna design* (see the *Background notes* on power beaming) and phased array microwave transmitters respectively.

A key topic of interest in rectenna design is overall receiver efficiency (microwave to direct current) [436] and, indeed, the end-to-end-efficiency of the ground-air system [553].

Phased array transmitters are ideal for unmanned aircraft applications, as the beam can be steered to track the vehicle without the need to mechanically steer the transmitter [707] (the phased array approach is not favoured on the receiver side, where greater redundancy and architectural simplicity is achieved via independent elements). Much research here is focused around *beam shaping*, that is, the optimum weighting of each radiating element [553].

Microwave beaming research is particularly active at present in Japanese academic institutions (the Universities of Tokyo and Kyoto), both in terms of phased arrays [707] and applications to unmanned aircraft [586]. Elsewhere (in particular in the US) the use of the 'optical window' appears to be commanding greater interest, motivated chiefly, it appears, by the fact that beam coherence is easier to ensure in the case of lasers than microwave beams.

The proof-of-principle on laser beam powered flight is over a decade-and-a-half old at the time of writing: NASA's MOTH1 and MOTH2 first flew (indoors) in 2003 (see Figure 3.6, [115]), with a human operator tracking the vehicle with a manually steered laser beam.

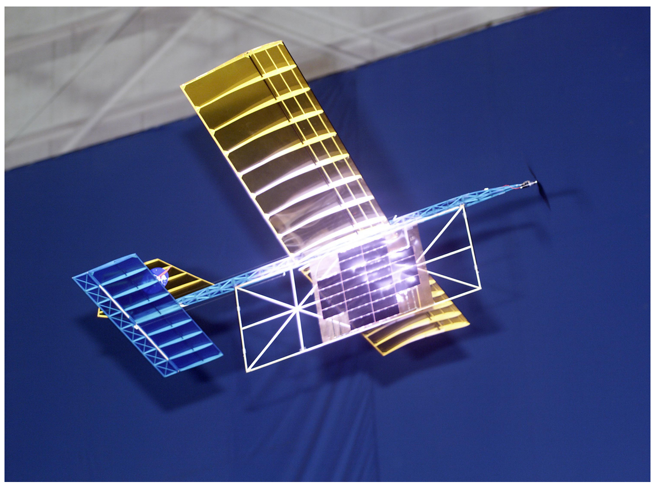

Figure 3.6: MOTH2 – the first aircraft powered by a ground-based laser, developed at NASA Marshall and the Dryden Flight Research Centre in 2003. The laser being shone at the photovoltaic cell seen underneath the fuselage was a 1.5-kW 940-nanometer (nm) diode array with 50 percent efficiency [552]. Image courtesy of NASA.

Accurate and safe targeting has been one of the critical technology areas considered since this pioneering experiment (clearly, manual steering is impractical outdoors, particularly at higher altitudes), with a patent published in 2006 by Baldis et al. [199] proposing a system with a passive receiver side, requiring no additional on-board power source (the patent is listed as 'abandoned' as of 2019).

In 2011 *Ascending Technologies* of Germany and *LaserMotive* of Seattle (US)[7] reported on power beaming experiments conducted as part of an FP7 research programme [164]. They flew a 1kg quadcopter indoors, for a duration of 12h27' (claimed to be an endurance record for multi-rotor micro air vehicles). The energy required for the flight was transmitted via an infrared laser beam and collected by the drone via a solar array. Outdoor experiments followed in 2012, this time powering a Lockheed Martin Stalker, a Solid Oxide Fuel Cell powered, hand-launched, fixed wing aircraft. The experiment *"demonstrated net positive power to Stalker in flight, at ranges up to 600 meters"* and *"the beam director tracked the receiver for long periods, with centimeter accuracy at 500 meters, despite turbulence and aircraft maneuvers"* [130]. The experiments included both day and nighttime operations and the endurance of the UAV was reported to have been increased by 2,400% [12] (this indicates that while the laser may not have covered all the energy needs of the loitering platform, it came quite close).

[7] The company is currently known as *PowerLight Technologies* (URL: `http://powerlighttech.com`).

3.7 Other Energy Sources

Beyond the energy sources discussed above, a few other means of providing energy for flight are being studied, especially for certain niche applications.

A 'fringe' energy source that has been explored explored for decades for potential use on aircraft and spacecraft is *nuclear power*. A recently published Sandia National Laboratories report [676] ignited some discussion of nuclear-powered unmanned aircraft powerplants, but a feasible aerial platform and suitable concept of operations remains unlikely in the near future. Radioisotope thermoelectric generators (RTGs) routinely used in spacecraft applications [225] may have some technical feasibility for powering pseudo-satellite payloads, but concerns related to safety and environmental contamination, as well as performance issues mean that ubiquitous unmanned aircraft applications are not on the immediate horizon and thus not on public domain research agendas at the moment.

A much more benign, and far cheaper, as well as lower risk means of generating energy for flight is balloon-launching. The concept is simple: a glider is attached to a gas balloon, which lifts it to a very high altitude launch point, where the glider releases to begin its mission, with ranges of the order of hundreds of kilometres achievable. The potential energy resulting from the work done by the buoyancy of the balloon over its long ascent is thus 'converted' into flight (kinetic energy) via gravity doing the same work buoyancy had done, but in the opposite direction. While this launch method has numerous drawbacks – the balloon/glider launch process is very weather-sensitive, the range of possible missions is generally highly dependant on winds aloft, payload capabilities are limited, helium is expensive, etc – it has the great advantage that extremely high altitudes can be reached with very simple systems (indeed, several amateurs have succeeded in such flights) and in certain niche applications the system has great potential. A recent example is the weather forecast model validation flight reported by Schuyler et al. [694]. In a defence context, DARPA's 2015 'Unrecoverable Systems' call [295] also envisaged the design of a balloon-launched vehicle, with target figures of 35,000ft release hight and lateral distance covered of at least 150km.

Chapter 4

Mission Planning & Navigation

The ultimate goal in the development of future UAS is for the system (or systems) to complete a mission without any human intervention. Mission planning is therefore an important part of the process of any UAS operation for both civil or defence applications and includes the consideration of scheduling, mission management or re-planning and route planning – both global and local path planning. Navigation is, of course, central to a UAS being able to complete any mission that has been planned.

The following chapter reviews the state of the art in both of these areas. Current research trends in mission planning employing, for example, enhanced collaboration, machine learning and artificial intelligent are considered before advances in navigation including, for example, GNSS, inertial navigation systems, visual navigation systems etc. are examined.

4.1 Mission Planning

Mission planning (MP) is an important part of the process of any military operation. How the mission should be conducted is planned in great detail in order that operational requirements are achieved. Therefore the complexities of mission planning vary depending on the mission or military operation to be conducted. MP covers a wide range of meanings and includes, people carrying out planning tasks, inputting data to automated systems and a wide range of different automated systems for planning activities. Consequently, MP is an activity that often requires interaction between multiple entities. This may be to support distributed planning, in which the responsibility for different aspects of mission operations planning is spread over multiple entities. It may also be to facilitate collaboration between missions, or to allow the planning of payloads by multiple end-users.

BACKGROUND NOTES

MISSION PLANNING

Pre-mission planning Planning carried out before any execution starts. This implies using a predicted start state but being able to take time to plan and allows for significant human involvement.

Mission Management / Re-planning Planning during execution (for a vehicle while it is moving) to adjust a plan in the light of new information. Implies a tighter time restriction on the planning. Specialised algorithms exist to trade off coverage and optimality against run-time.

Planning Finding a set of actions to achieve a goal. The problem is finding a set of actions from many possible actions. Involves an explicit model of what the future state of the world is predicted to be if the actions are undertaken.

Scheduling Finding the best order in which to carry out a set of tasks. Typically the set of tasks is well defined and simple to achieve individually. Involves an explicit model of what the future state of the world is predicted be if the actions are undertaken.

Route planning (global) Finds a route from a start position to a desired goal position, based primarily on pre-gathered map information. May include elements such as risk, exposure and ground type (for ground vehicles). Ground route planning is primarily concerned about finding the best route given details of the terrain. Air route planning, while having an extra dimension to worry about, is generally simpler as terrain has a much lower impact. Global planning can take a long time to carry out and may be undertaken before a platform starts moving (pre-mission route planning) or while a platform is moving (route re-planning).

Path planning (local) Path planning is concerned with short term paths for a platform to avoid collisions with obstacle detected by local sensors. Usually takes a planned global route into account but is primarily concerned with giving fast responses to sensor detected obstacles in a local map.

The functions of mission planning in unmnanned aircraft systems operations:

- Planning access to the airspace where the UAS needs to operate including transition to the point of operation
- Planning that exploits the performance characteristics of the UAS and sensor and payload characteristics, cognisant of system limitations
- Planning to penetrate advanced enemy air defences; understanding the threat environment (enemy air defence threat analysis) and planning to avoid or survive them
- Planning for target surveillance and/or tracking; Information gathering to enhance situational awareness
- Planning to engage or strike a target (weapon delivery planning) or to support other assets undertaking a strike mission
- Planning for mixed UAS and manned aircraft teams
- Planning to provide battle damage assessment information post-strike
- Planning that takes advantage of environmental/ geo-data to minimise being seen by the enemy including line-of-sight analysis
- Planning that ensures communications with the ground control station is always maintained and if lost, planned recovery positions
- Planning to deliver supplies in logistics operations
- Planning that incorporates the needs of other operating forces that may need local situational awareness, however fleeting.

Unmanned aircraft system mission planners are in many cases developments of MP tools previously developed for fixed wing or rotary wing aircraft due to similarity of requirements, enabling manufacturers to build capability more rapidly and in some cases to incorporate requirements for manned unmanned teaming missions. The following sections provide a non-exhaustive sample of MP technologies currently available and /or under development.

4.1.1 A Selection Of Mission Planning Tools

Lockheed Martin SharkFin

SharkFin [13] is a Lockheed Martin developed MP capability which provides navigation control, video display, and payload control of multiple UAVs in one integrated package. It includes a sophisticated toolset of decision aids, optimization algorithms, and situational awareness displays. Supported by auto-routing algorithms and physics models, an operator is able to optimally position the UAV for target collection, communications coverage, and detection avoidance. High level planning is provided through a video-game-like interface which allows operators to manage complex UAV missions in a simple, intuitive way. Users focus on the mission objectives rather than flying an aircraft. SharkFin is based on STANAG 4586 and can control any compliant UAV.

Lockheed Martin Multi-Domain Synchronized Effects Tool (MDSET)

In 2018, Lockheed Martin revealed their Multi-Domain Synchronized Effects Tool (MDSET) [14], which has the ability to operate across a resilient network that connects disparate systems and assets across different domains. MDSET addresses the complexity of the multi-domain battle by transforming command and control into a collaborative cross domain decision-making framework. Assimilating essential information from stove-piped systems into one intuitive system, MDSET creates a comprehensive picture of the integrated plan, allowing decisions to be made based on concurrent (vs. serial) situational awareness of activity in all domains. Unfortunately the open literature does not reveal what algorithmic approaches are being exploited in the MDSET system, nor is it clear how the system copes with limitations and uncertainties inherent in the disparate systems that MDSET seeks to link together.

Collaborative Airborne Planning, Task Evaluation & Authorisation Manager (CAPTEAM)

The QinetiQ developed CAPTEAM [153] system provides a real-time mission planning/management and situational awareness capability. The MP system was originally designed and sold as a Rotary Wing Mission Planning application (Onboard Mission Planning System - OMPS), but is platform agnostic and could be exploited in Fixed Wing or Ground Vehicles. Developments undertaken to date support Manned, Unmanned-Teaming (MUM-T) with STANAG 4586 Levels of Interoperability (LOI) for control/exploitation of UAS Platforms/Sensors. CAPTEAM also provides a (airborne) demonstration platform for Policy Management and Electronic Negotiation technologies to manage autonomy technologies supporting the mission. One of the benefits of STANAG 4586 LOI is that it enables remote tactical users to task and exploit the integrated UAS. The systems provides a Live or LVC airborne MUM-T node for exploitation of UAS capabilities; currently this capability only exists in the USA. CAPTEAM is available as a portable tablet computer-based situational awareness software tool, which optimises human attention, allowing operators to manage their workload using adaptable autonomy. Illustrated in Figure 4.1, this tool can therefore integrate with a variety of manned platforms with the following immediate functionality: carry-on mission planning and execution system for air platforms, tasking and de-confliction of air platforms through a map, managing co-operative search of large areas, sensor control, sensor imagery mark-up and distribution.

The Task Execution Framework

The TEF [161] is a QinetiQ in-house research level hierarchical framework that provides multi-level autonomous control and coordination of single and multiple UAS. The system is designed to be distributed such that different elements of task execution can happen at the appropriate level in the system such that team tasks may be managed from a central hub but the platform level tasks are managed on the platform. The TEF supports research into task models that are used to determine

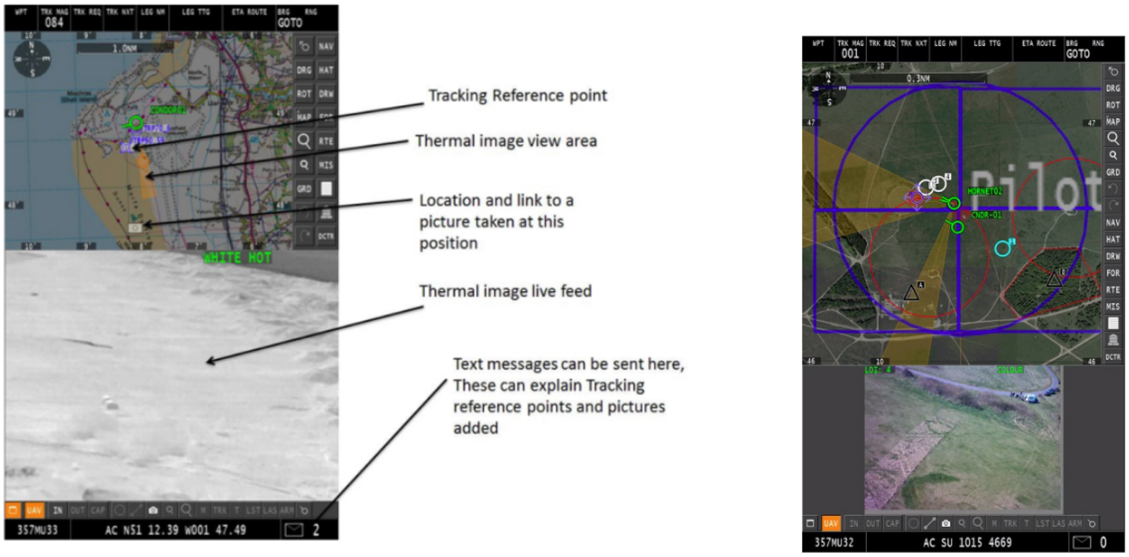

Figure 4.1: QinetiQ CAPTEAM application and tablet.

how low-level (primitive) autonomy behaviours are combined and sequenced to form more complex mission tasks, tactics and goals.

QinetiQ UxV Autonomy Research Capability (QUARC)

The QUARC [161] system provides a Single Operator, Multi-UxV ground control station (GCS) with autonomy, policy management and electronic negotiation capability, developed for UAS MP and control but potential for UxV systems. The QUARC system is being developed as a Windows-based research capability, but with potential to productionise targeted sub-sets of functionality. QUARC currently supports experimentation with simulated UxV and payloads, or real UxV and payloads, or a hybrid Live Virtual and Constructive capability. Additional functionality includes MUM-T technology enablers through STANAG 4586 LOI hand-off of tasking/exploitation of UxV Platforms/Sensors. The system is also being used to support the rapid-prototyping of Configurable Operating Model for Automated Control of Tasks (COMPACT) [154] concepts in support of control or management of autonomy functionality there-by providing platform-level policy management and negotiation within layered C2. Figure 4.2 shows a view of the QUARC Mission planning system.

A tool box of several search planning algorithms is available with QUARC which vary in complexity; examples include: local search algorithms based on simulated annealing, several variants of A* and Djikstra graph search, and Monte-Carlo search optimisation algorithms.

DreamHammer Ballista

Ballista [15] is an intelligent control platform that integrates unmanned drones and robots from different manufacturers into one system across space, air, sea and land. It can be run from nearly any computer, tablet or smart phone. In 2013, Lockheed Martin provided the US Navy with a capability demonstration of unmanned aerial systems controls in support of the US Navy's Unmanned Carrier Launched Airborne Surveillance and Strike System and Command Control System programs. The UAS were operated from a single command and control system, which a Lockheed Martin team integrated with intelligence, surveillance and reconnaissance systems to provide mission planning, sensor and common operational controls. This allows operators to manage multiple UAS platforms simultaneously and provides them with one comprehensive mission picture. After delivering a complete image,

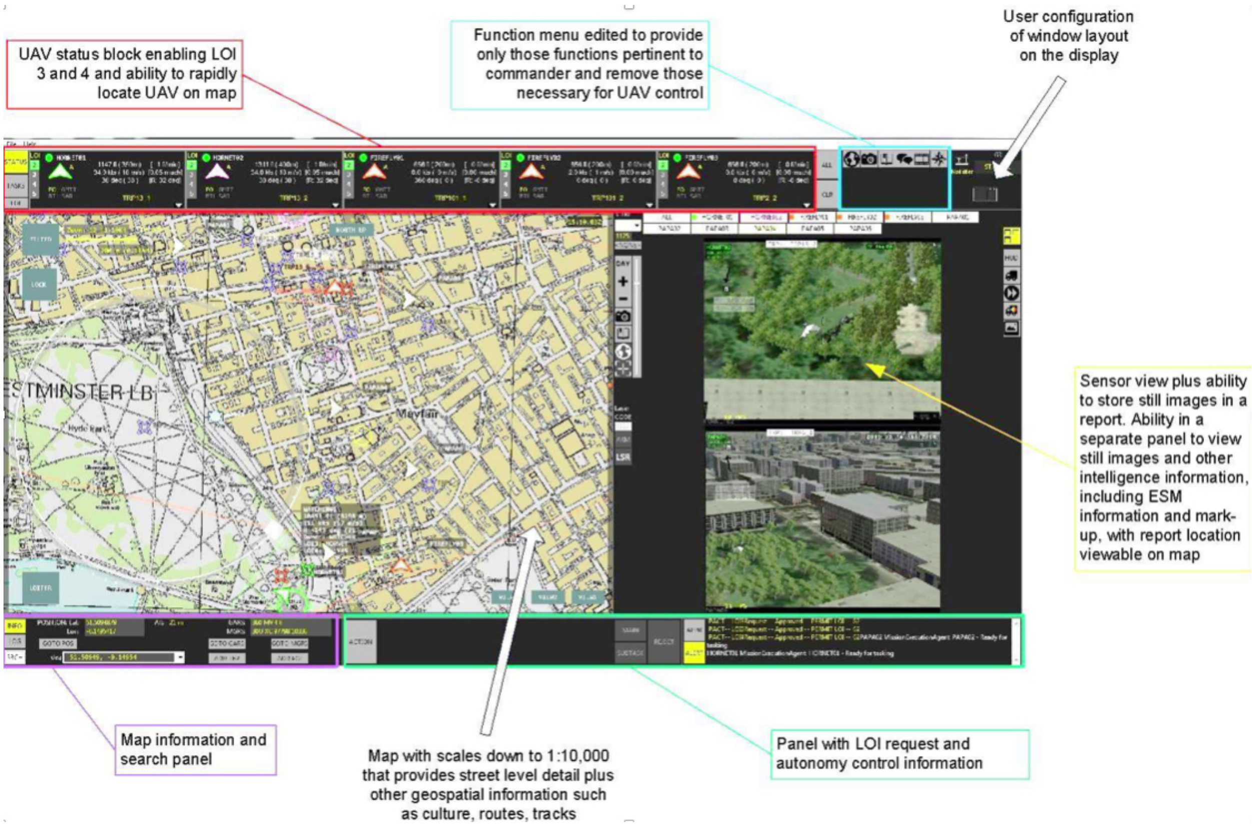

Figure 4.2: QUARC mission planning and viewing system.

the team then used the picture to rapidly re-task and re-route the UAS.

4.1.2 Research & Trends

Developments that are likely to provide benefits to future mission planning systems are in the areas of improved computer processing, distributed, potentially embedded sensors with smaller form-factors, greater connectivity in terms of access to cloud computing and more robust communication systems to ensure that connectivity is maintained. The developments are needed to ensure that greater agility is achieved in the future battle space which will be constrained, cluttered and complex with near-peer adversaries.

In the near term, developments in machine learning (ML) and AI algorithms will support humans in the analysis of data and multi-objective decision making. Trust in such approaches for mission critical tasks remains to be proven, but there are several initiatives to understand where ML/AI systems can support the human with mission planning and Command and Control (C2). In addition to academic applications of ML/AI algorithms, examples of Industry applications currently being evaluated include Deep learning Convolutional Neural Networks for target recognition [158], distributed reinforcement learning for UAV behaviours [160], Combining Planning with Reinforcement Learning for multi-robot task allocation [160] and AI based decision aids for Mission Planning [155].

The post-2025 time horizon might see ML/AI algorithms that are developed and are integrated into sensors, for example, evaluation of the threat, characterisation of the target, assignment of the most appropriate weapon system and positioning of a future UAS to achieve maximum engagement success and battle damage assessment is likely to be demonstrable. From a weapons system mission management perspective, the functionality could include algorithms to optimise the engagement through launch and trajectory/guidance optimisation with the Human on the loop ready to press the stop button. QinetiQ are experimenting with the COMPACT [154] conceptual architecture to manage ML/AI and autonomy algorithms which should be exploitable in this time frame subject to continued investment. COMPACT provides a means for monitoring and controlling UAS using variable levels of autonomy and automation, and by variable techniques, based on a set of pre-determined (and configurable) rules.

Beyond 2030, a greater exploitation of Augmented Reality (AR) and Virtual Reality (VR) within MP systems may be expected. In a robustly and resiliently connected environment, more agile mission planning and C2 (more closely coupled), with human supervision via an immersive C2 environment may be possible. The role of the human at this stage may be to intervene for the more complex engagements, provision of oversight and fine tuning of responses.

4.2 Navigation

Navigation solutions are a core capability requirement for unmanned aircraft systems (UAS). UAS could be considered as platforms for carrying either sensors to enhance situational awareness or payloads to improve communications or payloads that deliver effect. Consequently, the need to navigate safely and accurately is a key enabling requirement. Moreover, the navigation solution needs to be robust and resilient in environments that are constrained, cluttered, contested and complex and, potentially, contested against peer adversaries. The following sections identify a number of navigation technologies that enable a current and/or future UAS to deliver operational requirements.

4.2.1 Global Navigation Satellite Systems

Developed by the Department of Defence (DoD), the Global Positioning Service (GPS) was initially launched in 1973 and completed in 1995, with a total of 24 satellites providing global coverage. It offered geolocation and timing services to receivers in various weather conditions. At first only an encrypted military signal was broadcast, however the system soon became dual-use, offering a civilian signal to everyone.

There are now four operational Global Navigation Satellite Systems at different levels of maturity: the original GPS, which has subsequently been undergoing significant modernization, the Russian GLONASS system, the European Galileo system, and the Chinese Beidou system. These have been designed with a certain level of interoperability in mind due to the trend towards taking advantage of the resilience of multi-constellation, multi-frequency receivers. As of 2016, around 30% of receivers were capable of receiving signals on more than one frequency from the satellites in the same constellation, although 65% of receivers could support 2 constellations. The most common constellation combination is GPS+GLONASS [16].

Multi-constellation capability typically provides an increase in the number of GNSS satellites in the field of view which should improve GNSS performance in terms of:

- availability: overcoming issues related to blockages in the field of view, such as foliage and urban canyons;
- accuracy: more satellites in view means an improved position confidence;
- robustness: some signal diversity if one constellation is being interfered with or has malfunctioning satellites;
- Time-To-First-Fix; improved chance of having satellites with a sufficient signal quality to enable acquisition

Multi-frequency operation allows the virtual elimination of one of the primary sources of error in GNSS position accuracy, namely ionospheric error. This is achieved by comparing the delays in the signals received on multiple frequencies from the same satellites, where each frequency will be impacted differently but somewhat predictably, relative to one another. Some mitigation against interference can also be provided by multi-frequency operation – if one frequency band is being affected, other frequencies can still be used.

GNSS provides a worldwide navigation and positioning capability that is available to everyone with an appropriate receiver. However, the low received power at the Earth's surface makes all GNSS susceptible to intentional and unintentional interference which can easily deny the signal to receivers. Portable personal jammers (that can be attached to car cigarette lighters) have proven to be effective at 6-8 km with an omni-directional patch antenna and a transmit power of around 650 mW (across 20 MHz L1 bandwidth) [133]. Note GNSS jamming is discussed in detail within Section 9.1.2.

All GNSS constellations are susceptible to natural phenomena such as solar flares [143] and could be simultaneously disrupted if a sufficiently large solar eruption occurred. The vulnerabilities of GNSS necessitate a reversionary mode of operation and are currently limiting its usage in critical applications.

Multi-constellation, multi-frequency can provide an enhanced level of protection against spoofing, in that, spoofing multiple constellations across multiple frequencies will be a more challenging task than a single frequency on a single constellation. This is because a successful attack must spoof (almost) every signal which a receiver is receiving, otherwise the receiver can easily do consistency checks between the different signals. More constellations on more frequencies will require more signals to spoof, that will need more processing, as it will pose a more complex synchronisation problem, and will require more power/hardware to combine and transmit signals without losing timing information between them.

The most resilient approach to defend against spoofing is to take advantage of the encrypted GNSS signals such as the military P(Y) and M-Code signals for GPS, or the Galileo Public Regulated Service (PRS). However, these signals are only available to authorized users.

Multi-constellation, multi-frequency GNSS receivers are highly applicable to all sizes of UAS. They are ubiquitous and already embedded within small handheld devices such as mobile phones. Increased performance does increase the SWAP, but the chip size is still of the order of centimetres as shown in source [16] below. For GNSS, it is likely that the technology would be used not just for positioning in isolation, but as part of an integrated navigation scheme, such as with an INS [149].

Most major chipset manufacturers produce mass-market chipsets/System-on-Chip solutions with multi-constellation capability, albeit single frequency (typically L1). Multi-frequency capable chipsets are fewer in number and mainly used in professional markets[1].

Multi-constellation operation will become standard across GPS chipsets in the next few years. Already, low cost chipsets are available that support all current GNSS (and Space Based Augmentation Systems (SBASs)).

As of 2016, multi-frequency operation was limited to the high precision sector (e.g. surveying and agricultural control), where accuracy and integrity are paramount. These relatively low scale sectors mean that receiver costs are high, with increased complexity and power demands due to the multi-frequency operation.

Multi-frequency operation will begin to permeate high volume markets as the improvements in accuracy and integrity become apparent to the developers and users in those markets.

A further future possibility is the provision of a further constellation in the form of a British Global Navigation Satellite System [147, 145]. This will provide multi-frequency capability as well as its own encrypted signals to provide authorized users additional resilience to the spoofing threat. It will also

[1] Providers include: Novatel (dual frequency): OEM6/7nnn range, OEM 7660 (GPS L1 C/A, L1C, L2C, L2P ; GLONASS L1, L2 ; BeiDou B1, B2 ; Galileo E1, E5b ; SBAS L1 ; QZSS L1 C/A, L1C, L2C) [119] and Septentrio (quad frequency – true MCMF experience): AsteRx4 OEM, Supported signals: GPS (L1, L2, L5), GLONASS (L1,L2,L3), Galileo (E1, E5ab, AltBoc, E6), BeiDou (B1, B2, B3), IRNSS(L5), QZSS (L1,L2,L5) (Galileo, Beidou, IRNSS, E6/B3 and Altboc are optional features), all-in-view SBAS (EGNOS, WAAS, GAGAN, MSAS, SDCM) (including L5 tracking) [142].

be designed with multi-constellation compatibility in mind.

4.2.2 Inertial Navigation Systems

High-end INS

An inertial navigation system (INS) uses measurements of angular rate and specific force provided by three orthogonally mounted gyroscopes and three orthogonally mounted accelerometers, in order to propagate a navigation solution consisting of attitude, velocity, and position, forward in time. Consequently, an INS is a dead reckoning system. In the 1960s, ring laser gyroscopes (RLG) became available, which were able to measure much higher angular rates than their gimballed predecessors and making it possible to mount the ensemble of three accelerometers and three gyroscopes, which is known as inertial measurement unit (IMU), directly to the vehicle. Therefore, these INS are known as strap-down INS, and are the majority of the systems used today. INS systems maintain a continuous navigation solution in environments where GNSS is unavailable with a horizontal position growth of up to 1NM/hr. Vertical positioning requires the use of baro-altimeter to stabilize the height channel.

The major error source within inertial sensors is the bias variation. The inertial sensor bias can be seen as composed of a constant and a varying part. Most of the constant part can be calibrated, while the varying part, if not estimated continuously during operation of the INS, directly contributes to the growth of INS navigation errors with time. A high-end INS accumulates a position error of around one nautical mile after one hour of operation. In order to achieve such a performance, gyroscope biases of 0.01deg/h and accelerometer biases of 0.01mg or better are required. Besides the improved sensor quality, a high-end INS might differ from a lower grade INS in the gravity model used. In a tactical grade INS, a simple gravity model is usually used, in which gravity is modelled as a function of latitude and height only, pointing strictly in the down direction of the north-east-down (NED) frame. In a navigation grade INS, more sophisticated gravity models, considering deflections and variations of the gravity vector by means of maps, might be applied. In order to allow for longer stand-alone operation, the height channel needs to be stabilized e.g. using a baro-altimeter.

An INS cannot be jammed or spoofed, and is not dependent on a line of sight to satellites. Therefore, the INS navigation solution is continuously available, which makes it ideal for UAS that may be operating in a GNSS denied environment. However, SWAP for high-end INS is large, making it only applicable for the larger UAS platforms.

A typical example that can be seen as a benchmark is the Honeywell HG9900[2] [121], which has following characteristics: size: 13.97 x 16.26 x 13.56cm, weight: < 2.95kg, power: < 10W. The system will also require a position correction from an alternative navigation source for extended mission durations.

The future trend is not necessarily to improve upon the performance of high-end INS, but to provide this capability in a smaller form-factor. Consider, for example, the DARPA programmes to develop a navigation-grade Micro-Electrical-Mechanical-System (MEMS) IMU, e.g. [105], [140]. The trend for miniaturization could potentially make high-end INS capability available even to the smallest IMUs. However, this capability appears very optimistic given the rate of improvement in the accuracy of low-cost sensors over the last 20 years.

[2]Honeywell is a leading producer of tactical and inertial grade IMUs for aerospace, military and commercial applications. With the HG9900, Honeywell offers a high-end RLG-based IMU [121]. Other suppliers: Northrop Grumman manufactures the LN-100 high-end INS, which is also available integrated with a GNSS receiver as the LN-100G [137]. Safran is active in optronics, avionics, electronics and critical software for both civil and military markets. Safran offers the Sigma 95N, an inertial grade INS, that is also readily integrated with a GPS or GPS/GLONASS receiver [141]. KVH is a manufacturer of tactical grade IMUs, INS, and integrated navigation systems for defense and commercial guidance and stabilization applications. The high-end product by KVH is the GEO FOG 3D INS [128].

Low-end INS

As with high-end INS, lower grade INS technology is also based on the integration of angular rate measurements provided by gyroscope and accelerometer measurements. Following on from Ring Laser Gyro technology, Fibre Optic Gyroscopes (FOG) and MEMS gyroscopes became available. FOG sensors typically provide tactical grade performance, such as that required for missiles, while MEMS sensors are typically more for commercial applications such as smartphones or for automobiles.

MEMS are built from tiny electronic components of 0.001mm to 0.1mm that are packaged within an electronic microchip around 1mm in size. Through exploiting the electrostatic effect, the MEMS enables the measurement of acceleration and rotation within three axes.

The error characteristics for MEMS grade sensors can be of the order of 100deg/hr and 10mg for the static biases meaning that it is not possible to navigation purely on MEMS IMU data alone, the position error can be several or dozens of metres within seconds. This why low-end INS are typically combined with alternative sensors such as GNSS to provide a continuous integrated navigation solution.

The benefits of GNSS/INS integration are that the INS' estimates can be corrected by the GNSS data and that the INS can provide position and angle updates at a quicker rate than GNSS. Additionally, GNSS signal losses may occur and the INS can continue to calculate position, velocity and orientation angles during outages, providing significant advantage over a standalone GNSS solution.

Four categories are possible for the integration of GNSS and INS to provide a combined navigation solution (from un-coupled to ultra-tightly coupled, we are more closely correlating the physical parameters issued by the INS and GNSS sensors):

- un-coupled: the two systems operate independently, but when a GNSS position and/or velocity measurement is available the IMU is reset.
- loosely coupled: it uses GNSS and INS position and velocity measurements in a Kalman filter that models INS error dynamics.
- tightly coupled: it uses separate GNSS tracking loops for each satellite channel, with an extended Kalman filter operated independently using the measurement output from the GNSS receiver and modelling the INS error dynamics.
- ultra-tightly coupled: the extended Kalman filter uses the correlator output from the GNSS receiver and models the INS error dynamics. The outputs from the INS processing, when projected into satellite line-of-sight coordinates, are used to control the code and carrier replica signals for each satellite channel.

The ultra-tightly coupling is considered a more robust design to jamming and vehicle dynamics but is the hardest to achieve given the combination of GNSS receiver signal processing and extended Kalman Filtering.

An INS cannot be jammed or spoofed, and is not dependent on a line of sight to satellites. Therefore, the INS navigation solution is continuously available, which makes it ideal for UAS that may be operating in a GNSS denied environment. SWAP for low-end INS is small enough to make it appropriate for all sizes of UAS platforms. At the small end of the scale, an electronic microchip typically measures 3x5x0.9mm, taking 2.16V to 3.6V supply voltage with 1 mW power consumption. Slightly larger, and fully integrated with GNSS, as an example[3], the VectorNav VN-200 [149] has the following characteristics: size: 24 x 22 x 3mm, weight <4g, power <500mW.

The future trend is to improve MEMS quality such that they can perform as well as a navigation-grade MEMS IMU, e.g. [105], [140]. The trend for miniaturization could potentially make high-end

[3] Examples of manufacturers: VectorNav is a leading producer of miniature, high-performance Inertial Navigation Systems (INS), including the VN-100, VN-200 and VN-300 series [149]; Invensense produces MEMS IMU chips such as the MPU-6050 that may be integrated with other navigation sensors [125]; UTC Aerospace Systems produce MEMS IMU and integrated sensors such as the SiIMU02, MinIM and SiNAV which are applicable to medium sized IMUs, [148].

INS capability available to even the smallest IMUs. However, this capability appears very optimistic given the rate of improvement in the accuracy of low-cost sensors over the last 20 years.

Further research is also ongoing into Ultra-Tightly-Coupled integration which will also improve performance in GNSS degraded environments, although this is a niche capability that requires close co-operation between the integrators and GNSS receiver manufacturers.

Quantum Inertial Navigation through Cold Atom Interferometry

There is currently research underway exploiting the quantum interference of ultra-cold atoms to build gyroscopes and accelerometers that could enable advanced INS with unprecedented accuracy. Such devices are expected to be capable of maintaining a positional accuracy to within 1 metre during the course of a day's movement; this is several orders of magnitude greater than current classical devices.

The physics behind this innovation concerns interferometry and exploits the wave-like property of matter and the quantum phenomenon known as superposition. It is similar in principle to optical interferometry, where light waves are sent on different paths and then combined, creating fringing patterns due to constructive or destructive interference. Atomic interferometry exploits the wave-like nature of atoms, sending them on different paths, in different quantum ground states. Through analysing their subsequent interference it is possible to make extremely sensitive measurements of quantities such as rotation and acceleration. It also enables sensitive measurement of the strength and direction of gravity. Some sources [146], claim a thousand-fold improvement on existing inertial measurement devices and envisage that, when mature, such technology could augment or even replace satellite navigation solutions for many applications.

At the current time there is still concern as to how such technology would perform as part of a system of systems. This has yet to be established.

Whilst still immature and a topic of research, the prospect of quantum inertial navigation has received a lot of interest, particularly by the military. Nevertheless, the technology will only become relevant to UAS when it becomes available in a small form factor that is transportable, standalone and lightweight. At least one source from 2016 [124], claims the technology could be in a state that is usable in mobile phones in ten years, but this is highly unlikely.

There are currently at least two research groups active in this field. These are based in the US and UK, although it is suspected that there are research teams operating in other countries, such as Australia and the Far East. Known progress includes:

- The US Defence Advanced Research Project Agency (DARPA) Quantum-Assisted Sensing and Readout (QuASAR) project is developing quantum devices that are expected to find broad application across the Department of Defence (DoD), particularly in the areas of biological imaging, inertial navigation and robust global positioning systems [109].
- Imperial College London (ICL), Birmingham University and other members of the UK Government's National Quantum Technology Programme are developing a portable cold atom interferometer for greatly improved inertial navigation [124].
- In late 2018, a team from Imperial College London and the photonics company, M Squared, demonstrated a quantum accelerometer for navigation [114].

According to researchers involved with the UK National Quantum Technologies Programme [146] Quantum IMUs are expected to arise between 5 and 10 years from now and to offer a thousand-fold improvement on existing IMUs. This appears very optimistic given the maturity of current research. However, the rewards for successfully building a reliable Quantum IMU of millimetric accuracy, that is secure, practically non-jammable and highly resilient, are enormous, notwithstanding the huge advantage in capability that could be realised by those militaries that adopt the technology. For these reasons alone, one can expect continued research efforts in this field, and the appearance of a commercially available IMU in the next ten years cannot be ruled out.

4.2.3 Terrain Referenced Navigation: Visual, LIDAR and SLAM

Visual navigation is the exploitation of visual sensor data in order to navigate. One research method focuses on using visual navigation to calculate the geo-location of a target [152]. This method exploits visual odometry to enable a Micro Aerial Vehicle (MAV) to perform low cost navigation. This is limited to a reference area of catalogued images, however, it works in non-GNSS viable areas such as urban canyons and areas of large interference. Other methods are based on open service databases; using computer vision to identify objects observed by an Unmanned Air Vehicle (UAV), correlating with maps of the relevant areas, and subsequently estimating the UAV's location [116],[157]. It is possible to extend this concept to many drones, resulting in a network of navigation data [681]. The low-cost of visual navigation systems contribute to the attractiveness of the navigation technique, and this contribution will only increase as camera technology becomes cheaper and its form factor reduces.

LIDAR (Light Detection And Ranging) is a remote sensing method that utlises the same physical principals as radar, but with laser light, compared to radio waves[135]. LIDAR is used to generate a 3D map of the vicinity of the sensor, which can then be exploited as a means for robots and drones to navigate. Indeed, the LIDAR version of Dronevolt's Heliplane [135] is a recent example of LIDAR technology achieving integration with UAVs.

SLAM (Simultaneous Location And Mapping) is defined as the synchronous location awareness and recording of the environment in a map of a computer, device, robot, drone or other autonomous vehicle [324], [253]. It is the computational means of constructing or updating a map of an unknown environment while simultaneously keeping track of an agent's location within it. This technology was developed within the robotics industry and is now used by autonomous vehicles to concurrently map and navigate through unfamiliar environments. SLAM algorithms employ information from sensors (often LIDAR and/or visual imagery) to compute a best estimate of the device's location and a map of the environment around it. A recent example of the application of SLAM is its use in enabling the safe landing and recovery of drones [827].

Use of LIDAR, visual sensors and SLAM are highly relevant for drone and robot navigation. Such techniques can be supported by Inertial Navigation Systems (INS) and prove particularly useful in urban environments, indoor settings and areas where Global Navigation Satellite Systems (GNSS) are unavailable. Several commercial solutions are available[4].

The current trend appears to be a greater adoption of LIDAR over visual techniques. LIDAR is currently one of the most popular sensor systems for autonomous vehicles. With specific regard to UAVs, there are challenges in mounting LIDAR sensors on drones that will then have appropriate battery life. This is a symptom of most LIDAR units being too heavy for the payload of most drone batteries. That said, the previously mentioned Dronevolt Heliplane [112], [113]. is a recent breakthrough, however, the general trend is yet to catch up; LIDAR sensors are still not light enough to mount on most commercially available small UAS.

The future is likely to witness PNT systems that utilise a variety of sensors to provide the highest level of accuracy.

4.2.4 Ground-based Navigation: Enhanced Long Range Navigation (eLoran)

The current leading Hyperbolic navigation system is enhanced LORAN (eLoran) which is built on internationally standardised LORAN-C. eLoran improves on former versions of LORAN in that it utilises an added data channel to the radio signal to provide the requirements for high accuracy Position

[4]Dronevolt is a drone manufacturer, based in France, claims expertise on the development of new technologies based on UAVs, see use of LIDAR [112],[113]. Livox offers LIDAR devices for autonomous navigation, robotics, and UAV or automotive-based mapping rigs [120]. GeoSLAM - this company specialises in Geospatial mobile mapping using 3D SLAM technology [117].

Navigation Timing (PNT) applications. This includes real time differential corrections, station identity information and an absolute time based on the Coordinated Universal Time scale (UTC).

Similar to GNSS, the position is derived from a time of flight system. The master towers contain atomic clocks and send this accurate time to the slave towers in their respective chain. With advancements in antenna technology, the user is able to exploit an “all-in-view” approach, utilising every possibly chain system in view. The previous systems (e.g. LORAN-C) could only use one chain at a time to determine a user’s location.

The differential corrections are provided through monitor stations that analyse and measure propagation delays in the groundwaves, analysing them and relaying corrections to compensate.

The eLoran system is currently one of the most popular solutions as a back-up for Global Navigation Satellite Systems (GNSS), with countries such as the US, South Korea and India looking to budget and build a system in the near future [107]. South Korea has already signalled its intention to use eLoran for autonomous vehicles and drones [17, 150]. The main advantage of eLoran is its powerful signal, which is very resilient to jamming and can be received indoors, underground and underwater accurately and reliably. Typical performance: position to within 5m [258], timing to within 30 nanoseconds [779], weight (receiver): 0.7kg (UN-152A), power (receiver): 14W (UN-152A). Key players in the field include:

- ExCom - Helped champion the consideration and support of a bill in the US to budget and put forward a plan to build an eLoran system [18]
- Babcock International - Owners and operators of the eLoran system at Anthorn Radio Station and developing it as a navigational aid for mariners. Transmitting at 100kHz
- United States Coast Guard - Responsible for evaluating and possibly constructing the new US eLoran service
- UrsaNav - Supplier and consultant of eLoran design technology
- Chronos - European manufacturer of eLoran receivers.

There is increasing interest in eLoran, particularly as a backup to GNSS. This interest is likely to drive investment in the technology and as a result, one can expect further sites to be built to increase the current coverage. In early 2018 there were signs of support for eLoran from the UK Government [19].

4.2.5 Infrastructure Independent Navigation: Automated Celestial Navigation

Current state-of-the art celestial navigation systems have developed as a result of automatic systems that were mainly designed for space and high altitude applications.

The popular approach for many of these automated celestial navigation (ACN) systems is to use automatic star trackers that can observe multiple stars simultaneously. Such systems combine a telescopic device and a photo sensor, such as a Charge-Coupled-Device (CCD), to capture the light from a star field and convert it into a digitised signal. The aim is to recognise the pattern of stars captured by the CCD. To this end, pattern recognition algorithms and database matching techniques are used to identify the star field and thereby determine a celestial frame of reference.

The evolution of such technology, coupled with recent advances in sensor and star tracker technology, is encouraging the development of smaller, lightweight, inexpensive, reliable celestial systems that can be coupled to existing INS for aircraft and ships.

The trend towards smaller, lightweight celestial navigation systems is making ACN systems more viable for the larger UAS. Characteristics include:

- ACN systems are highly secure as they are generally self-contained units. They are highly resilient (particularly to jamming, spoofing and radio frequency interference).
- Arc-second precision enabling $<$ 30 metres positional accuracy [386] is potentially possible.

- ACN systems are dependent on suitable weather conditions, although some state-of-the-art systems can operate in daylight using the Sun and other celestial bodies.

One of the key players in this field is Lockheed Martin. A typical example of a state-of-the-art ACN system is their AST-201, which has been developed for satellites. This system has an 8.8° field of view and observes multiple stars in the visual band down to magnitude 7 with 0.7 to 2 arc-second precision (the human eye can only manage to see magnitude 6 on a very dark night) [19]. Another company developing ACN solutions is Trex Enterprises Corporation. They have been involved in the development of day/night ACN for US Navy Aircraft/Ships using K-band or H-band infrared light from multiple stars.

The accessibility of improved technology, such as low-cost, but accurate, CCD sensors coupled with cheaper computing resources, is now making it easier to develop low-priced ACN systems. It is worth noting that the former issue of discontinuous operation, due to inclement weather conditions, can now largely be mitigated by Inertial Navigation Systems. All of these factors combined with the superior security and resilience of ACN systems (compared to GNSS) are likely to make ACN systems a more attractive alternative in the future.

4.2.6 Signals of Opportunity & All Source Positioning & Navigation

The term 'Signals of Opportunity' (SoOP) refers to PNT systems that use signals that are not transmitted for navigational purposes, but may be exploited for such. ASPN (All Source Positioning and Navigation) is a specific instantiation of SoOP that is currently receiving considerable support. ASPN researchers are developing multi-sensor systems that pick up 'signals of opportunity' such as television, radio and even lightning, to assist in location tracking. ASPN is being pursued by DARPA in its Adaptable Navigation Systems (ANS) program in order to provide GPS-quality PNT to military users regardless of the operational environment. SoOP, and ASPN in particular, could prove useful to some UAS in the longer term, given that they promise high accuracy, low cost, robust, and seamless navigation solutions.

SoOP and ASPN are still very much a research topic. Most work is being conducted by academia, the defence industry and military organisations. Here are a few examples: DARPA's Adaptable Navigation Systems (ANS) project [110], NAVSOP (BAE Systems has developed an advanced positioning system that exploits existing transmissions such as Wi-Fi, TV, radio and mobile phone signals, to calculate the user's location to within a few metres [136]) and a Massachusetts Institute of Technology and Georgia Tech collaboration on an ASPN project that seeks to enable low cost, robust, and seamless navigation solutions for users on any operational platform and in any environment [132]. In general, ASPN development is expected to be heavily dependent on the results of US Defence research.

Chapter 5

Communications

When discussing communications for unmanned air systems, it is wireless digital communication that is of interest and there are several different applications which need to be considered (Salehi and Proakis [670]).

In the military domain, White [805] identifies a problem that has long existed for manned aircraft – the need to interact with multiple independent systems in order to operate effectively. As a hint of the complexity of modern aircraft communications systems, Hargreaves reports that there are up to 20 antennas on modern civil airliners [20], which serve a variety of purposes including, for example, direction finding, positioning, collision avoidance, distance measuring, telecoms etc.

When considering unmanned aircraft systems, the number of individual communications systems is unlikely to reduce, but there is an interesting systems architecture question about whether the communication needs to be with the platform, or the operator.

5.1 Control & Telemetry

Control and telemetry provides the capability necessary to remotely operate a UAS. In the space sector, this function is formalised as tracking, telemetry and control (TT&C) when applied to launch vehicles and satellites [395]. When a UAS is being remotely piloted, TT&C provides the data necessary for a pilot to maintain situational awareness and control the platform. The General Atomics Predator, for example, uses RF communications at C-band for line-of-sight communications and Ku-band satellite links for over-the-horizon operations [21]. TT&C channels are usually encrypted [395].

The ICAO has identified additional communication channels that could be considered as part of TT&C when an unmanned aircraft system is operating in civil airspace shared with manned aircraft [22]. These include air traffic management (ATM) VHF voice [23] and UHF transponder data links [24]. Note that the ATM voice link does not need to be available at the unmanned aircraft, but the pilot must be able to communicate with the airspace controllers where the aircraft is actually operating [22]. Nolan provides a comprehensive study of the US air traffic system [597], which highlights the procedural as well a technical complexities involved.

NATO has developed standard interfaces for controlling UAS, with the aim of promoting interoperability across platforms and services [25] [26] (Lockheed provide a good plain-language summary in [27]). The US is developing this further by specifying a UAS control segment architecture [209] (a shorter summary paper [388] is available) which will enable an open architecture for military unmanned aircraft systems.

One trend that has been seen in the space sector, and which is relevant to unmanned aircraft systems, is the move to very large constellations [634] (or swarms of unmanned aircraft [459]). For these systems to be operationally feasible, a large amount of automation is necessary [415]. In the case of swarms, this requires the individual UAS to have a degree of reasoning and decision-making capability ('autonomy') [28]; it is not tractable to control all individual UAS in a swarm the same way that large UAS are flown today [21]. Efficient execution of swarming missions will also require inter-UAS communications to coordinate activity and optimise resources. Campion et al. have looked at different architectures for command and control of swarms [259] and Zeng et al [846] discuss a particular swarm communication approach using cellular infrastructure.

The missions addressed by swarms will become more sophisticated, with diverse platforms, potentially operating in different environments (Ball has reported recent DARPA trials of exactly this scenario [29]) which in turn will increase the amount of autonomy that must be delegated to the swarm, and the individual platforms [775].

The use of swarms with a large degree of autonomy raises new communications issues; how does the user communicate with the swarm as an entity (rather than with individual platforms) when updating mission requirements, for example? Some of these issues are raised by Gupta [397], but there are still many open questions.

5.2 Mission Data

UAS are used for a wide array of applications, from shooting wedding videos through making geophysical surveys, to mineral exploration [758], or tracking multiple moving ground targets of interest [202]. In all these cases, information is collected and needs to be provided to a user in a timely manner.

Data rates from UAS sensor systems can vary widely, depending on sensor size, frame rate, data encoding approach etc. As a hint of the data rates required, Summerson reports that Netflix requires a little under 6 Mbps when streaming 1080p resolution video [736]. This should probably be taken as lower bound, as sensor resolutions are set to increase over time; Nedomansky's survey of video cameras commercially available in 2014 showed data rate requirements up to 3.5Gbps [589].

The technology required to provide the mission data communication channels is dependent on the application, and will probably be shared with the command and control channel [21]: the ability to communicate over the required range is the same, even when the data rates may be quite different. The size of the platform will also have an impact as the power constraints of smaller UAS will restrict data rates or effective range.

UAS swarms have been mentioned in the context of command and control, but inter-UAS sharing of sensor data will become more widespread [175], either to reduce mission data rates by transmitting composite results rather than raw data; provide resilience against congested RF environments [729] by sharing sensor data; provide range extension by data relays [438]; or support swarm autonomy by sharing situational awareness between platforms [353].

5.3 Radio Frequency

Radio frequency (RF) data communication is a well-established engineering discipline (see Gustrau [399]), which continues to develop rapidly, primarily from the commercial drive for very high bandwidth mobile data systems [473]. RF systems are always a trade-off between range, data rate and power consumption: see Sharma et al for one example of a low power wireless data network design for drones [704].

The choice of RF communications technology for Line-of-Sight (LOS) operations will be determined by various constraints such as bandwidth, directionality and available antenna size [670]. For example, high resolution video streaming (say 3 Gbps) will not be possible using VHF RF systems with a centre frequency of 150 MHz. Beyond-Line-of-Sight (BLOS) operations will usually require satellite communications capabilities [617]. BLOS RF operations using HF are possible with voice bandwidths and very low data rates, but not for the data rates demanded by most sensor payloads.

5.4 Software Defined Radio (SDR)

The term ‘software defined radio’ (SDR) refers to the technology where the received RF signal is digitised before being demodulated. What is meant by SDR is a little imprecise, but the American Radio Relay League (ARRL) summary is a good working definition: *“Software Defined Radio attempts to place much or most of the complex signal handling involved in communications receivers and transmitters into the digital [domain].”* [189]. While the ideal is to covert the signal at the antenna directly to digital, in practice some RF signal conditioning is still required. Tuttlebee describes the technologies necessary to implement SDR [764] and Bard and Kovarik discuss the system-level considerations of SDR when defining a Joint Tactical Radio System architecture that is implementation agnostic [205].

SDR offers the promise of significantly reducing the amount of RF hardware required in any communications system, digitising the antenna signal and reprogramming the SDR to operate on the desired frequencies with the desired waveforms. This is one reason SDR is popular with radio amateurs [234]. White, as mentioned earlier, recognised the potential for SDR to reduce hardware complexity for military aircraft in 1999 [805], while early satellite communications terminals for civil airliners using SDR [198] (although still with fairly complex RF front-ends) were in operational service in 1994 [662].

The civil aircraft industry continues to be an incubator for new RF technologies, due to the demand for data services, taken for granted on the ground, being available in the air [789]. Much of this development is transferrable to the problems of UAS communications systems.

While the ideal of SDR is to digitise the RF signal at the antenna, this is not practical today, so interim approaches are used which have a few RF modules to create a digital intermediate frequency (IF) signal as soon as practicable, and then distributing the IF across the platform. One example of this approach is the FAST architecture [217]. The practical advantages include reducing the number of different radios on a platform, and reducing weight by removing the need for heavy, shielded RF cabling from the antennas to the radios. Digital IF signals are distributed using the Integrated Modular Avionics (IMA) systems [176] (for a more future-looing view of IMA, see Gaska et al [358]).

The pace of change in communications technologies means that SDR is necessary to allow complex platforms to keep up with new developments, without the need to develop and add new radio systems. There are major changes on the horizon for satellite communications, for example, with Iridium [443], SpaceX [726] and OneWeb [603] launching large constellations into low earth orbits. Low earth orbit satellite communications places new burdens on receiving systems [285] such as rapid satellite handoff and high Doppler components [177].

5.5 Data Networks

Mobile data networks are widespread [565] and Gupta has started to address the issues around data networking in a swarm of UAS [397], but this is still an active research area. There are several standard RF data networking protocols [472] that could be used or adapted for this purpose (eg Bluetooth [235] or IEEE 802.11 WLAN [30] standards). It seems likely that swarms, especially swarms with a high level of autonomy, will require very dynamic networking capability, possibly based on peer-to-peer [569] or one of the many Mesh networking protocols [169].

When considering the issues around UAS swarms, it will be worth watching the field of autonomous vehicles, which is already trying to address similar problems. One of the key themes already emerging from connected vehicle developments is that 5G communications technologies will be crucial [31] [280].

BACKGROUND NOTES

5G

5G is the latest iteration of mobile data networking technology to become widely available [32]. It is different from previous mobile data networks [33] in that it is technology agnostic, providing a set of protocols that will allow different networks to interoperate seamlessly. Users will generally be unaware of which networks are being used. For example, video streaming to a car might cross a satellite data network, an LTE mobile data network and finally a dynamic mesh network containing the destination vehicle.

5G has strong support for machine-to-machine communications as one of its design principle [186] [531], which makes it an interesting candidate communications technology for autonomous platforms.

5.6 Optical Technologies

Infrared (IrDA) is used as a data network technology, usually at very short ranges [34] for 'personal area networks' connecting computer accessories together. Line of sight is not always required, as indoor operation can provide reflective surfaces to distribute the IR.

Free-space optical (FSO) communications [178] is a LOS technology, which uses modulated lasers to provide potentially very large data rates (similar to optical fibre). For space-based applications (inter-satellite communications for example) FSO communication have been used successfully [465] on several missions [724].

FSO systems have been marketed (Blackbox [35]) as medium data rate (≈16 Mbps) short range (≈1,500 m) network elements, intended to provide business LAN connectivity between buildings. FSO systems need accurate pointing; have heavy optical elements and are susceptible to local environmental conditions. If mounted on a mobile platform, accurate tracking between the transmitter and receiver is required [466].

5.7 Acoustic Communications

Acoustic communication is usually associated with underwater systems where other technologies are not effective and water provides a good transmission medium. Acoustic data communication in free space has been demonstrated in the laboratory [571], with low effective data rates. Ultrasonic acoustic systems have been demonstrated for indoor positioning (see Khyam for one [474]), but they only operate over short range in benign acoustic environments.

5.8 Metamaterials

Metamaterial is the term used to describe materials whose characteristics are defined by their exacting structure rather than their chemical composition; metamaterials fall broadly into three categories electromagnetic, acoustic and seismic [752]. The earliest metamaterials were electromagnetic and as the bulk of research is still in this field [564]. Much of the practical application of metamaterials has been in wideband communications [669] [181], but the underlying concepts of wide bandwidth, omni-directionality and planar steerable arrays are equally applicable to radar and ESM.

A potential major application of metamaterials is the manufacture of conformal antennas. The prospect of using metamaterials for conformal antennas is not new [534] (it was one of the first applications to be seriously pursued), but now the technology has reached the point where it can be seriously considered for low and medium cost radar systems [246]. The advantage of conformal antennas is that they can become structure elements in small manned and unmanned aerial vehicles (wing and body panels, depending on required pointing direction).

Recent work with metamaterial antennas suggests that they can be fabricated to replace reflector antennas at reasonably high power in some situations, which means they may be viable long range directional transmitters rather than just passive receivers in future [389].

The development of conformal antennas for UAVs has been sponsored by the US DOD for many years now [680], and an interesting summary of the particular problems and possible approaches to UAV conformal antennas can be found in work published by the Naval Postgraduate School [449]. A particularly good overview of technologies for conformal ultra-wideband phased array antenna for space-based applications is available from NASA [599].

Chapter 6

Sensor Systems

Unmanned aircraft systems require sensors in order to sense and understand their environment, to sense and be aware of their own states, to sense external and internal threats (security), to sense how well they are delivering against goals that they are set, to sense mission relevant data for human decision makers. Consequently, today sensors on unmanned aicarft are generally discrete, compartmentalised elements measuring and providing data to be interpreted by processors on-board the UAS or is often more likely, communicated off-board to humans managing the system. Future sensors are more likely to be distributed, incorporated directly into surface structures, including processing such that sensors are providing information in context as opposed to data.

In this chapter we discuss sensing via sensor systems, rather than sensors per se, with an emphasis on the *capability* that the sensor system enables. For example, while Hall effect sensors are in widespread use and can be fabricated in many different ways [651], our focus here is the ability to determine variation in the local magnetic field. A sensor 'is a device that converts a physical phenomenon into an electrical signal' [808] and as such requires additional processing of that electrical signal in order to extract usable information. Where the underlying sensor technology is important to the functioning of the sensor system, that will be highlighted (for example when discussing the change in capability that may be enabled by new materials such as graphene [36]).

Although sensor systems are discussed in isolation, in practice it is now normal that the output from different sensors are combined in order to supply users with information which no sensor alone can provide; this is called either data fusion, or sensor fusion [330].

6.1 Radar Systems

Both radar systems and UAS platforms are evolving rapidly in defence and civil markets, and both are wide areas of technology. Radar systems in particular cover a vast array of different sensing techniques and applications. This review outlines the trends and state-of-the-art technologies in radar systems as they are applied to UAS, discussion the constraints, capabilities and applications of radar systems on unmanned platforms.

A radar is an electronic device for the detection and location of objects – see [722] for a good introduction to the basic concepts and [649] for an up-to-date account of how information is extracted from the sensors. For more detail on how contemporary radar systems function, the reader is referred to the works of Galati [349] and Meikle [561].

Radar systems (like many other sensor systems) have capabilities that may be used by the platform in order to operate effectively – many current UAS have short-range radar to support automatic landing or collision avoidance [582, 667]. However, the majority of radar systems will be UAS payloads, which provide the capability and justification for using the UAS in the first place.

For payloads, the ability to transmit information to either a user or another platform which can use it in a timely manner is also crucial: data fusion is considered a key capability of the F-35 Lightning, for example [37], while SAR observations using relatively cheap technology, use accurate positioning information to build high resolution images, as demonstrated by the space radar start-up ICEYE [38, 39]. Given this, the separation of sensor, communications and PNT functions is somewhat artificial as it is the combination that provides the desired payload capability.

BACKGROUND NOTES

RADAR

Radar systems operate on the basic principle of detecting reflections from a 'target' object which has been 'illuminated' with radio frequency energy. In traditional systems, the radar transmits a series of RF pulses, and detects the reflections from object that the pulses hit. Processing of the reflections (or returns) over time can determine the distance and speed of the target. Additional processing can determine direction, material composition and even shape information. Although initially an important military sensing technology, radar is increasingly finding applications in security and civilian markets.

Radar systems operate at a wide range of frequencies (see below) and powers depending on the particular application, from proximity detection for vehicles (parking radar) to air traffic control to deep space object tracking. Long range systems tend to need low frequencies (hence big antenna) and high power, and are consequently physically large, whereas short range systems tend to be smaller with high frequency and low power.

Conventionally radar systems transmit pulses of RF energy in order to detect and locate targets in the environment. However, modern radar systems are able to do far more, and are more properly described as multi-function RF systems (MRFS) – the term 'radar' is still used as a convenient shorthand. These modern systems may have the ability to operate actively, passively, multi-statically, cognitively and adaptively.

Radar systems are used in a wide variety of applications which make use of the characteristic properties of the sensor. Firstly, radar systems can operate day or night since they do not rely on the Sun's illumination. In most cases the radar will transmit its own illumination beam. Radars can be 'all weather', particularly at lower frequencies. As frequency increases beyond 10GHz, rain and moisture attenuation increases. Radars can provide wide area coverage, for both detection and imaging. Radars directly measure range (unlike most optical systems) and therefore can provide information for target locations and for tracking. The radar signal itself can provide unique information about a scene. Radar signals can be polarized and then carry information which can reveal details of crop orientation or soil moisture content. Synthetic Aperture Radar images carry phase information that can be used for highly sensitive change detection, or for three dimensional height mapping of terrain.

Frequency bands. Radars operate across a range of frequency bands (Table 6.1). The radar operating band determines many characteristics of the radar system and its applications. Lower frequency radar signals are more penetrative – can pass through foliage, snow and even buildings. But low frequency components are large and high bandwidth signals (necessary for resolution) are not possible. Higher frequency signals have compact components and great imaging properties, but are highly attenuated by the atmosphere and so are only able to operate at limited ranges. For airborne applications the physical size of components operating below UHF becomes difficult to incorporate into an airframe. The vast majority of airborne radar systems operate in X-band and Ku-band, where the compromise between size of physical components, microwave circuits, available bandwidths and attenuation is most beneficial. Systems are available outside of these bands, but they will trade out performance in one aspect in order to enhance something else.

Atmospheric Attenuation. The atmosphere is not transparent to microwave energy at all frequencies. Atmospheric attenuation broadly increases with microwave frequency. This has the effect of limiting the frequency bands that can be used for different applications. Long range radar systems tend to be designed around X-band in order to maximise antenna gain and minimise atmospheric attenuation. Smaller platforms compromise attenuation by going for higher frequency Ku-band which provides smaller components and higher gain. These are not suitable for long range applications. Very small UAVs can go to even higher frequencies in order to achieve imaging performance in tightly constrained component sizes. However this necessarily limits range performance.

Antenna. The interface between the radar system and the outside world is the antenna, and this determines and constrains important characteristic of the radar such as the beamwidth. The beamwidth (in radians) is approximately given by the wavelength divided by the antenna width. A tightly focussed radar beam therefore requires an antenna which is many wavelengths across. A 3° beamwidth will require an antenna 20 wavelengths across. At X-band (0.03m wavelength) this antenna would be 0.6m across, at 1GHz 6m, and at 100MHz a 60m antenna would be required. A more focussed beam will put more of the radar energy where it is required, and hence enable the radar to see further. There is some trade-space however, in that the tighter the beam the smaller the area illuminated. For some applications (maritime surveillance for instance) a very narrow beam is not desired. Antenna technology has moved quickly from mechanically scanned devices (physically moving the antenna face via a gimbal mechanism) to phased arrays. A phased array contains a large number of small elements (transmit/receive modules - TRMs) which can be phased to change the characteristics of the beam, including the pointing direction. Semi-conductor development and new materials such as Gallium Arsenide and Gallium Nitride have enabled rapid evolution in the frequency and power available from solid-state microwave devices. Microwave devices are now smaller, lighter and provide higher sensitivity [156]. This trend is continuing. The size of antenna required in order to achieve the necessary level of performance will be one factor in determining the size of UAV required.

Radar technology continues to develop incrementally, but there are some major innovations related to new materials or novel approaches to signal processing: the increase in computer processing power particularly allows for performance improvements even with existing microwave technologies.

One particular trend that seems likely to continue is the move to III-V semiconductor materials which have several advantages over traditional high power RF materials. Silicon-germanium (SiGe) alloys and gallium nitride (GaN) are emerging as serious technologies to displace gallium arsenide (GaAs) in high-power, high-frequency RF applications such as solid-state AESA radars (Tee and Quinlan [753]). A key component of these radars is the large number of active high-power microwave elements required to provide the beam-steering, so technologies that support element size reductions while maintaining RF power handling, high-frequency operation and which can be readily fabricated are prized [230].

SiGe is potentially cheap to manufacture and integrate with existing semiconductor technologies and appears to offer useable performance at X-band frequencies. SiGe could become an important technology, particularly for high-volume applications at short-range and low power (for example collision avoidance radar for autonomous vehicles which could be adapted for UAS [582, 667]).

Table 6.1: Radio frequency band designations

Designation	Frequency band
High Frequency (HF)	3 - 30 MHz
Very High Frequency (VHF)	30 - 300MHz
Ultra High Frequency (UHF)	300MHz - 1GHz
L	1 - 2GHz
S	2 - 4GHz
C	4 - 8GHz
X	8 - 12GHz
Ku	12 - 18GHz
Ka	27 - 40GHz
V	40 - 75GHz
W	75 - 110GHz
mm	100 - 300GHz

6.1.1 Synthetic Aperture Radar

Synthetic Aperture Radar (SAR) is the most common active sensor used for Earth observation (EO). Transmitted electromagnetic pulses are reflected or scattered by features on Earth's surface. The intensity of the return pulse and the time it takes to arrive back at the antenna are used to generate SAR imagery. The key feature of SAR is that a single antenna with a known motion in space and time provides measurements that are processed to provide the higher resolution of a significantly larger antenna [339].

The main advantage of radar imaging for Earth observation is that it is insensitive to the day / night cycle and most of the time to the meteorological conditions (shorter wavelength signals such as X band can be degraded by heavy intense rain cells). The selected frequency band impacts what is observed from the scene by influencing the level at which the incident radiation will backscatter. SAR can be used for detecting ships and oil spills, or monitoring sea ice, forests, soil moisture, and critical infrastructure etc.

SAR interferometry makes high accuracy measurements of surface geophysical characteristics. The phase of two or more complex radar images, acquired from slightly different positions or at different times, is compared. Phase information is accurate to a small fraction of the radar wavelength, so it is possible to detect and measure path length differences with millimetric precision. Comparison of the coherence between several data acquisitions can be used for change detection such as vehicle tracks or foot tracks in fields [40].

SAR for Earth observation is now readily available as a space-based sensor system , but the technology is suitable for use on piloted aircraft, as demonstrated by JPL [41], or operational UAV platforms such as ScanEagle [42].

6.1.2 Radar Altimetry

Radar altimeters provide precise measurements of height above a surface by measuring the time interval between the transmission and reception of very short electromagnetic pulses [810]. Radar altimetry could be useful when generating precise terrain mapping, but is more likely to find application when used as part of the platform flight management system, especially when flying close to the ground.

6.1.3 Microwave Radiometry

For space-based Earth observation applications, microwave radiometry (MWR) is used to measure the integrated atmospheric water vapour column and cloud liquid water content to obtain correction terms for radar altimetry. MWR also measures surface emissivity, soil moisture and ice characterisation. Small instruments are available which can be mounted on aircraft to be used for specific tasks such as measuring oil spill quantities (for example, the Optimare MWR-P).

6.1.4 Radar Scatterometry

Radar scatterometers are specifically designed to measure scattering of incident RF energy from a diffusing media [528]. Space-based scatterometers provide important information for Numerical Weather Prediction (NWP), oceanography and climate studies and can also provide information such as sea ice cover [43]. Ground-based systems can be used to determine wind speeds (for example, at airfields).

BAE Systems have demonstrated a laser scatterometer which can determine the platform airspeed (replacing pitot tube systems) [44], but there does not appear to be any investigations into using radar for this purpose.

6.1.5 Passive Radar Systems

Passive radar is a radar technique that uses 'signals of opportunity' (such as broadcast television signals) which are not under the control of the monitoring agent. The radar processing compares the signals received at a known location and one or more other locations to infer the existence of, and information about, a target.

Passive radar is not a new technique but the availability of massive signal processing capabilities means that it is becoming more widely adopted, and is a trend that we would expect to continue. A significant advantage of passive radar is that it does not require scanning or rotating transmitters and receivers, and the receiving elements can monitor continuous signals, not just pulses [45], [391]. An additional advantage is that signals at frequencies not usually associated with radar systems can be used with very good results against targets optimised against microwave systems.

Traditionally passive radar systems have been terrestrial, but the trends in processing power, navigation sensing and signal processing algorithms, means that having airborne receivers with varying geometry is feasible.

6.1.6 Bistatic Radar / Holographic Radar

Bistatic radar uses transmitters and receivers which are not co-located [281]. This may be considered a controlled form of passive radar (at least at the receiver) with the advantage that the radar signals can be crafted to optimise collection of a particular data type. As available signal processing power increases it will be possible to extract ever more useful information from such systems.

A form of bistatic radar that is receiving attention at the moment is the so-called holographic radar [46] from Aveillant [47]. This radar system potentially provides a continuous 'staring' surveillance mode with the ability to detect and track small targets [46] and identify and remove complex environmental noise (e.g. wind farms [48]).

This type of radar system is usually ground-based, but as positioning technologies improve, it seems possible that very wide aperture staring radars could be built using flying platforms as either transmitters or receivers. The processing would be a form of complicated SAR to account for the continually variable relative positions of transmit and receive elements, and the use of multiple sources and receivers could be used to build resilience into such a surveillance sensor.

6.1.7 Quantum Radar

Quantum radar [650] is one proposed application of the developing quantum technologies. As with other quantum technologies, practical deployment is many years in the future although experimental results by Barzanjeh et al [208] suggest that there could be a real effect that might be exploited in practical systems (a summary of the paper can be found in the MIT Technology Review [49]). For example, Durak et al have recently published results of a proof of principle object detection and identification using quantum radar techniques [322]. It has been speculated that quantum radar may be effective against current airborne stealth technologies [777], but this has yet to be verified experimentally.

BACKGROUND NOTES

QUANTUM TECHNOLOGIES

Quantum technology refers to exploitation of the physics of the very small scale (atomic-level), which requires the mathematics of probability to describe the properties of matter and energy rather than the absolute quantities we are used to measuring in the macroscopic world. The quantum physics principles being exploited are either superposition, which is the simultaneous existence of a particle in all possible states (position, momentum etc.) until a measurement is made, and entanglement, in which multiple particles share a probability distribution so that a measurement of one determines the actual state of the others.

Superposition is exploited in quantum computers and quantum sensors such as gravimeters or inertial navigation sensors. Entanglement is the underlying principle exploited in quantum imaging, quantum radar and quantum key communications, where entangled particles are separated and the interaction of a distant particle has an observable effect on the local article.

Quantum technology is extremely susceptible to interaction with the environment, and much of the development effort related to quantum technologies is the engineering required to prevent unintended 'measurements' destroying the desired quantum states prematurely.

6.1.8 LIDAR

LIDAR is an active sensor technology which works in a manner similar to radar except that it uses a laser as the transmitted source and is able to accurately measure distance due to the short wavelength of visible light [50]. When used to scan in two dimensions, LIDAR is able to generate accurate three dimensional models of the scene being viewed.

LIDAR is now commonly used on autonomous vehicles as a navigation aid [51] where it is used to build a model of the local environment, including obstacles, with accurate depth measurements that would otherwise be difficult to determine from visual imagery alone. There is some discussion about whether LIDAR technology is mature enough to be used as a safety-critical element for self-driving vehicles which interact with humans (see for example Simonite [52]) although the technology is developing rapidly [53].

It can be seen that LIDAR is a technology that could be part of the unmanned platform navigation and control system (particularly ground vehicles), as well as one of the mission payloads carried by those vehicles.

6.1.9 Platform Considerations: Size, Weight & Power

The size, weight and power of the UAV will determine the radar system that can be installed. There is a very wide variety of UAV platforms available and in development, from tiny tactical systems weighing only 100g up to large aircraft. Typical small radar systems such as the Leonardo PicoSAR [108] have a mass of 10kg. Experimental systems operating in the V-band have been demonstrated on 6kg class quadcopters, but these will have effective ranges of only a few tens of metres [131].

The QinetiQ RIBI experimental system weighs less than 6kg and can be carried on a 20kg class quadcopter, operating in the S band using a software definable radio [426]. Mid range radar systems with ranges of tens of kilometres will be 50kg to 100kg, and large high power systems for longer ranges (one hundred kilometres plus) will be even heavier. These obviously require large and very large UAVs.

Smaller UAVs also have less power available, and much shorter endurance. The QinetiQ RIBI system [426] has less than ten minutes of useful flight time before the battery is exhausted. This is ideal for imaging areas which are close by, but would not be practical in many applications where transit to the area of interest is necessary or where persistent surveillance is a requirement. Larger air platforms using conventional fuels can have much longer endurance, though the power requirements of the radar may take up a significant chunk of the energy available to the aircraft.

6.1.10 Radar & Autonomy

Depending upon the application the UAS will require different levels of autonomy. The collection of radar images close by could be entirely achieved by an operator-in-the-loop, with very little autonomy. Conversely a penetrating UAV system designed to operate far into hostile airspace may need to be entirely autonomous. Between these two extremes are platforms such as the UK MOD Watchkeeper [54] (Thales), and the USN Fire Scout [55] (Northrop Grumman), which are flown by an operator, and the autonomous systems are there to make the job easier.

Autonomy can help with the tasking of the radar too. A fully autonomous system will have to search for and find its own targets, cross-cueing and fusing information as required. This will require significant onboard processing for image formation (in the case of an imaging radar), target detection, tracking and recognition.

A semi-autonomous system will be able to undertake tasks at the command of an operator, and may process onboard or potentially stream the data back for processing in a ground station. For short duration systems the data may just be stored onboard for later retrieval and processing. The large amounts of data that can be generated by radar systems will place stresses on communications data links, especially as the distance of remote operation increases. These data links are vulnerable to deliberate attack (via jamming) and accidental interference through congested RF spectrum as well as obscuration. Robust data links are essential for remote operation of UAS radar systems.

6.1.11 Persistent Radar Surveillance

One significant advantage of UAV platforms over manned aircraft is the potential for very long endurance on tasks that would otherwise be extremely taxing for the crew. There are two particular classes that are of military interest High Altitude Long Endurance (HALE) and Medium Altitude Long Endurance (MALE). An example of a HALE platform is the Northrop Grumman RQ-4 Global Hawk, a UAV with a 40m wingspan and an endurance of more than 30 hours [56]. An example of a MALE is the MQ-9 Reaper with a 20m wingspan and 24 hour endurance [57]. Both these platforms can be equipped with highly capable radar systems – in the case of Global Hawk this has a mass of nearly 1000kg, and in the case of the Reaper over 50kg.

The Zephyr UAV [58] can remain inflight potentially indefinitely due to the solar recharge of its batteries. However, use of RF systems will be seriously constrained by the requirements both for lower power and low mass.

6.1.12 Perching Platforms

One way of achieving longer endurance for persistent surveillance is perching. This has been demonstrated by a number of academic institutions. Essentially the UAV lands (perches) in a location with good view of the area of interest, such as a rooftop. This then enables the system to monitor the area of interest without having to remain airborne. For radar systems the application of perching is quite limited. Radar imaging techniques such as SAR require the platform to be moving. However, scanning an area and alerting to moving objects via their Doppler signatures could achievable and may be useful in some surveillance applications.

6.1.13 Mission Fit Sensor Payloads

There is a trend currently for medium and large UAV platforms to have role-fit sensors. Essentially these expensive systems have to be reconfigurable to undertake a number of different roles. One way of achieving this is to have sensor bays or pods that can carry a variety of sensor packages. Sometimes this might be a radar sensor, sometimes a camera, sometimes a LIDAR, sometimes ESM. This can make for a highly versatile UAS, but does provide challenges for the sensor manufacturers. Typically the radar system will need to be entirely self-contained and fit within the confines of the bay or pod. The I-MASTER radar (installed on Thales's Watchkeeper platform [59]) is a good example of such a system. Close integration with the rest of the aircraft platform is not possible since compromises will be required in order to meet the differing requirements of the disparate sensors. This may require that the radar payload carry its own high grade INS/IMU systems, for instance, to enable SAR, or its own atomic clocks to enable coherence between platforms.

6.1.14 Applications of Radar Systems

Sense & Avoid

Radar systems on larger UAVs can provide a 'sense and avoid' function ensuring that they are safe to operate in airspace that may contain other users. These systems can be safety critical and therefore have to be highly reliable, but successful systems will enable the UAVs to operate effectively in shared airspace. MIT Lincoln Labs have been developing the Airborne Sense and Avoid (ABSAA) Radar Panel [60], a lightweight radar that can perform quick and repeatable scanning of the search volume meeting the exacting timeline and reliability demanded of search and avoid. The ABSAA supports both the detection of other aircraft and weather sensing. A Ku-band system, this provides good all weather performance in a fairly compact package and is principally designed to meet the Federal Aviation Authority requirements for aircraft to be able to sense and avoid other air traffic. If approved this will remove one of the serious limitations to the use of UAS in US airspace.

Surveillance

The majority of radar applications for UAS fall within the broad category of surveillance. Radar provides advantages of all weather, day/night operation and potential for wide area coverage. There are surveillance applications of UAS radars across both military and civil space. For military applications UAVs may offer surveillance opportunities where the mission would be too dangerous for a manned aircraft, or where close range and time criticality mean that a small UAV is much more practical. In civil applications UAVs may offer radar data that it would be too expensive to collect with a manned platform. Surveillance radars will typically offer a variety of modes in a single system making use of the same basic radar hardware and reconfiguring the waveforms, scan patterns and processing. SAR and GMTI are commonly offered in a single system, and maritime and ESM modes are also easily integrated. The General Atomics Lynx Multi-mode Radar [61], is a good example of a multi-mode surveillance radar designed for medium scale UAV platforms.

Change Detection

Change detection is a specific application of synthetic aperture radar. This requires that two images of the same area are collected from the same geometry but at different times. Comparison of the two images allows determination of changes within the scene over the intervening period. These changes can be macroscopic movement of objects detected through changes in pixel brightness (Amplitude Change Detection), or more subtle changes in texture detected through changes in phase (Coherent Change Detection). Comparison of the two images can be done in a ground-station by an operator, in which case the only demands on the UAV are to fly the same aperture twice to collect the images. Alternatively an autonomous UAS would need to carry previously collected images in order to undertake onboard change detection. The Thales Bright Spark system has published some particularly impressive results [159]. The General Atomic Lynx radar system offers change detection as a standard mode [61].

Ground Moving Target Indication (GMTI)

GMTI is the equivalent of scanning a radar speed gun over an area of interest. As the radar beam is scanned back and forth, moving objects are detected by virtue of their Doppler shifted reflections, and their range, bearing and velocity measured. These are then plotted as dots in real time, in range and azimuth from the platform. The I-MASTER radar on the Watchkeeper UAV is an example of a GMTI radar [59]. GMTI is a useful tool for building up 'pattern of life' information, looking at a large area to determine traffic flow, sources, sinks and pinch points. The real time information is also very useful for tactical applications. For UAVs a data link is necessary for operators to make use of the data and the data is collected continually. In low traffic environments (where only a small number of moving targets are in the beam) individual targets may be tracked, but this is quickly overwhelmed when traffic increases as placement inaccuracies make target association impossible.

UAS may use GMTI as a cross-cueing aid, allowing camera systems to be quickly slewed to image moving vehicles in an area of interest, where long persistent will support security applications like border monitoring [62].

Foliage Penetration

The use of lower frequency radar signals allows Foliage Penetration (FOPEN). Radar signals at these frequencies do not scatter from the tree canopy and therefore are able to look beneath the foliage at the ground and possible targets below. Typically operating at L-band and below these systems carry large boom antennas in order to form a focussed beam and typically operate at short range due to the low gain. A FOPEN system such as FORESTER [63] can form SAR imagery or collect GMTI data of areas under tree canopy with both civil and military applications. This system operates at UHF and is able to provide GMTI and SAR with real time, onboard processing. Low frequency operation typically requires large antennas or aerials, and this is not easily accommodated on a small drone. Quadcopter systems have been trialled for ground penetration using long, lightweight aerials for use in agriculture monitoring.

Maritime Applications

Radar systems on UAVs are proving particularly popular with naval users who are faced with the 'what is over the horizon?' problem. A ship's view of the horizon is limited by the height of its crow's nest. Getting sensors airborne allows the horizon to be pushed back, giving the vessel a much greater situational awareness. This role was until recently filled by the use of manned helicopter systems, however UAVs provide significant advantages. A small UAV can be launched from any deck area and can quickly provide real-time surveillance and situational awareness out to long ranges. The Skeldar V-200 [64] from Saab is typical of such systems. This is a 4m long rotor UAV able to carry a payload of up to 40kg, and can be fitted with a variety of small form-factor radar systems such as the Leonardo PiocSAR [108]. Radar operation allows the wide area detection of vessels including small FIACs in all weathers, as well as operation in littoral regions to provide SAR and GMTI information along coastlines.

Electronic Sensor Measures (ESM)

Electronic Sensor Measures (ESM) covers the use of the radar RF system in a passive mode, detecting and locating the emissions of radar and communications systems. Many modern RF systems are able to provide this capability as one of their operating modes, but dedicated specialist systems are also available. Saab produce the EPS-50 electronic surveillance payload [65] which is able to provide Electronic Order of Battle via a datalink to a ground-station. This small system (16kg including bother the antennas and the controller) provides high accuracy Direction Finding of emitters from 0.5GHz to 18GHz (L-band to Ku-band). QinetiQ have developed the AS3 COMINT system for Watchkeeper [66] with ability to detect, locate and listen to military communications. This system can be swapped into one of the two sensor bays on the Watchkeeper UAV to provide a quick change of role. The advantage of a dedicated system is that it can typically provide a much wider band of operation than a multi-function radar can achieve.

Agriculture

There are a wide variety of uses of radar systems in the agricultural technology (agritech). Many satellite services are now being offered that can provide farmers with detailed information regarding their crops on a vast scale. Civil satellite constellations such as Copernicus [67] are able to provide data that can be exploited by third parties to derive agricultural information. SAR polarimetry is especially useful in providing indications of poor crop quality or variations in soil content. UAS can also undertake these measurements, but at a smaller scale and with a shorter timeline. This can have benefits for certain applications – for instance when change detection measurements are required with a time separation of hours rather than the revisit time of many days available from satellites. Agritech applications are seen as a potential growth market by military system designers such as Lockheed Martin [68]. High resolution 3D mapping can help with flood monitoring and water catchment, ground-penetrating radar (L-band and below) can provide root survey information.

Search & Rescue

Radar sensors can be used to search for a locate victims under rubble in collapsed buildings, landslides and avalanches. Penetrating microwaves are required, so typically L-band and S-band systems are developed for these applications. Researchers have investigated the detection of vital signs of life via the Doppler returns of radar signals caused by the movement (breathing, etc.) of buried victims. Imaging techniques can be used to discern cavities where survivors may be trapped. In avalanches, nonlinear and harmonic radar techniques have been used to find and locate small passive transponders attached to clothing. All these techniques are applicable to UAS. Emergency services could be able to deploy small drones with dedicated radar systems to quickly search for victims without having to rely on lighting conditions [773].

Environmental Monitoring

Environmental monitoring is a significant growth area and radar-equipped UAS can provide valuable capability. UAS can reach otherwise hard to image areas – forests, mountain regions, glaciers, volcanoes, etc. – and allow operators to collect sensitive measurements. Radar systems are particularly useful for imaging areas that are continuous covered in clouds. Real time data can be collected by researchers at a safe distance [69].

6.1.15 Advances & Trends

Advances in critical radar system technologies are currently being driven by the mobile communications and computing civil market. Microwave technology has leapt forward through the investment of mobile phone manufacturers, making previously expensive materials and devices affordable and undertaking miniaturisation research and development on a scale that would not have been possible with military defence spending. This is fuelling a growth in available radar technologies in specific areas, while other areas are being left behind. Multifunction RF Systems which offer radar functionality along with communications and ESM in a single array architecture are going to dominate in future – capabilities and modes are primarily software enabled, and so can be easily changed.

Advances in solid state materials are providing ever more efficient means of generating microwave power across increasing bandwidth. This is enabling compact radar systems to be developed which are suitable for installation on small and medium UAV platforms. New materials are being developed that will lower the cost of antenna elements, making phased array systems cheaper.

The selection of radar operating bands will remain critical in determining the capabilities of the system. Wide tunable transmit bandwidths are difficult and expensive to achieve. For most applications it would be more efficient to design different radar systems to concentrate on different bands, rather than a single expensive system able to cover several.

Spectral congestion will be a problem in the future, with the proliferation of RF sources across mobile communications. Operation in a highly congested environment will make increasing demands on the radar system, interference will cause increased noise to erode image and detection quality. Equally the controls placed on the design of the radar systems will likely increase in order to better manage a crowded spectrum; spectral leakage will be limited through better design. Operation at bands where there is greater atmospheric attenuation will be beneficial in applications where the radar imaging can be conducted at close range. These signals do not propagate far and therefore do not suffer from spectral congestion and interference as much as the lower bands. V-band and W-band systems can provide very high resolution imaging and measurement at close range, and are available as very compact systems suitable for small UAVs.

Phased array antennas are dominating in the larger radar markets for military applications, but other antenna solutions are also in development for specialist applications. Small patch antennas can provide adequate performance at higher frequencies, while lightweight helical and spiral antennas have advantages in terms of bandwidth and polarization. For low frequency radars such as FOPEN long aerials are necessary in order to achieve a usable beam and this requires the development of lightweight structures for small UAV applications.

Radar processing can be computationally intensive. Advances in computer processors are allowing more and more to be squeezed onto smaller chips. However, these processors do come with penalties in terms of increased power and cooling requirements, and this does provide limitations for aircraft applications.

Current advances in computer power are focussing on multi-core processors (MCP). These processors offer multiple processing cores that share common functions such as I/O, network interfaces and memory management. They offer a substantial increase in performance over conventional single core chips, and reduce the overall chip count necessary for a system implementation. MCPs are increasingly dominating the civil computer markets due to the performance advantages that they offer. However, the shared-resource nature of MCP make them very difficult to certify for use in aircraft. This is being addressed, but could prove a significant limitation on the computer processing power available to future UAV radar systems. CAST have produced a useful position paper on these issues and their implications [70].

Cognitive sensing [71] is a current buzzword to describe what is, essentially, adaptive radar. The radar itself has some understanding of its environment (either through its own sensing, or other cues) and can adapt in characteristics and behaviour accordingly in order to make best use of available RF power for the task in hand. This could involve changing frequency of operation in congested environments, adjusting clutter filters or changing waveforms to adapt to the properties of the target. Cognitive sensing techniques and concepts are well suited to the principles of autonomous UAVs. A multifunction RF system is able to undertake a variety of modes pseudo simultaneously and cognition will allow this to be optimised to the prevailing conditions.

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Data and information fusion are essential for autonomy and understanding. Tightly integrated systems and common data structures will enable the effective combination of information derived from different sources in order to achieve a single fused picture or understanding. Sensor fusion covers the combination of data derived from disparate sources such that the information derived has a higher quality and less uncertainty than the individual sources this is particularly important for radar systems which have strengths in target detection and location, but are potentially weak in imagery understanding and target recognition. Intra-platform sensor fusion will take the sensor feeds from the platform itself and all small UAVs that might be quite limited. Inter-platform fusion will take off-board and on-board data. This will be a critical enabler of UAV swarms (see below).

Robust and reliable communications are essential for radar-equipped UAS. Short and medium range systems may require line-of-sight communications links with their operators in order to maintain high bandwidth datalinks. This is clearly quite limiting for military applications where deeper penetration may be an advantage, but this is also true for some types of wider area environment monitoring. Data links are highly vulnerable to interception and jamming in a military context and to interference in all situations. Some platform autonomy can help cover gaps in communications, but operating a UAV in deep theatre will require almost complete autonomy. This clearly limits the missions and roles that such a platform can undertake. Surveillance UAVs can be sent out to monitor an area of interest and only report back when they find something, which increases the burden of onboard processing. Systems operating in the deep will necessarily be large, requiring long endurance, multiple sensors, onboard radar data processing and exploitation, sensor fusion and long range communication links.

The exploitation and understanding of radar information is difficult. Conventionally this has been undertaken by high trained and experienced personnel. However, this is no longer sustainable – the proliferation of radar systems is leading to a data deluge – the existing radar data analysts are simply overwhelmed by the amount of data. This can be addressed by lowering the training burden and enabling the experts to focus on the critical tasks. Both of these activities are enabled through automated exploitation, and this is therefore directly relevant to future UAS.

Automatic target recognition techniques are in development for surface targets (using SAR) and air targets (using Range Doppler Imaging). These allow the radar to classify and recognise the target object. In the case where there is a human operator in the loop this simply allow ?eyes-on? to be achieved much faster; the imagery can be annotated with candidate target locations and identities that the operator can then analyse. In fully automated cases the ATR can provide cross cueing information to collect more data on the target of interest, or to report back to base only when a relevant target of interest is discovered. Data links can be far more efficient if only the imagery of detected targets is sent back, rather than streaming the full raw data. Current imagery understanding and ATR research is investigating the use of Convolutional Neural Networks, Deep Learning and Artificial Intelligence. There has been a great deal published, particularly by Chinese researchers, around the world. Useful performance is now being achieved in aspects such as pre-screening.

Multistatic imaging is a broad term to cover the situation when the transmitting and receiving platforms are different. A bistatic situation is easiest to consider, with one UAV illuminating an area and a separate UAV receiving the reflected signals and processing the data. There are advantages to this geometry. The receiving platform can remain entirely passive and hence more stealthy; any jamming will be directed at the transmitting platform and not the receiver. The receive-only platform can be smaller and simpler by not having to incorporate a transmitter. However there are significant penalties, chiefly the maintenance of coherence between the platforms to enable high accuracy image formation or target location to occur. This will require highly accurate time references (atomic clocks) and high grade GPS. The case of multi-static imaging extends this to more platforms; this could be a single transmit platform (possibly stand-off, conceptually a satellite) illuminating an area of interest, with multiple receive platforms collecting the scattered signals. Alternatively, it could be multiple platforms, each operating as transmitters and receivers in a complex multi-baseline scenario; and this is the situation being investigated by the QinetiQ/Dstl RIBI programme [426]. The advantage of multi-baseline imaging is that it can allow images to be built up in three dimensions (volumetric imaging); this is particularly useful when imaging the inside of buildings.

A further extension of multistatic imaging is the situation with non-cooperating illuminators, so-called *illuminators of opportunity.* These systems use the RF signals already within the environment to undertake target detection and imaging. This might be mobile phone signals, DVB-T signals, wifi routers and the like. These passive radars are able to operate most effectively in congested spectral environments. This is a likely use of future UAS RF systems, but will require significant development of PNT (positioning navigation and timing) technologies to be integrated.

Finally, let us consider an idea that has been considered for a number of years: *swarms of radar equipped-UAVs* . The concept is that the swarm is able to form up as required to undertake different radar tasks; for instance gathering in a close proximity to provide more gain and power in a certain direction, or spreading out around a target to achieve multi-baselines and volumetric imaging. Swarm approaches for mini UAVs equipped with radar sensors have been considered [72], often taking inspiration from the natural world in terms of flocking and stigmergic behaviour. Achieving the benefits of swarms requires dozens of drones, which therefore requires them to be relatively cheap and simple. This may run counter to the complexity of the tasks that they are then required to carry out, and the range at which such systems can operate. For military applications some form of delivery system may be required to get a sufficient number of short-lived drones to the area of interest before deployment.

The use of drone swarms in general is likely to have a significant impact on all areas of defence and security [73]. The communication links and computing power necessary to allow self-organising drone swarms is coming and their potential (and threat) as elements of a radar network should not be underestimated.

6.2 Hyperspectral & Optical Sensors

Hyperspectral and optical sensors are passive imagery systems which can detect electromagnetic emissions from constituents of the Earth's surface and atmosphere. These emissions can be locally produced (e.g. thermal radiation from vegetation in the infrared spectrum) or be the result of reflected sunlight in the visible spectrum. Much of the following information is based on satellite Earth observation technology [40], but the same concepts apply to aircraft mounted sensors.

6.2.1 Panchromatic Sensors

Panchromatic sensors measure light intensity over a broad range of the electromagnetic spectrum which allows a large energy per pixel to be collected leading to high resolution images. A typical panchromatic sensor will record the light intensity from the observed scene in the full visible spectrum, typically wavelengths between 0.47μm and 0.83μm , as a greyscale image.

Panchromatic imaging may include thermal infrared sensors at wavelengths between 10μm and 12μm; IR is constantly emitted by the Earth and clouds it is possible to obtain IR imagery even when the scene is not illuminated by the sun.

6.2.2 Multi-Spectral

Multi-spectral sensors image a scene in several narrow bands of the electromagnetic spectrum. This is similar to the way commercial digital cameras generate 'true' colour images from three narrow-band sensors (RGB). Narrowband sensing elements have less energy available so need to be larger than panchromatic sensors, resulting in lower resolution images. Multi-spectral sensors are not restricted to the visible spectrum: measurements can be done in the infrared (IR) fields, ultraviolet (UV), microwave, etc. presented as 'false' colour images.

Many combinations of bands are possible, depending on the information required. For example:

- Shortwave infrared (red), near infrared (green), and green (blue) is often used to show floods or newly burned land;
- Blue (red), two different shortwave infrared bands (green and blue) is used to differentiate between snow, ice, and clouds;
- Blue (blue), near infrared (green), mid infrared (red) is used to represent, on one image, water depth, vegetation coverage, soil moisture content, and the presence of fires.

6.2.3 Pan-sharpened

It is possible to use common front optics (i.e. main lens) and then use prisms or dichroic mirrors to divert different wavelengths to different sensor arrays. However, this typically requires bulky packaging to encompass the different optical paths and multiple focal planes. Such solutions are practical for gross spectral discrimination: the JAI AD-080 uses a single prism to separate visible band and near-infra-red energy giving four broad spectral responses (red, green and blue sensed using a conventional CFA-based colour image sensor, and NIR using a separate panchromatic image sensor).

A more simplistic approach is to co-site multiple cameras together, each with their own optics. This approach has been used for UAS sensors for agricultural monitoring applications for example. Each lens/sensor combination is sensitive to a different wavelength range. The offset in position of each lens can potentially introduce differences in the imaged scene due to parallax effects. However, as the difference in viewpoint position is small this is only likely only to be an issue when imaging scenes at very close range (i.e. within a very few metres).

It is generally impractical to have a multi-lens spectral sensor with anything other than fixed focus, fixed focal-lens optics so that data from the different sensors remains consistent. Additionally the cost, size, weight and power increase with the number of additional optics introduced. Consequently this approach is entirely practical for some applications such as agricultural monitoring where a small number of known wavelengths are of interest and observations are made from overflight at a limited range of predetermined altitudes (and hence enabling the use of fixed optical geometry). This is very different from applications where greater stand-off, altitude or variation in flight plan is required: here, larger optics to provide longer and potentially variable focal length lenses are required. It is impractical to have duplicated optics on grounds of size, weight and cost. Calibrating the optics such that images are consistently acquired between the multiple cameras is also more difficult – with narrower field-of-view lenses small variations in set-up can result in the poor overlap in scene coverage between the different cameras.

In summary, methods using multiple focal planes or lenses do not scale well to large numbers of spectral bands as typically required in hyperspectral imaging.

Pan-sharpening is a post-processing technique that merges multi-spectral and panchromatic data to get high resolution coloured images by exploiting the spectral resolution of multi-spectral images with the spatial resolution of panchromatic images.

6.2.4 Hyper-Spectral Sensors

It is desirable to extract spectral information in remote sensing applications, such as land use monitoring, vegetation health assessment in agricultural uses and detection of decoys and camouflage in military use. Spectral information provides additional information to that available in conventional imaging techniques.

Hyperspectral sensors capture data on a nearly continuous spectrum for each pixel in the image of a scene. Each pixel captures the light intensity in typically a few tens to several hundred contiguous narrow spectral bands. The high spectral resolution allows for detection, identification and quantification of surface materials, as well as inferring biological and chemical processes.

Until recently, hyperspectral sensing was limited to aerial imagery and scientific demonstration missions [74], but commercially available hyperspectral imagining systems are now available for small UAS able to carry a payload of 5kg [75].

Imaging sensors are typically 2D arrays of pixels, measuring scene intensity with broadband spectral response (e.g. visible band, or broad wavelength bands thereof such as red, green and blue). Images can typically be acquired in quick succession. Obtaining spectral information requires sacrificing aspects of conventional camera imaging. For example, the acquisition rate is reduced. This is because spectral information is obtained by repeatedly placing different narrowband filters in the optical path, thus obtaining a sequence of images with different spectral sensitivity. This means that multiple frames are required to generate complete spectral information for the scene, hence the rate sacrifice. An alternative approach is to use a spectrometer such that one axis of the 2D array is used to record spectral information with the other axis giving spatial coverage. In effect, a 2D conventional imaging array is operated as a linescan spectral sensor, requiring either the sensor to be scanned or moved (e.g. from platform motion) to construct spectral information over a scene. This is known as ‘pushbroom’ imaging (see below). Conventional colour cameras often use a single imaging array and sacrifice some spatial resolution to obtain colour information by using a Colour Filter Array (CFA) over the image sensor. Pixels are sensitive to either red, green or blue wavelength bands. This approach has been extended to use a greater range of narrower-band filters, e.g. using a repeating pattern of 4x4 or 5x5 filters rather than the 2x2 (red, green, green, blue) CFA patterns used for conventional colour imaging. A further approach is to use multiple cameras, each with its own distinct spectral response. However, there are size, cost, weight and power implications if more than a very few spectral bands are to be observed.

There are two further points to note. First, many approaches to spectral imaging provide a fixed range of wavelengths that are observed (e.g. using a CFA bonded to a sensor, or a spectrometer). Other approaches can by dynamic, such as using a liquid crystal tunable filter where the observed wavelength can be changed variably. The wavelengths and number of bands observed can be altered dynamically, allowing on-the-fly trade-offs between update rate and spectral coverage.

Secondly, observation of narrow wavelength bands means that the amount of energy reaching the sensor pixels is greatly diminished relative to conventional broadband imaging and consequently sensitive image sensors are required and/or increased integration times (reducing frame rate and potentially introducing motion blur). Typically, this means that sensors with large pixel sizes are required and, for thermal imaging bands, sensor cooling sensors is required to achieve useful sensitivity.

Pushbroom Imaging

Pushbroom imaging effectively provides linescan imaging functionality. One axis of the 2D sensor array corresponds to different spatial locations along a line, whilst the other axis is used to sense the different spectral content. Movement of the sensor (or equivalently the platform) is used to build-up an area view of the imaged scene.

Linescan imaging (whether conventional or spectral) typically requires that the imaged scene remains static and that movement of the sensor/platform is consistent. Otherwise various distortions can be introduced into the image. This is particularly true for independently moving scene objects (e.g. vehicles moving along a road) where objects may be stretched or compressed depending upon how their movement interacts with the movement of the sensor.

Conventional pushbroom imagers use an optical imaging spectrometer, with a slit and diffraction grating or prism, to separate out incoming light into its spectral content and project it across the imaging array. Whilst the aforementioned geometric distortions can occur, the spectral measurement is consistent with the different wavelength energy arising from the scene is measured simultaneously for all points along the line.

An alternative approach to pushbroom sensing is to use a conventional imaging sensor with a bespoke 'spectral wedge' colour filter array. Here different rows of the image sensor are sensitive to different wavelengths. Such devices have been fabricated by IMEC and can typically 100-150 different bands over visible and near-infra-red bands.

The advantage of this CFA based approach is that a very lightweight and robust system is possible. The CFA adds negligible weight and complexity to a conventional imaging camera. However, unlike a spectrometer based approach the acquisition of spectral data over different wavelength bands must occur sequentially at different times for any specific scene location. With a conventional spectrometer approach the shape or position of scene content may be distorted but the measure spectra should always be consistent. With a wedge CFA the actual spectral response may be distorted but is less prone to spatial distortion, as a full 2D images of the scene (rather than a line) are acquired, albeit with spatially varying wavelength sensitivity.

With the wedge CFA based approach it is important that the scene is scanned sufficiently slowly to ensure that each scene point is imaged by each wavelength band of the filter, otherwise sparse spectra will be obtained. For a spectrograph based approach the spectra will always be complete, but the scanning must at an appropriate speed to avoid gaps in spatial coverage.

The use of a CFA might be considered to be wasteful of energy collected from the scene, given the filter only transmits a narrow wavelength bandwidth at each location. This is different to a spectrometer based approach where the energy is spread across a range of pixels without filtering. However, because the spectrometer only senses in one spatial axis, all energy collected by the lens outside the line actually sampled is discarded (by the spectrometer slit), whereas the CFA sensor observes the scene simultaneously in both spatial axes.

For both the spectrometer and CFA based approaches the wavelengths sampled are fixed by the design and manufacture of the equipment. The choice of approach is dependent upon application. Where size or weight is critical, the wedge CFA approach is advantageous, whereas consistency of spectral measurements is inherently guaranteed by spectrometer based approaches.

Sequential Waveband Imaging

Pushbroom based techniques described in the previous section require movement of the sensor/platform to build up either spatial (using an imaging spectroscope) or spectral (using a wedge CFA) information.

An alternative technique is to use varying spectral filters in front of a conventional image sensor, i.e. imaging the whole scene but at a single wavelength band at a time. This can be readily achieved using mechanical techniques (such as a rotating filter wheel) that sequentially place a set of filters physically into the optical path.

Clearly a number of image acquisitions are required to build up the spectral information and this takes time. Either the imaged scene must be held static during the acquisition period (e.g. by physically stabilising the sensor) or the imaged data must be realigned in a post-processing step to ensure the spectral measurements made correspond to the same scene locations. Correction for objects moving independently within may be problematic and hence spectral measurements of moving objects and areas adjacent to the movement may be distorted.

Mechanical filter wheels are conceptually simple but undesirable in many applications: the power, weight and reliability of filter wheel mechanisms are concerns and the number of filters (and hence wavelength bands) is limited by practical considerations. Consequently filtering is desirably performed using other techniques for UAS applications.

- Liquid Crystal Tunable Filters (LCTF): the filter provides a narrow pass-band at a wavelength that depends upon the applied voltage. Switching between different wavelengths can be achieved at relatively high rates (above 20Hz) for some configurations. Filters are commercially available from suppliers such as PerkinElmer (VariSpec), MeadowLark Optics, Kurios and Kent Optronics.

- Piezo-actuated Fabry-Perot interferometers: a piezo-actuator is used to subtly change the distance between two mirrors and hence change the pass-band of a Fabry-Perot interferometers.

An advantage of both these approaches is that the pass band wavelength can be controlled dynamically. It is therefore possible to sample a discrete set of wavelengths of interest, rather than obtaining whole spectra.

LCTF filters have some limitations, in so far as there are losses in optical transmission (due to the use of polarising elements) and limited out-of-pass band attenuation (although this may be compensated for in post-processing). However, it is possible to commercially procure filters that can be dynamically tuned both in terms of passband wavelength and bandwidth (i.e. allowing spectral resolution to be traded against sensitivity). Senop (formerly Rikola) commercially produce a hyperspectral camera that use piezo-actuated Fabry-Perot interferometers, the HSC-2. This can acquire images (one band at a time) at up to 150Hz.

Area Based Imaging

The use of CFAs to provide spectral imaging can be highly advantageous due to the absence of bulky optical components. A spectral wedge type CFA has already been discussed in the previous section of pushbroom imaging but other options are available.

One alternative is based on a 'tiled mosaic' where the filter overlaid on the sensor focal plane has distinct rectangular regions with different spectral sensitivity. This requires additional optical components to replicate the incoming image to every rectangular region. The required optics (typically a field stop and microlens array) are compact and robust.

Another option is a 'snapshot mosaic' where the filter overlaid on the sensor focal plane differs in spectral sensitivity between adjacent pixels, much as a conventional single focal plane colour image sensor uses a pattern of adjacent red, green and blur sensitive pixels. The issue with this approach is that the scene may be under-sampled because each waveband is only sparsely sampled – there will be a gap of several pixels between the pixels sensitive to any particular wavelength. Aliasing distortions can be avoided using an optical low-pass filter. This can be achieved either on the focal plane, such as anti-aliasing filters used in high quality digital cameras, or by deliberate defocussing of the lens. In either case there is no significant impact upon size or weight. For the snapshot mosaic sensor, post-processing is used to estimate spectra at specific pixel positions using information from nearby pixels of different wavelength sensitivity (in a similar vein to the 'demosaicing' processing used in conventional cameras to estimate the red, green and blue component at each pixel site from nearby pixels with differing colour sensitivity).

These approaches permit rapid acquisition of hyperspectral video, albeit at reduced spatial resolution in comparison to a monochrome sensor of the same pixel count. However, to maintain reasonable spatial resolution the number of spectral bands is typically limited, currently to around 32 spectral bands (IMEC SNt32 sensor), on commercially available devices. In principle different CFA designs are possible and can be designed and produced on demand for specific applications, albeit at considerable expense.

There are a number of other techniques developed that can provide snapshot spectral imaging (i.e. instantaneous acquisition of spectral data for a 2D scene) that are outside the scope of this document but well represented in the literature. Some approaches have shown theoretical promise but have failed to be developed further and adopted for general use (e.g. due to cost or difficulties in fabricating required components).

Trends

Pushbroom imaging using conventional optical spectrometers is well established but has limitations when attempting to observe scenes with independently moving objects. The size and weight of optical components may impact upon platform performance (e.g. endurance) particularly for smaller UAS. However, pushbroom imaging can provide excellent spectral coverage (in terms of the number of wavelength bands). Other methods typically compromise spectral coverage to improve spatial representation.

It is likely that in the near future snapshot mosaic imaging (using Colour Filter Arrays on the focal plane) will become more established. This is relatively recent technology and, whilst commercially available, is not in mass production. Several scientific camera manufacturers now offer devices with this technology, operating over visible and near infra-red wavelengths. Increased demand and production could reduce costs substantially and the approach requires little variation from existing conventional camera installation.

Piezo-actuated Fabry-Perot interferometer based imagers are likely to become more popular. These offer faster switching between different wavelength filters than the more established Liquid Crystal Tunable Filter technique, enabling faster and more consistent scene content acquisition which is beneficial to UAS platforms due to movement. This type of technique is advantageous in so far as the number and selection of wavebands observed can be dynamically altered and provides the ability to trade spectral coverage against update rate.

The extension of existing multi-camera spectral sensors to an increased number of wavebands may be readily achieved. However, with cost, size and weight also increasing the technique will still limited to a relatively small number of wavebands and (due to lens size and weight considerations) close-range/low-altitude operation.

In the longer terms (into the late 2020s) techniques based upon principles of computational photography, such as compressed sensing, will likely be increasingly feasible. Conventional spectral observation attempts to measure each waveband response at each pixel. In practice mixed measurements can be made (of sets of pixels and/or sets of different wavelengths) with post-processing used to de-correlate the observations back into conventional spatially-localised spectra. There are strong statistical correlations in the data both spatially and spectrally. Compressed sensing techniques enable fewer data observations to be made: full spatial and spectral resolution data is generated by post-processing on the proviso that the imaged scene fulfils anticipated, but non-stringent, statistical properties. Making fewer data observations enables a faster update rate to be achieved which is useful with dynamically manoeuvring platforms and moving observed scene content.

It is difficult to predict developments beyond 2030 but, as a general trend, influences from technologies outside sensor development are likely to have an impact upon spectral sensor design. For example, the use of Deep Learning AI techniques is increasingly impacting upon automatic image analysis. Current image sensing is driven predominantly by historic applications requiring that data is in a form for human interpretation (i.e. a conventional image or spectral datacube). This requirement may become less dominant as the use of AI techniques increases, where data in non-conventional formats may be as acceptable, or even beneficial, as input to autonomous processing applications. Further, novel machine learning techniques may place different emphasis upon the relative resolution of, and potential distortions present within, spatial and spectral data. These factors may drive longer-term future sensor design and operation.

6.2.5 Electro-Optical & Infrared Imaging

A recent tutorial report on EO/IR systems, produced by The Institute for Defense Analyses by Koretsky [492], provides a very good grounding in the current technology and also a summary of trends in EO/IR imaging requirements that are driving new technology developments.

One area of particular interest is that of non-traditional optical systems. Several research groups are looking at electrically steerable optical assemblies which are hoped will replace the rotating mirrors and other mechanical structures in current IR systems. The reduced complexity, and associated weight and cost (both in manufacture and maintenance) have the potential to enable this technology on new, lighter platforms and for applications for which current technology is too expensive. Examples include silicon nanopillars for IR steering [76] and electrically controlled LCD refraction gratings (see Patent US6765644B1).

Metamaterial applications are being demonstrated at IR. An example is the construction of an IR diffraction grating by a team at Duke University that could be used to create small optical steering structures [762]. A considerably more detailed exploration of the theory of IR-effective metamaterials can be found in [761].

6.2.6 Visible Light

Digital still and video cameras are widely available for UAS use [77], and filming or visual inspection is probably the most common use of small UASs, at least in the commercial sector. The commercial market for digital imaging generally (not just for use with UAS) seems likely to drive continuing improvements in performance for these sensors.

Video cameras provide the basis for computer vision systems [460]. When incorporated with the flight management systems, visible imagery can be used to support navigation (visual SLAM, for example, can build maps of the local environment from video imagery [78]).

One particular application where visible light camera payloads are likely to remain important is photogrammetry [519] [730], where high resolution imagery is used to determine additional information about the scene, either by directly processing the image or combining the image with the outputs from other sensors (for example hyperspectral images or gravimeter measurements).

An interesting potential application is combination of a large number of video feeds from moving platforms to emulate continuously staring video of a particular location. Demonstrations of merging multiple video views of a scene from unstructured camera arrays have already been made by Disney Research in Switzerland [79] [80].

6.2.7 Sonar & Other Acoustic Sensors

Acoustic sensors are not often seen on UAS, but there have been some experiments [265] [593] where the UAS is used to replace existing anti-submarine helicopters [81] which use dipping sonar systems to lower acoustic sensors into the sea.

Acoustic sensors are sometimes used for distributed intrusion detection [82], or gunshot detection [138], but these systems require a network of sensors to triangulate the acoustic source, and may not be suitable for mounting on relatively noisy and mobile platforms.

6.3 Chemical & Radiation Sensors

There is growing interest in using UAS to host chemical and radiation sensors, especially when surveying areas after natural disasters or accidents. The ability to quickly and safely capture information about the extent of potentially harmful events is valuable when developing a response to those events.

Chemical and radiation sensors have not undergone the same degree of miniaturisation that other sensors (especially visible light sensors) have seen in recent years. Some work has been done tracing chemical plumes by detecting aerosol concentrations [840]. Determining chemical composition using spectroscopy is well-known and has been demonstrated from a UAS [162]; the technique is quite similar to hyperspectral imaging.

Measurements of radiation contamination by mapping gamma ray intensities have been demonstrated [83] [671] and UAS platforms with gamma ray sensors have been used to survey the area around Fukushima [572].

6.3.1 Graphene

Graphene is a form of molecular carbon [442] which has interesting electrical properties that are enabling commercial applications in, for example, flexible displays and wearable electronics. Graphene is also being investigated as a basis for small magnetic field sensors [725] and (along with the closely related material carbon nanotubes) novel chemical detectors [84]. The current maturity of graphene displays implies that industrialisation of graphene-based sensors could be close [631].

The properties of graphene suggest that future sensors, particularly chemical sensors, could be made small and conformal, so that they could be integrated into the structure of even very small UAV platforms for example [720]. Chemical sensing capability can be used to detect and track the source of precursor chemicals in the atmosphere, and the sensor should be built into a variety of platforms, from large high-altitude persistent monitoring to mission specific micro-UAVs close to the source.

Graphene is also being investigated for THz sensing [85]. The challenge here is that the ranges will be short, so to be useful (and covert) very small sensors on small UAVs will be needed [86]; however, the flexibility, and hence conformal possibilities of these sensors could make them practical at these scales.

Chapter 7

Autopilot Systems

Autopilots for aviation usage were largely developed towards the end of the second world war, although the first crude aircraft autopilot was developed by the Sperry Corporation in 1912. The early autopilots were analogue, largely mechanical devices. The first digital autopilots were developed in the 1960s.

Manned aviation autopilot systems tend to be expensive (as a result of the need for certification) and there has been little exploitation of these within the UAV community.

In recent years developments in the mobile phone industry have had a considerable impact in the technology of unmanned autopilots. This has largely been led by Apple who pioneered the use of MEMS (Microelectromechanical systems) sensing elements in mobile phones. A modern smartphone is capable of accurately sensing its absolute attitude thanks to the inclusion of MEMS accelerometers, gyros, and magnetometers. Similarly, the development of miniaturised, cheap, low power consumption GNSS receivers has allowed smart phones to geolocate quickly and accurately. The unmanned aviation community benefits considerably from this high-volume consumer-product led research. The extremely competitive mobile phone industry continues to develop smaller, lighter, lower power, more accurate, robust and low-cost devices. Interestingly, an open source project called Flone[1] has taken this trajectory to a logical conclusion in that it allows an Android smartphone on the ground to control one fitted onto an airframe via Bluetooth.

The industry leaders for small autopilot systems include *Micropilot*, *Piccolo*, *UAVnavigation* and *Embention*. Large military UAVs use autopilot systems supplied by defence avionics companies such as Bendix, Garmin and Thales.

A very significant development has been the availability of open source autopilot systems including PX4, Paparazzi, LibrePilot and ArduPilot. Although these started out being used in academica and the hobby community the PIXHAWK range is now starting to be used in large commercial UAV systems. The DRONECODE organisation now incorporates other software products including ground station software QGroundControl, communications software MAVLink and the development toolkit MAVSDK.

7.1 Case Study: An Academic Research Team's Experience

Academic research into unmanned aircraft systems is generally significantly limited by budgetary constraints, but it often has greater agility and risk-tolerance than industrial development processes; developments in autopilot technology are no exception to this and, as an illustration, this case study reviews the experience of such a team at the University of Southampton.

The first driver of autopilot developments at Southampton was a low cost air vehicle developed at the National Oceanography Centre for ship based science missions [802] (Figure 7.1). Featuring a range

[1] https://flone.cc/en/home-2/

Figure 7.1: NOC-developed Oceanographic UAV flown in 2008 (left), auto-landing repeatability trials at Ramsgate (centre), and BBC camera platform built in 2010.

of more than 1000km and carrying a payload of 2kg, the aircraft could be launched and recovered from a coastal research vessel. It flew successfully in Force 4 gusting Force 6-7 wind conditions, an important requirement for operation at sea. As part of this development the University team was compelled to develop its in-house autopilot system[226], as existing systems were either too expensive or immature at the time. The system implemented controllers that used Pseudo-Derivative Feedback (PDF). Innovative features included controlling the derivative of heading rate to command an achievable trajectory and controlling the closing speed on the path by adjusting bank angle. The advantage of using PDF based controllers as opposed to the PID (Proportional Integral and Differential) controllers typically used in autopilots is that PDF only has two tuning parameters rather than the three needed for PID (See section 7.3 for more on autopilot tuning).

This prototype autopilot went on to be developed into a commercial product (SC2), which was marketed by spin-out *Sky Circuits*. The SC2 is currently marketed by Callen-Lenz.

This autopilot was used successfully on the early 2SEAS (SPOTTER) prototype aircraft developed subsequently at the University. One of the critical aspects of flight automation is the ability to fly accurate and repeatable take offs and landings. As part of the 2SEAS project[2], trial flights of the aircraft were undertaken at Ramsgate port. The second panel of Figure 7.1 shows the tracks resulting from a highly successful series of continuous take-offs and landings using the SC2 autopilot. The tracks show a tight approach (from the right hand side of the image), resulting in repeatable touch-down points within a five metre radius.

Subsequently, an aircraft equipped with the SC2 autopilot undertook one of the UK's first Beyond Visual Line of Sight (BVLOS) flights at the MetOffice danger area near Cardington in 2009, by climbing to an altitude of 5000 feet. At this altitude the aircraft was invisible to the naked eye (though the noise of the propeller was just audible). The following year a large, fixed wing camera platform (Figure 7.1, right-hand panel) commissioned by the BBC was developed by the same team, receiving the UK's first Civil Aviation Authority permit for civilian drones heavier than 20kg.

7.2 Reliability

The aspiration for beyond visual line of sight operations requires highly reliable systems with predictable behaviour. With regard to the avionics, this can be achieved either by very tight quality control (to certified standards) of both hardware and software (which is costly), or by the use of redundant systems.

The development of fully certified avionics hardware with fully traceable supply chain components is both complex and expensive. Suppliers of components are not always prepared to provide this level

[2] https://www.sotonuav.uk/projects/#2seas

Table 7.1: Target failure rates for a range of design assurance levels.

Design Assurance Level	Description	Target failure rate per flight hour	Example
A - catastrophic	Causes deaths	10^{-9}	Flight controls
B - hazardous	May cause deaths	10^{-7}	Braking system
C - major	May cause stress, injuries	10^{-5}	Backup systems
D - minor	May cause inconvenience	no safety metric	Ground navigation systems

of quality control and this can narrow down the choice of parts. This can also lock the system designer into the use of legacy parts and not allow access to the latest technology.

For avionics and safety critical software there are standards that define procedures for the development of code, such as DO-178C. This standard defines Model based development and certification, formal methods as well as tool qualification (commercial tools have been developed that embody and comply with DO-178C standards, such as SCADE [87]). The cost of complying with safety critical standards for avionics software is very high. The ultimate goal is to develop systems capable of achieving a target level of failure rate (seeTable 7.1). It is clear that a large platform flying beyond visual line of sight in un-segregated airspace arguably requires Design Assurance Level (DAL) category A flight control systems.

The traditional approach to this in, for example, commercial airliners is to use a triple redundant autopilot system, which may even mean that each of the three autopilots is developed by a different team using different hardware in order to mitigate against common mode failures. Such multiply redundant architectures require a master controller in order to arbitrate the multiple autopilot outputs. At its simplest, this master controller is essentially an automatic 'switch' that directs the output of one of the autopilots to the flying controls of the aircraft. In order to switch from the primary autopilot to a secondary device some form of health monitoring logic is required. The master controller needs to be capable of monitoring all of the available autopilots and applying criteria to switch to a secondary backup (and tertiary backup if required). The master controller, whilst being a functionally simple device, in practice is relatively complex involving both hardware and health monitoring software. Furthermore, the master controller represents a single point of failure in this architecture. If the master controller malfunctions, then this can lead to catastrophic failure. There are many possible failure modes. An architecture with a master (centralised) element is vulnerable despite the use of redundancy within it.

The inadequacy of current avionics architectures has been recognised by the research community and alternative have been proposed. A recent paper [237] argues the case for the use of Integrated Modular Architectures (IMA) within UAV platforms. However, this does not explicitly deal with the need to eliminate logic or physical single points of failure. Even within an avionics system based on the IMA logical switching between partitions is required.

In 2018 researchers at the University of Southampton developed an alternative to centralised or switch-based architectures. This work partially builds upon ideas outlined in a paper proposing the use of arrays of low-cost sensors to provide high performance [549]. This paper presents three advanced array-based techniques that could be applied to improve the performance of low-cost (uncalibrated) MEMS IMUs. The new architecture developed by the university uses a fully decentralised approach which has no master controllers. A test platform was flown in 2018 (see image below). This work is now being developed as a commercial offering by *Distributed Avionics Limited* and a patent has been submitted to cover the IP.

Figure 7.2: A world first: maiden flight of a platform controlled using a 'masterless' flight control architecture.

The advantages of the Distributed Avionics Limited system are:

- it provides extremely high robustness
- it can achieve high DAL levels using building blocks that are themselves low DAL (and therefore low cost)
- extra resources (sensing and computing) can easily be added
- it is applicable to a wide range of platform configurations including fixed wing, rotary wing and hybrids.

Some simple numerical analysis of the robustness of the DAL masterless architecture has been carried out.

This analysis estimates the fault state space of the overall system by running a Monte-Carlo model which randomly assigns either a faulty or functioning status to the devices within the system. This model is illustrated below. This analysis shows that the conventional architecture has an overall fault-free state space of only 4.3%. On the other hand, the masterless architecture has an overall fault free state space of 51.8%. In other words, this new architecture, using the same resources, has more than an order of magnitude better robustness.

7.3 Auto-Tuning

Most autopilot systems use standard control techniques with the use of Proportional, Integral and Differential (PID) algorithms, the proportional gain, differential gain and integral gain parameters need to be 'tuned' in order to establish a 'best' control response [400]. This is generally a compromise between stability (robustness) and response. For a fixed wing aircraft, the PID parameters need to be set for the roll, pitch and yaw axes, which involves estimating nine PID gain parameters. Historically, tuning of control loops has been a subjective, heuristic process, with control engineers relying on existing knowledge of the system and on skill [427]. This is a time-consuming process when carried out manually but can also entail some risk to the platform.

Automatic tuning techniques have been developed based on classical control theory. If the UAV platform has well-understood performance, aerodynamic and inertial properties they can be modelled, and tuning carried out as a simulation exercise [170]. However, the effort needed to characterise the drone accurately is substantial. Furthermore, validation and verification of this model may require

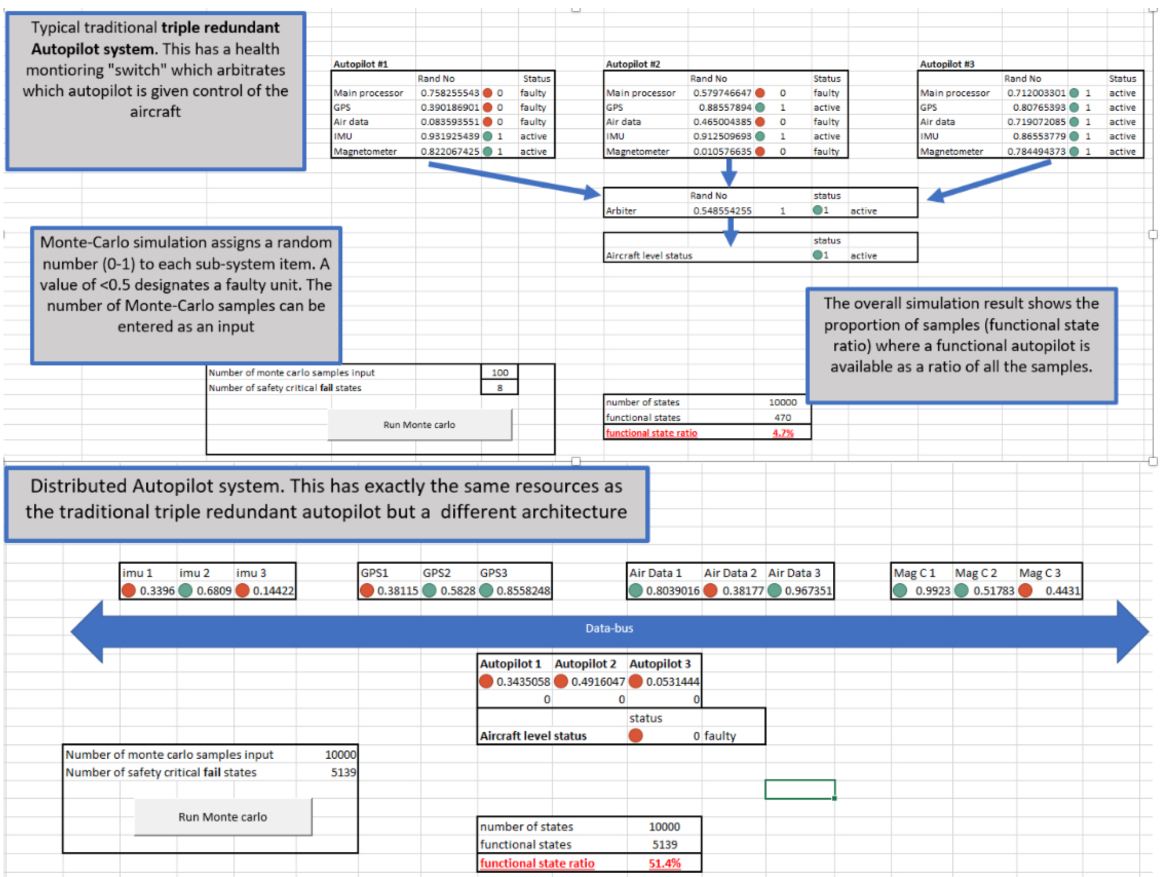

Figure 7.3: Robustness analysis: conventional triple redundant autopilot (top) and masterless architecture.

flight testing anyway [417]. Techniques have been developed that essentially use hardware in the loop testing whereby the platform undertakes a series of flight manoeuvres with step inputs to control axes. The PX4 family of autopilots is capable of auto-tuning to establish good first order estimates of PID parameters. By flying the platform in auto-tuning mode, the aircraft progressively 'learns' the necessary gains to achieve a given level of response. This level of response can be selected; for example, the *Ardupilot*[3] ground station allows operators to select a value that corresponds from 'weak' (ie slow but stable) to 'aggressive' (i.e., highly responsive) auto-tuning. In the case of Ardupilot, the platform is flown, and each axis is tuned starting with the roll axis (for fixed wing aircraft). This involves undertaking fast full deflection of control surfaces for a number of iterations to represent a 'step' input.

Auto-tuning is a very important development and leads to safer, and less time-consuming establishment of satisfactory control parameters for both fixed wing and rotary wing platforms. This capability is continually developed especially by the open source community with tools such as PX4, and QGround control.

7.4 Path Planning

7.4.1 The Unmanned Aircraft Systems Context

The current generation of unmanned aircraft can best be described as 'remotely piloted'. These vehicles are commanded and monitored by a human operator and generally follow a pre-programmed path. Such vehicles are currently unable to (and not generally allowed to) automatically modify a flight plan. Furthermore, the initial flight plan is generated and checked manually.

In the future there will be a need for automatic and dynamic path planning. Many experts predict that, in the event of the widespread commercial deployment of unmanned aircraft, a 'one to one' allocation of human operators to unmanned platform will be both uneconomic and impractical. In particular, the dynamic nature of airspace and changing conditions such as weather and emergency occurrences means that 'on-board' sensing and decision making is needed [329].

In order to plan a collision free path through a cluttered environment, a set of mathematical tools are needed to model these constraints and to store such data. From an optimization theory point of view, finding a 3D path is an NP-hard problem and heuristic solutions are required.

In a recent paper Yakolev [823] solves the path planning task for a multirotor unmanned aerial vehicle. The work proposes an approach of automatically estimating path geometry constraints based on drone flight dynamics model and control constraints. Jiang et al. show how stereoscopic cameras can be used to automatically navigate, avoid obstacles and plan a path [705]. They compare four algorithms (Dijkstra algorithm, Floyd algorithm, A* (pronounced A-star) algorithm and Ant colony algorithm) and find that the Dijkstra algorithm has the shortest run time. Cabreira et al. show examples of path planning for terrain coverage, such as surveillance, smart farming, photogrammetry, disaster management, civil security, and wildfire tracking [256]. Shiri et al [405] show how machine learning (ML) can be used to solve the path planning problem by use of an ML enhanced mean-field game (MFG) model to solve realistic problems including wind disturbances. Dogancay [314] demonstrates a model path planning for drones trying to geolocate an emitter using passive payload sensors. The objective is to generate a sequence of waypoints for each vehicle that minimizes localization uncertainty.

Of course, such research based on idealised mathematical model is hard to validate using realistic conditions.

Schuman has demonstrated how an agent based simulation model can be used to model and compare search and rescue missions and evaluate their metrics [691]. This work was later developed in order to show how agent based simulation can be integrated into the platform design process in order to match platform performance with path planning [690]. This work is continuing using agent-based

[3] http://ardupilot.org

modelling to evaluate different platform assets undertaking generic missions with simulated weather and stochastic target locations. In general, one of the key research directions at the moment is the development of stochastic agent-based models [215].

Within the EPSRC CASCADE project[4] a consortium is developing a very detailed and realistic simulation environment to evaluate a future unmanned aircraft traffic scenario with very crowded, stochastic events. The CASCADE team is collaborating with both NATS (National Air Traffic Service) and their Swedish counterpart Luftfartsverket (LFV) and Linköping University. LFV and Linköping have been undertaking air traffic modelling for many years. For example Lundberg et al [532] developed UTM50, an environment that simulates very high-fidelity path modelling and obstacle avoidance. In particular, it demonstrates automated path planning to avoid collisions. UTM50 uses a detailed ground and airspace model and utilises physics-based modelling of platform performance.

7.4.2 A Broader View: General Approaches & Their Potential In Autopilot Design

Path planning is probably the most important function of all mobile robotic systems. In general, the objectives of path planning involve computing collision-free trajectories and ensuring that the robot reaches the goal location in the shortest time possible. Specifically, motion planning involves the following key elements: (i) the start pose of the robot, (ii) the goal of the robot (iii) a model of the robot (iv) a model of the world. Then, we need to find a path that moves the robot from start to goal while never touching any obstacle. Moving a robot in a geometrically defined model of the world requires first defining all the possible ways the robot could move in that space. This is important to define based on the various parts and degrees of freedom of a robot. The set of all possible configurations is typically termed the configuration space or C-Space. If a well defined model of the world is available, the C-space is generated by sliding the robot along the edge of obstacle regions and motion planning can be summarised as the task of finding a continuous path while assuming the robot is simply a point in the C-space.

Network Models

The C-space is typically discretised before path planning algorithms can be used and there are a number of ways in which such planning can be done. For example, the free space available can be discretised into a network and then finding a path simply involves applying combinatorial optimisation algorithms to find the shortest collision-free paths. Examples of such approaches include: Visibility graphs, Voronoi Diagrams, Exact Cell decomposition, and Approximate Cell Decomposition. While providing optimal or quality guarantees, most of these approaches unfortunately do not scale well as the dimensionality of the C-space increases, particularly when robots can have many different moving parts or degrees of freedom, leading to a number of non-linearities and turning C into a non-trivial manifold.

Another class of path planning algorithms involve sampling, whereby collision detection is incrementally used find out where the obstacles and free spaces are and compute a path. Two key techniques are typically applied (i) Probabilistic road maps (PRM) [467] and (ii) Rapidly Exploring Random Trees (RRTs) [506]. Both methods are non-optimal but can compute solutions for high-dimensional C-spaces. PRMs in particular, do not work well for narrow passages and are not complete algorithms (i.e, a solution may not be guaranteed). RRTs instead guarantee a solution but the rate of convergence to a solution may not be determined. In general, such sampling based approaches have been show to be more efficient and are more widely used.

[4] https://cascadeuav.com/

Potential Field Methods

The above approaches focus on a network model of the C-Space and finding a route through a set of nodes. Instead, potential field methods look at the use of forces to direct the motion of a robot with a grid-based representation of the search space. Specifically, obstacles generate repulsive forces while the goal exerts an attractive force. The robot then moves as a particle under the influence of such forces which constitute the potential field. Based on this model, a number of algorithms can be applied to find a collision free path e.g., gradient descent, A* search, or standard breadth/depth first search methods. The selection of the algorithm typically depends on the amount of information available about the environment. For example, breadth-first search may be used if there is no information about the cost/ benefit of choosing the next best point. If more is known about the benefit of certain cells over others then A* or D* may be used.

A particular challenge for robots working in partially known or unknown environments is the fact that obstacles may be detected as the robot navigates the environment. Furthermore, algorithms such as A* do not scale well with large maps. Recent work on path planning for micro-UAVs (MAVs) introduced Receding Horizon Planning [525] which continuously plans trajectories within a safe flight corridor for UAVs. Their technique uses the Joint Point Search technique [409] to reduce the number of points to consider within A* search [664]. This technique is particularly useful in a uniform cost grid where symmetries can lead to A* evaluating many equivalent states and increase computation time. Other recent works in receding horizon planning include [273, 502, 574, 309, 342] and [555]. All these approaches look to provide collision-free navigation for different kinds of environments. For example, [342] look to build more reactive models that avoid the use of a map and apply probabilistic estimates of obstacles using depth information. Mohta et al. [574] actually demonstrate how systems using receding horizon control could combine a number of sensor feeds (vision, LIDAR, etc) to deliver a working platform that can navigate cluttered environments with no apriori knowledge about the potential obstructions. More recently, Zichao and Scaramuzza [853] proposed a system that could account for uncertainty in perception, thus building solutions that can more robustly estimate the state of the UAV and therefore plan more robust trajectories. While many of these approaches have been demonstrated to work in real-world trials as prototype systems, they are gradually being adopted by many commercial UAV manufacturers. A key driver for adoption is the wide availability of open-source code bases that include many if not all of the algorithms published on path planning under uncertainty.[5]

[5] A simple search on Github.com will reveal many ready-coded algorithms for UAV path planning, camera calibration, and collision avoidance as derived from published papers.

Chapter 8

Artificial Intelligence & Machine Vision

The ability for an autonomous system to think and collaborate independently from human intervention is a key requirement for future autonomous unmanned systems. In previous chapters we have already discussed how researchers are beginning to deploy artificial intelligence and machine learning to improve mission planning, radar and other UAS focused technologies. Artificial intelligence and the related field of machine vision are therefore key technologies and it's important to understand the state of the art in both areas in order to understand the potential benefits to UAS that both might help realise in the future. To that end the following chapter captures the current state of the art in swarm intelligence and swarm robotics as well as advanced recognition systems including computer vision, deep learning, object detection, image segmentation, generative adversarial networks and beyond.

8.1 Swarm Intelligence

Inspired by nature, *Swarm Intelligence* is the study of simple agents operating in large sets that can solve problems by interacting with each other and the environment. One of the benefits of decentralized systems, in general, is that there is no single module capable of affecting or controlling the whole system. Avoiding single points of failure is the main motivation to study agents that operate in a group with decentralized control.

8.1.1 Definition of Swarm Robotics

"A group of non-intelligent robots forming, as a group, an intelligent robot" is called *intelligent swarm* [223]. Throughout this document the term robot swarm refers to the concept defined above as an intelligent swarm. As the definition implies each agent in the swarm is not an intelligent robot but the collective of all agents is intelligent in a way that its behavior is neither predictable nor random [224]. It is not predictable because intelligent robots should have the freedom to choose for any decision and it is not fully random as we assume that its intelligence is not the result of pure random selection. "The study of how large numbers of relatively simple physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment" is called *Swarm Robotics* [668].

8.1.2 Advantages of Swarm Robotics

Robustness is the first advantage of swarm robotics to avoid single points of failure, assuring that the swarm continues to operate even when failures occur in some of the robots. Robustness is the result of:

- Redundancy; if a robot fails, there are other functioning robots that compensate the error.

- Decentralized control; one of the main characteristics of a swarm robotics system is that the robots do not have access to centralized control [241]. Robots interact with each other and with the environment and decide their behavior individually without having a central control unit.

- Simplicity; in swarm robotics, the robots are simple in comparison to single complex robots. The simplicity in the design of the robots helps the designer to easily detect anomalies of robots. Simplicity also helps in decreasing the costs and allows mass production of robots.

- Distributed sensing; the likelihood that the majority of the robots in a swarm have faulty sensor values is quite low making the swarm a robust sensing system as a whole.

Adaptivity is the second advantage of swarm robotics. The swarm is flexible and adapts to changes in the environment or the tasks. It is easier to reconfigure a system that consists of multiple separate modules compared to a large system with tightly coupled components. *Scalability*, as the third advantage, means that scaling the swarm size up or down should not largely interfere in the operation of the system. If the swarm density—the area divided by the swarm size—changes, then a direct impact may be expected on the efficiency of the system [403].

8.1.3 Local Information: Communication and Sensing

Robots interact with each other and with the environment. Interaction between the robots can be implicit or explicit. Explicit communication is a direct transfer of information between robots via a specific channel such as infra-red or Bluetooth. In implicit communication the information is inferred without an explicit engagement in interaction [367]. Robots also get an understanding about their environment using simple sensors (e.g., ambient light sensor) that provide the information needed for mapping robot states to suitable actions. An important characteristic of a swarm robotics system is that robots receive information from a limited range in their neighborhood. Swarm robots can only communicate and sense locally which is a precondition for scalability [241].

8.1.4 Collective Decision-Making

With no agent in charge of decision-making, how does a swarm overcome the chaos and reach a consensus?

Collective decisions are the outcome of competition among individuals for different types of information [356]. The probability of selecting an option raises non-linearly with the number of the individuals that selected the same option [260]. Starting from a random set of options, the positive feedback gradually leads the swarm to a consensus on a decision.

There are many collective decision-making strategies including the local majority rule where every individual obeys the dominant decision in its neighborhood [494]. Different varieties of majority-based decisions are introduced and tested on various robot platforms [767, 769, 768, 325].

8.1.5 Design Challenges

There are two levels in a swarm robotic system: *micro-* and *macro-level*. The micro-level is the level of individual robots and what they perceive, how they act based on their rules, etc. The macro-level is the level of the whole swarm as a group. Reaching from one level to the other might not be trivial. For example, on the macro-level we can define a task for the swarm to move an object in an arena. The design decisions on the level of individual robots (micro-level) may be to let the robots follow a moving light source to accomplish the goal defined on the macro-level [216]. Tasks are defined on macro-level and it is the duty of a designer to find the local control algorithm for individual robots so that the swarm successfully performs an intended task. There are studies that investigate the micro-macro link but a general approach for relating the features of the two levels stays as a challenge [404, 647, 402]. Another challenge is to understand the sources of a behavior in a swarm. It may often be unclear whether a behavior is caused by an individual robot, several robots independently, or interactions of multiple robots over time.

8.1.6 Swarm Robotics vs Multi-Robot Systems

We should clarify the boundaries of swarm robotics with multi-robot systems. It is not easy to distinguish the two fields by looking at the size of the system. A multi-robot system is a collection of two or more autonomous mobile robots [360] (e.g., soccer playing robots [318]); whereas for the swarm there is no consensus for a certain size among researchers [403], even though the term 'swarm' implies a large number. The difference is in the communication range and relying on local or global information. While in a multi-robot system there can be global information, in swarm robotics the information has to be communicated only in local neighbourhoods. Global communication with non-scalable technologies, such as wireless local area networks, is not allowed in swarm robotics. Any global consensus needs to be the result of local interactions. For instance, there is no access to a global clock for synchronicity in swarm robotics. The swarm has to reach synchronicity through local interactions and information rather than an easy access to a central clock.

8.1.7 Examples of Swarm Robotics Systems

There are a number of examples of swarm robotics systems within the literature. The projects Replicator and Symbrion demonstrated robots crossing a barrier to a charging station [470]. Other examples include the Swarm-bot crossing a gap [577] and the CoCoRo underwater robots [668].

8.1.8 Aerial Robot Swarms

Low cost of production and removal of single point of failure have not created enough motivation for applying swarm robotics into real world applications yet. Despite the interest in using large set of robots, for example in Amazon warehouses [863], the robots are not fully autonomous and they have access to central coordination. An application domain that might bring the missing motivation is using multiple Unmanned Aerial Vehicles (UAVs) or aerial robot swarms [284]. Researchers are now studying the challenges that lie ahead of multi-UAV systems. Some of the main challenges are task allocation and planning [513, 351, 734, 624], vision-based state estimation [563], path planning [277, 312, 218], transportation [557] in applications such as disaster management [556, 684, 333, 332], remote sensing [195, 407], and many more.

8.2 Advanced Recognition Systems

UAS platforms are used to recognise targets, obstacles, and scenes in order to carry out its mission to completion, while avoiding collisions, detection (in some cases), and to determine what course of action to take. Latest advances in computer vision systems and multi-sensor fusion techniques will soon enable platforms to orientate and act fully autonomously rather than rely on humans in the loop. In particular, here we cover the latest advances in computer vision and machine learning techniques used in UAS navigation and mission execution.

Detecting and understanding objects captured in images is a key task for UAVs. [490] present one of the earliest system architectures to integrate computer vision and machine learning techniques into a UAV vision system for airborne surveillance system. The typical task involves extracting features from images (sensed from across the electromagnetic spectrum) and determining whether the features can be used to recognise objects of interest. Combined with proximity sensors, GPS, altitude measurements, this can be used to reconstruct scenes in 3D, detect obstacles, and route optimally in an environment. While, [490] use a simple threshold-based technique to detect fires in the wild, [545] proposed an extended Kalman filter (EKF) that performs sensor fusion using GPS and machine vision-based data to support aerial refuelling of a UAV from a tanker. The solution generates accurate measurements of pose, distances between the tanker and the UAV, and the orientation of the two platforms. Corner detection algorithms are applied on images from a digital camera to calculate orientation and positions. Other approaches such as [520] also use lasers for object detection, and RGB image analysis (colour, markers etc..) to detect specific items in live video streams [180].

Applications of UAV vision are increasingly getting more complex, and going beyond taking measurements, raising alerts, or orientating the UAV. Indeed, applications will increasingly need higher degrees of intelligence that can capture the *meaning* or *semantics* of the scene around a UAV (e.g., as perceived through one or many sensors). In this vein, many new approaches based on Machine Learning (ML), and in particular, efficient Deep Learning algorithms based on GANs (generative adversarial networks) [375] and transfer learning, are being developed to provide on-board vision capabilities [568, 544, 774]. In the next section, we delve into more detail on the specific use of deep learning for computer vision.

8.2.1 Computer Vision & Deep Learning

In recent years, the state of the art in computer vision has become very tightly coupled with deep learning. Deep learning allows models to encompass several layers of abstraction; for computer vision this means the shallow learning of edges and textures which can be interpreted by models as human-recognisable concepts such as cars and faces. The rise of deep learning is due in part to the increased accessibility of large labelled datasets (essential for the training of deep neural networks), and improvements in computing power, notably the transfer from CPUs to GPUs, providing significant improvements in the speed at which large models can be trained [787].

The shift from traditional computer vision to the modern era of deep learning powered computer vision is best captured by the progress in the ImageNet competition (a very large dataset for visual object recognition, consisting of more than 14 million images across over 20,000 categories). In the 2012 iteration of the competition, a deep convolutional neural network (CNN) won with an error rate of 15.3% compared to the 26.2% achieved by the second-best entry - a staggering result for the time that arguably marks the start of the deep learning revolution [495]. The ImageNet Competition focused on the classification of images - assigning specific images into distinct classes, with the main target of the models being accuracy of classification. The use of deep learning within computer vision has now branched out into several other areas and we elaborate on the state of the art in the following sections.

8.2.2 Object Detection

The process of object detection encapsulates image classification but with localisation of objects, i.e. identifying objects within an image and providing a *bounding box* that surrounds the object in question. This can be extended to locating several objects within an image, with differing sizes and classes. Object detection is applicable in many domains, such as facial detection [830] and autonomous driving [275], and it is closely linked to further computer vision tasks such as segmentation and scene understanding. The persisting framework for object detection is to provide a *sliding window* over an image that finds regions of interest that may be applicable for image classification (covering both multiple scales and aspect rations), however recent efforts have investigated avoiding an exhaustive search over the entire image by using deep learning [523] with some promising results.

8.2.3 Image Segmentation

The goal of image segmentation algorithms is to assign pixels into semantic groups. Its extension beyond generic object detection with bounding boxes is two-fold: segmentation aims to provide much finer detection of objects in the image, but can also segment unknown categories (i.e. segmenting but not labelling) [396]. In a similar vein to image classification tasks, deep learning has rendered traditional methods of image segmentation (such as edge detection and clustering) obsolete, with many of the current stage of the art algorithms using variations on CNNs. For a comparison of object classification, detection and segmentation, see Figure 8.1.

Image segmentation also provides the foundation for multi-object tracking and object instance segmentation. This allows models to deal with several objects of the same class that overlap within an image, e.g. identifying individuals within a crowd as distinct objects rather than a single human group [785]. Deep learning for image segmentation has been applied heavily in medical image analysis, where it plays an important role in clinical diagnosis [501, 445, 573].

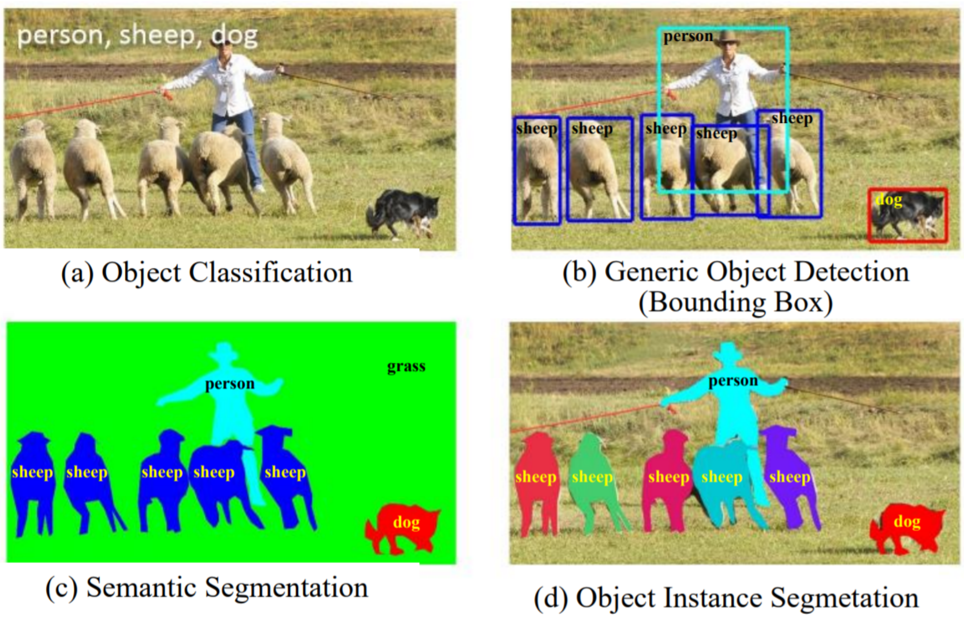

Figure 8.1: A comparison of computer vision applications for object recognition and localisation (from [523]). Note the improvement from (b) to (c): generic object detection suffers from an overlap of bounding boxes, but semantic segmentation does not.

8.2.4 Generative Adversarial Networks

A generative model is one that learns the underlying representation of a dataset such that in can produce new, unique data points that are similar to other elements of the dataset. For example, it is possible to create photorealistic images of fake celebrities by training a generative model against a dataset of real celebrities [463]. The most prominent generative methods within deep learning use generative adversarial networks (GANs). In this method, two networks are trained simultaneously, with one generating new images and the other attempting to discriminate if the images are real or fake [376]. Both networks learn simultaneously, resulting in a generator network that can produce new data that is indistinguishable from the original data.

GANs have been utilised for a diverse range of tasks within computer vision. Super resolution is the process of producing a high resolution image from a low resolution one, such that elements like texture detail are not lost at high upscaling factors; recent research has successfully used GANs to provide start of the art results [508]. An additional use of GANs is image-to-image translation, where a target image is converted to an image of another type, for example translating line drawings to fully rendered images or converting satellite images to maps [860]. For UAV or multi-UAV systems, this capability can be particularly useful in generating maps of a given area on-the-fly for human operators to update their missions or for the UAVS to coordinate their movements. The wide applicability of GANs is due to the deeper understanding they provide of the target dataset, allowing better semantic understanding of the relationships in the data.

8.2.5 Beyond Computer Vision

The area of computer vision does not stand on its own within deep learning. By combining the state of the art deep learning methods for computer vision with other areas of machine learning, it is possible to create even more powerful systems with wider applications. One such related area is natural language processing (NLP) - the family of techniques for understanding human language. When used in conjunction with NLP, computer vision can be applied to tasks such as image captioning [838], visual question answering [858], and text to image generation [819]. Going further, NLP can be used to support voice-based interactions between UAVs and their human counterparts. In Chapter 10 we elaborate on the variety of interaction modalities that are being explored.

Chapter 9

Protection Technologies

Protection technologies mitigate against known or anticipated threats, either to the UAS itself, or to the mission it is executing, and need to evolve as threats change and new threats appear. For UAS, protection technologies may be roughly classified under avoidance, mitigation and redundancy.

Avoidance, or stealth, attempts to reduce the likelihood that the UAS will be detected so that there is no attempt to actively interfere with the platform or mission; mitigation encompasses steps that can be taken to reduce or eliminate the effect of actual interference with the platform or mission, while redundancy attempts to reduce the effect of the threat by distributing essential functionality to avoid single points of failure. There is, of course, overlap between these approaches and successful protection probably uses several together, depending on a risk evaluation.

The following chapter reviews the state of the art in each of these three areas. Mitigation against electromagnetic interference e.g. jamming, spoofing and EMP is considered, followed by avoidance through signature reduction methods. Finally, redundancy is addressed, including through the use of swarms of unmanned systems.

9.1 Electromagnetic Interference

Electromagnetic interference (EMI), either accidental or deliberate, is probably the most common non-physical threat to the operation of UAS. EMI may affect either the navigation, communication or payload systems of the UAS, resulting in a range of effects from mission degradation to compete platform loss.

EMI can affect any electronic component in a system. EMI is a well understood discipline of electronic engineering, and any UAS subsystem that is expected to operate in an adverse EM environment should combine best practice EMI compatible design and physical shielding [263] [320]. EM shielding uses conductive enclosures to prevent radiation reaching susceptible components; this becomes difficult when complex shapes, or apertures are required.

Research is ongoing into new materials that provide robust shielding against EMI while being lighter and stronger than existing ones; Singh et al provide a good overview of work in this area [719]. Other materials that might be useful include graphene, and composites of graphene and related nano-carbons [442]. When EMI shielding materials are used as major structural elements, they may also help reduce the radar signature of the platform [630] [673].

When the EMI is affecting systems that are intended to receive RF energy, protection becomes more complicated.

BACKGROUND NOTES

JAMMING AND SPOOFING

Jamming describes the situation where relatively high powered electromagnetic signals interfere with the operation of the platform by saturating a receiver, preventing the detection of desired RF signals. Complete saturation is not necessary to cause problems, as any unwanted signal will increase the receiver noise and consequently the Bit Error Rate (BER) which in turn will reduce the effective data rate, potentially to zero. Jamming may be accidental or deliberate. Platforms with multiple RF systems require careful 'co-site' design in order to avoid jamming themselves [728]. The effect of jamming depends on how the platform is designed to behave when control and navigation signals are lost.

Spoofing is a deliberate attack on a target receiver, with the aim of causing the receiver to decode and act upon incorrect information. Spoofing is a particular concern for radio navigation systems where the signal at the receiver is very small, and can be overwhelmed by a locally generated signal which, when decoded, results in incorrect position information. Whereas jamming a global navigation satellite system (GNSS) signal can result in incorrect position information, spoofing can control what that incorrect position information is – effectively taking navigational control of the platform.

9.1.1 Jamming

Spread-spectrum RF systems are widespread as a countermeasure to jamming. Spread spectrum RF distributes the transmit energy across considerably wider bandwidth than required by the underlying data rates [861]. The two main spread spectrum techniques in current use are frequency-hopping and direct sequence.

Frequency hopping, as the name suggests, rapidly 'hops' a narrowband RF signal around in a bandwidth several orders of magnitude larger, according to a key-generated sequence [428]. This technique loses a small amount of RF energy when individual hops coincide with jamming signals, but the underlying assumption is that most signal energy will be received, and lost elements can be recovered using error correction.

Direct sequence spread spectrum (DSSS) modulates the narrowband data sequence with a pseudo-random spreading code sequence with a bit rate orders of magnitude greater than the data rate [861, 472]. The signal can be recovered by demodulating with the same spreading code sequence. In this case the signal energy is present across the full spreading bandwidth at all times, but only a tiny fraction should be lost to narrow band interfering signals, degrading receiver the signal to noise ratio slightly.

Ultra-wideband systems spread signal energy across a large part of the RF spectrum (significantly more than the spread spectrum systems discussed above) [310]. These systems tend to be very short range, as they use low transmit power in order not to interfere with other RF systems, and are capable of relatively high data rates. Reed [644] provides a good introduction to ultra-wideband systems. The non-interfering design of ultra-wideband systems means that it is also difficult to detect and jam these systems.

Spread spectrum and ultra-wideband RF systems are also used in applications where many transmitters are operating in close proximity, and rely on the low probability that two transmitters will share a frequency when operating with different sequence codes (frequency-hopping), or that a DSSS signal demodulated with the wrong spreading code appears as low level noise against the high level desired signal. Frequency hopping is central to the Bluetooth system [235], while DSSS (described as

Code Division Multiple Access, or CDMA) is used in UMTS 3G mobile telephony data networks [565], and GNSS positioning systems [504].

Frequency hopping is used in some military systems where deliberate jamming is anticipated [248], such Link16 with the US forces [88], [766]. It is noted that deliberate jamming technology is also developing (see for example, Zhang on a technique to identify the modulation used by low probability of intercept signals [848]), so there is a de facto arms race between jamming and jamming resistant technology (see Grover for a recent summary of jamming techniques and countermeasures [393]).

Free-space optics [178], has been proposed as a jamming-proof short-range communications option which uses modulated lasers to transmit data. For relatively long-ranges (100s of metres) these systems are highly directional and relatively large, requiring optical structures with accurate pointing maintained between transmitter and receiver. For very short range (10 metres) infrared wireless network systems using the Infrared Data Association (IrDA) protocols may be an option [34]. Free-space optical systems can be susceptible to local environmental conditions, being affected by water vapour and dust, for example.

9.1.2 GNSS jamming

GNSS receivers are particularly susceptible to jamming, either deliberate or accidental, because the receive signal is very low power so that the necessarily sensitive receiver is easy to saturate. The vulnerability of GNSS systems was described in detail by Volpe in 2001 [89].

Whilst illegal, it is easy to purchase a small GNSS jammer (for 'personal' use) for around $100 [90] and such devices have been implicated in major service outages at airports [91].

Volpe [89] recommended that the Loran terrestrial positioning systems be retained as a backup position and time source. Loran works with high power signals in a different frequency band (100 kHz centre frequency) to GNSS, but the support for the infrastructure is still patchy and the receive equipment is still rather large compared to GNSS. GPS World discussed the state of Loran and its applications in 2015 [92].

The main countermeasure to GNSS Jamming is the use of controlled radiation pattern antennas (CRPA) which use multiple receive elements to create nulls in the antenna radiation pattern, steered in the direction of the interference source [93]. Recent developments additionally steer high-gain radiation-pattern beams in the direction of individual satellites, providing even better jammer rejection[129].

While somewhat effective, CPRA require comparatively large antenna structures (for the element spacing necessary to generate the required radiation patterns) and intensive signal processing to detect and track the interfering signals. As such, CPRA antennas are usually only found on larger platforms where space and power are not a big problem (see the IAI ADA products for example [94]).

Although current CPRA antennas are large, there is some hope that metamaterial antennas [389] [181] may be able to cheaply implement large arrays of antenna elements that could be incorporated into UAS structures such as wings, while continuing improvements in signal processing hardware will allow the required processing to be feasible for small platforms.

There is significant research into signal processing approaches to interference mitigation for GNSS systems (for example Amin [183])and Inside GNSS has a good overview from 2017 [95], but these all require at least a workable amount of signal to be received, something which cannot be guaranteed, especially against deliberate jamming.

The deployment of new space-based satellite constellations such as Iridium, which provide a positioning signal, means that in future there could be a diversity of positioning signals on different frequencies available [96]; however, the signals will still be small at the receiver so deliberate jamming would be straightforward. Loran, and its variants, might also be used to diversify positioning sources and increase resilience [92]. An alternative 'protection' against GNSS jamming is to fuse together data from a range of sensors e.g. optical, radar, IMU, altimeter and avionics sensors in order to generate reliable odometry.

9.1.3 Spoofing

Spoofing describes the situation where an attacker causes a target to receive, and act on, a signal other than the one the target desired. The attacker effectively impersonates the desired signal to gain some control over the target.

The main defence against spoofing is signal authentication [182], which is usually implemented using cryptographic techniques. In many communications systems, especially wireless systems, data encryption is commonplace and serves protect the message content being observed by eavesdroppers [688, 336]. When data is encrypted in a closed membership network, correct cryptographic key management and distribution is sufficient to authenticate a signal – the encryption protects the data content, and the fact it was encrypted with the correct key authenticates the transmission.

Spoofing of GNSS signals is particularly concerning. Although some GNSS signals are encrypted [206], access to receivers capable of decrypting these signals, particularly the GPS M-code, is restricted. Most systems relying on GNSS today, and for the foreseeable future, use unencrypted positioning signals.

Spoofing of GNSS was demonstrated in 2012 at the University of Texas Austin [97]. Since then, there have been several incidents which implicate Russia in spoofing incidents against shipping around its border [98], and some speculation that the loss of a drone in the Middle East was due to a spoofing attack by Iran [99].

GNSS spoofing is difficult to prevent but the techniques described to protect against jamming are applicable. There is active research into detecting the existence of spoofing signals in real time (for example Psiaki [628]) although some of these approaches require additional antennas, special receiver hardware or additional sensors, such as IMUs [742] [743].

9.1.4 Electromagnetic Pulse

Electromagnetic pulses (EMP) are extreme events where short, wideband and very high energy pulses (potentially produced by nuclear explosion or solar flares) are produced. Protection against EMP is always at best partial, and usually focused on survivability, resilience and recovery. The guidelines from the US National Coordinating Center for Communications (NCC) are probably the best available overview of this EMI threat [100].

9.2 Signature Reduction

Technologies and techniques that reduce the visibility of a platform are referred to as signature reduction, and sometimes by the more popular 'stealth technology' (Samso [673]). Stealth usually refers to radar but also covers optical (camouflage), acoustic (damping) and thermal (shielding) visibility. The principles of signature reduction in platform design are well described by Zikidis et al [862].

Radar signature reduction uses a combination of techniques to design a platform which has a minimal, or misleading, radar return. Kumar and Vadera [496] describe materials that contribute to small radar returns while Qin and Brosseau [630] focus on microwave absorbing carbon composite materials. Graphene (and other forms of molecular carbon) is being investigated as a constituent of microwave absorbent materials by Munir [584], among others.

Plasma layers created around the platform absorb and re-radiate incident RF energy which makes them a potentially interesting stealth technology. Singh et al discuss the theoretical principles involved in plasma radar cross-section reduction [721], although it is not clear whether the engineering for practical application is close to being ready yet.

Metamaterials [101] are of interest because it seems possible that they can be fabricated as structural components of the platform while designed to actively disperse incident microwave energy (a bit like an inverse antenna) [331] [181]. Laboratory experiments have suggested that metamaterials can become completely transparent to microwaves, shielding anything within the metamaterial structure [269]. While exciting, such shielding technology is far from practical and only works at very narrow frequency ranges [752].

While stealth technologies are being applied, and continue to develop, there is concern that radar technology is outpacing them too fast for the more expensive approaches to enter widespread use. Passive radar techniques in particular appear capable of defeating the state-of-the-art airborne stealth platforms quite cheaply [804], while there is speculation that, should it be practical, quantum radar will also defeat stealth technologies [777].

When considering physical protection, a range of airborne countermeasures, such as flares and decoys, are used by military and some civil aircraft (for example the Saab CAMPS systems [102]). These are probably too large for use by smaller UAS, but may be appropriate for larger platforms.

9.3 Redundancies

Redundancy, where important functionality is implemented multiple times, is a core principle of safety-critical systems, including avionics systems. As platform size reduces, the ability to provide redundancy is restricted by size and power constraints. Redundancy on UAS has been addressed by Hiergeist [420] and Duan [319] among others.

One topic that is attracting attention is how to maintain safety-critical performance as the aviation industry moves towards integrated modular avionics subsystems [614] and increased software functionality [421]. These concerns are equally relevant to UAS.

9.3.1 Swarms

There are many good reasons for using swarms [459], including providing sensor arrays and data fusion platforms. In the context of protection, a large number of relatively low cost UAS provide mission redundancy – the ability of the swarm to withstand a large amount of individual unit loss while still achieving the mission aims.

In this sense, redundancy is the opposite of protection: defences are overcome by attrition rather than stealth with low cost [103], possibly improvised payloads [539]. There is an argument that the 2019 attacks on Saudi Arabia oil refineries meets this low-cost, improvised payload UAS swarm scenario [192], even if there were no significant air defences systems to be overcome.

Chapter 10

Collaborative Robotics & Human-Machine Teaming

No matter the form that a future UAS may take, a requirement that will never go away is the need for interaction on some level with humans. Predominantly this interaction takes the form of an instruction which defines a task or mission for the system to perform. However, other forms of interaction also exist, for example, where humans and machines collaborate to complete a mission. A thorough understanding of the current research in this area is therefore necessary in order to predict the possible future directions that human machine interactions may take.

The following section begins by reviewing the current state of the art in human-UAS interactions considering, for example, gesture, voice and brain-computer interfaces. This is followed by a comprehensive review of the state of the art in collaborative robotics and human-machine teaming.

10.1 Interaction Modalities

The traditional mode of interaction with UAVs (whether rotor-based or fixed wing systems) have focused on the use of joy sticks for granular manipulation and way-point-based routing through ground control stations. In recent years a number of approaches have emerged that attempt to provide other ways to interact with UAVs, for example, using speech, hand or body gestures, or virtual reality-based approaches. There are a number of circumstances where such interaction modalities could prove to be more useful than using joysticks or touch screens:

- Freeing a pair of hands (holding an RC-controller) or just one hand allows an operator to do more tasks.
- When operating in communication denied settings, visual or audio-based methods of interaction become more valuable in close-range interactions (i.e., human operator and UAV are co-located).
- High-level voice-based directives (e.g., move to a safe area, or take a picture of the target) are better undertaken by the UAV with minimal intervention, leaving the human to focus on other tasks.

In this respect, a number of approaches have been proposed in the last few years. We first focus on interaction modalities that are non-invasive (e.g., gesture, voice) and then go on to survey advances in brain-computer interface research.

10.1.1 Gesture & Voice

For example, Shan et al [701] develop a gesture-based interaction modality for collocated flying robots and drawing upon methods used in falconeering. [585] focus on localising human operators and detecting specific hand gestures. Both approaches were demonstrated to work on Parrot AR Drones using the onboard cameras. Pfeil et al. [620] show how upper body 3D spatial interaction metaphors for control and communication with Unmanned Aerial Vehicles (UAV). They carry out a study using Parrot AR Drone and Microsoft Kinect. They use a number of metaphors (i) first-person interaction where the user acts like a winged aircraft, (ii) a game controller metaphor where the hands mimic the movement of a joystick (iii) proxy manipulation where the user manipulates the UAV as if they were holding it, and (iv) a pointing metaphor in a similar vein to falconeering. Cauchard et al [266] followed up with a Wizard-of-Oz elicitation study that informs how to naturally interact with UAV and they show that gesturing tends to be a natural way to express specific instructions (e.g., start, stop, move closer). Body gestures are the least preferred mode, particularly because of the exhaustion they can cause and the variability in pose across different operators. In general, these gesture based approaches rely on very accurate detection of gestures, that can adapt to different operators' hand or body movements. This places significant constraints on the environments within which such interaction modalities can be used, which, more recently has pushed researchers to look at multi-modal interactions with UAVs. In this vein, Abioye et al. [163] introduced multi-modal interactions with UAVs whereby speech and hand gestures could be used to manipulate a UAV. Their system was shown to be more robust to environmental conditions such as low light conditions which would affect the gesture recognition system. Voice-based directives are also demonstrated to be particularly useful in issuing high level commands under the assumption that UAV is able to automatically avoid obstacles and guarantee safety around it.

Costantini et al [287], go further to consider emotional exchange through different channels: face muscles, body posture, voice modulation, skin responses, odors, etc. They show how a number of these channels can be measured using wearable sensors. This results in a system that is more empathetic to human needs and stress levels. This 'empathetic' aspect of interaction modalities is key if we are to deploy large swarms of UAVs while minimising cognitive workload (as we will see in Section 10.2. In particular, it is important to design systems that can adapt their input modalities (or feedback) based on the mental state of the human collaborators. In this respect, in the next section, we review work on brain-computer interfaces which have shown some promising results.

10.1.2 Brain-Computer Interfaces

Brain-Computer Interfaces (BCIs) rely on neuroimaging technologies such as the Electroencephalogram or Functional near-infrared spectroscopy (FNIRS), to help assess cognitive and motivational states of human operators. FNIRs in particular has been shown to be particularly appropriate given its low cost and being non-invasive (requiring only a light headband in some applications).

Several works have demonstrated that neurophysiological variables can be good indicators of cognitive activity [612, 806]. Going beyond providing measurements of cognitive workload, spatial working memory and other brain functions [196], BCIs provide an exciting opportunity for human-machine collaboration by virtue of being able to recognise when both cognitive workload levels and human intent. In particular, in the past, BCIs have focused on systems that help those suffering from neuromuscular disorders resulting, for example, in locked-in syndrome [627]. Typical applications include the virtual keyboard and the P300 speller [267]. However, BCI technologies are likely to make a significant impact in more advanced real-time brain-controlled robotic systems. Some of the most common applications include robotic wheelchairs and exoskeletons in the health domain. In the same vein, due to the high cognitive workload faced by UAV operators, BCIs are being developed to help reduce operator workload and drive systems with low operator to vehicle ratios. BCI interfaces are still in their infancy and research is being done in order to determine both the neurological measurements that can be used for robotic control and interaction mechanisms that support smooth interactions between humans and autonomous agents, depending on the architecture adopted (e.g., man-in-the-loop v/s man-on-the-loop).

A BCI is particularly useful for high-level control elements (e.g., routing, adjusting course, choosing targets) rather than having direct control over inner-loop elements that involve fine grained navigation parameters. In particular, the interpretation of commands via a user-interface powered by a machine learning system (that interprets signals from a BCI) plays a central role in the control loop. BCIs could be complemented by other wearable technologies such as eye-tracking, or gesture recognition (see previous section).

The challenge in designing BCIs for UAV or multi-UAV control requires an understanding of biomarkers used by different BCI technologies. These biomarkers can effectively be categorised in terms of 'evoked' or 'induced' potentials. Evoked potentials are those that are generated by external stimulus. All other biomarkers are induced potentials. Recognising the difference between the two can be difficult and requires significant amount of training of machine learning algorithms to ascribe intent to specific biomarkers. For example, most evoked potentials are shown to be linear in behaviour, have short peaks, and are consistent across subjects while induced potentials tend to be non-linear, have shorter peaks, and are subject-specific [598]. These can result in poor performance of BCIs, particularly in the UAV control domain. As a result, there has been a push to create hybrid systems that couple BCIs with other wearable technologies as well as autonomous decision-making, effectively using other ways of transferring information between humans and machines, while also providing more options to confirm or reinforce control actions predicted by other sensors.

10.2 Collaborative Robotics & Human-Machine Teaming

Man-machine collaboration has been a growing area of research since the seminal work of Sheridan in the 1960s [337] and more recently by Goodrich et al. [378]. The latest reviews by Miri et al. [570] and [763] have summarised some of the main open issues and challenges relating to collaborative robotics, human machine teaming, with emphasis on the manufacturing/production environment. In relation to human-swarm interaction, Kolling et al. [487] provide a deep survey of swarming approaches and the interactional issues they raise. We elaborate on these in what follows, as well as new approaches developed for human-machine collaboration to manage multi-robot teams.

10.2.1 Interacting With Multiple Robots

Indeed, [602] provide a framework to study interactions with multi-robot systems. Interactions in such settings tend to break down as follows, where each takes a portion of time:

1. Robot Monitoring and Selection - assess the state of each robot and deciding which one to monitor or control.

2. Context Switching - when shifting attention to another robot, the user must understand the context within which the robot is deployed and the goals it is trying to achieve.

3. Problem Solving - working either on her own or with decision support aids, the user must plan paths or decide on the next best steps for the robot.

4. Command Expression - the user may need to manipulate the robot in case it has a low level of autonomy or give it a high level set of goals to achieve in case it has high levels of autonomy.

The total time dedicated to all these activities form part of what [602] call the *interaction time* which, along with *activity time* (i.e., the amount of time the robot does its work), help define the concept of Fan-Out. Fan-Out is a ratio of activity time to interaction time and is effectively a measure of how much human attention is useful in helping all the robots accomplishing their mission. A high interaction time and a low activity time would lead to a low Fan-Out measure, indicating the human may be quickly overloaded. The Fan-Out model can be a good method to measure the effectiveness of human-machine teaming in terms of a cognitive complexity measure but can be difficult to use to design new systems as it only provides clues as to where the key interactional challenges might be without explicitly revealing the causes.

To reduce interaction time while still providing some level of control to the user, Miller et al., [567] develop a 'Playbook' of tasks for automated agents to perform when faced with certain situations (upon request from human controllers). Similar to a football team, the robots try to match the context they find themselves in with an appropriate plan that involves actions for each individual member of the team. Once they complete their tasks, another play is selected depending on the state reached. Such an approach is commonly used in defence settings (for human teams) to simplify the planning process and define predictable behaviours. In a similar vein, [377] study how different levels of autonomy (as per [706]) given to teams of agents can impact on performance and workload. Specifically, they show that reliance on team autonomy (i.e., a team allocates tasks amongst its members independently of human control) results in neglect from the operator though it reduces workload. Hence, they suggest there should be shifts between different levels of autonomy as per the requirements of the tasks.

Cummings et al. [291] evaluate a mixed-initiative system with a single pilot and with an auction-based task allocation scheme. However, they focused on how *often* an operator should be asked to re-plan, and through a set of lab studies, show that operator performance with too many frequent re-planning requests. Tasks are generally specified and the UAVs (acting as bidding agents) create allocations of tasks by themselves based on the context (e.g., position of UAVs and tasks) and can offer to the pilot to replan (by applying the task schedule offered or constructing one manually, or adjusting the one offered.

While the above solutions typically experiment with a team of UAV operators at a single location, Franchi et al. [343] instead develop a control framework to allow a group of UAVs to be controlled by two groups of operators. Their framework is shown to allow for decentralized topological motion control which effectively ensures the UAVs have coordinated trajectories. Furthermore, they show how autonomy can be adjusted based on the tasks faced by the team of UAVs. They also consider how individual UAVs can be Finally they show how force-feedback can be used to improve the telepresence of the human assistants. Specifically they show how haptic cues can be used to indicate UAV behaviour.

Finally, Ramchurn et al. [637] present a study of human-machine collaboration whereby a swarm of UAVs need to be controlled by only two commanders to carry out search and rescue missions. They demonstrate how multi-agent coordination algorithms can be used to recommend efficient routes for sets of UAVs (where their capabilities may be complentary), particularly in situations where UAVs may drop out or new tasks are discovered. They show that significant challenges remain in translating human intent into plans that can be assimilated and executed by such multi-agent techniques. They also show that interfaces designed to support human-machine collaboration need to be designed to be more responsive to operators' cognitive workload and task focus. While their scenario is limited to no more than 5 UAVs, their conclusions can be extended to robot swarm systems which, in addition to workload challenges, also imply many more control challenges as we see next.

10.2.2 Human-Swarm Interaction

Swarm robotics originate from research in bio-inspired computation. In an attempt to recreate the highly resilient behaviours that exist in nature, researchers have developed a number of swarming models: (i) using computational models of animal or insect behaviours (e.g., flocks of birds, or groups of ants) (ii) physics inspired models [782] or (iii) control theory driven [361]. The typical swarm characteristics include short range communication, use of simple decision rules rather than explicit communication, and high scalability. A typical metric of performance of a swarm is Neglect Tolerance [290], whereby a robot's performance degrades if the robot not monitored for some time (i.e., neglect time). Along with this, a measure of the time of interaction and frequency of such interactions can be used to measure the workload of swarm operators.

Models of interactions with a swarm have focused on minimising the number of operations required to manipulate members of the swarm. Specifically, a key goal is to ensure that swarms reduce the interaction to specifying a few parameters or goals that does not grow with the number of agents n (i.e., $O(k)$ where $k \in \mathcal{Z}$ rather than $O(n)$). This is different to interactions with multi-robot systems where supervisory control is used and can be much more complex (e.g., manipulate individual limbs of a robot or orientate a camera for a specific robot). This is particularly harder in the context of human-swarm interactions due to the added complexity of swarm behaviours and interaction modalities. Kolling et al. [487] summarize key approaches that have been proposed to interact with swarms as follows:

1. Switching or optimising the swarming algorithm to use: a swarm may use a number of models (bio-inspired foraging models or flocking behaviours, or even leader follower behaviours) and the operator may choose to switch between them depending on the needs of a task.

2. Parameter adjustment: this involves tuning a given swarm algorithm (E.g., reducing the speed of the robots, or increasing the frequency of communication).

3. Environmental influence: this may involve adding constraints on passable areas or pheromone trails that decay over time to induce adaptive changes.

4. Leader-follower manipulation: picking a specific robot and driving its behaviour with either explicit (where others are meant to follow it) or implicit (where others do not know it's a leader) impacts on the behaviour of the swarm.

These different approaches can be difficult to design using traditional models of supervisory control or teaming as proposed by [337] or the PACT framework [623]. Indeed, traditional human-machine interaction principles can be difficult to translate to a multi-robot setting or swarm settings due to the emergent nature of behaviours resulting from coordination between robots or swarming algorithms used. In particular, the communication restrictions, the complexity of the robot states and their joint beliefs, as well as those of their human counterparts can present significant challenges for engineers to design systems of humans and machines that work in a predictable way.

In terms of UAV control, the seminal work by [515] developed and trialled interfaces to help operators interact with large numbers of UAVs (hundreds). The platform is tested with experts and is shown to reduce the workload of operators by automating target detection, (re) planning through a set of user-friendly widgets.d Bertuccelli et al. [228] instead, developed operators models for UAV control and, under simulations, study the performance of their 'human-in-the-loop' algorithms whereby operators are unreliable detectors and the algorithm may not perform well in search tasks. In [229] they experiment with re-queuing models for visual search tasks and help reduce operator performance drops. In a non-UAV setting, Kolling et al. [487] develop an interface for human-swarm interactions (for different models of swarms including bio-inspired). They identify two types of interactions: (i) Proximal interactions: observe part or whole of swarm and swarm can directly interact with the human (ii) Remote interaction: centralised control by a human. They go on to discussing the challenges of state estimation and visualisation, based on which a swarm can then be controlled by one or multiple operators (e.g., allowing them to select different algorithms or setting different parameters or even directly influencing their environment).

10.2.3 Human-Machine Teaming

In this section, we focus on human-machine teams where there are may be more than one human and more than one machine in the team (i.e., a team of three or more). To conceptualise such teams, Jennings et al. [450] proposed the paradigm of Human-Agent Collectives (HACs), systems involving humans and machines working in partnership, where neither human nor machine may always be in control or be willing to collaborate (i.e., there may be self-interested parties involved). They define four key aspects of HACs: (i) Flexible Autonomy: control may shift between humans and machines according to the needs of the situation (ii) Agile Teaming: teams of humans and machines may form and disband over time and interactional arrangements between them may also change (iii) Incentive Engineering: incentives may need to be provided to co-opt rather than coerce actors into working for the benefit of the whole team (iv) Accountable Information Infrastructure: the data generated by individual actors and decisions made are tracked and audited to guarantee the system is working correctly and safely. This framework can be used to characterise large systems of humans and machines and ensure that teaming, control, incentive, and accountability elements are factored in the design.

Specifically, work on HACs has led to a number of advances in human-machine teaming, focusing on planning support for emergency response teams [811, 638, 636]. Although there is much literature dealing with planning support, task assignment, and human-agent collaboration, very few real world studies of how human teams actually handle agent support have been carried out. For example, [807] propose a framework for humans to monitor large teams of agents and robots, but they ignore the interactional challenges when such teams need to work in different interactional arrangements (e.g., agent as commander or team member). Work by by [683] and [692], focuses on humans acting as peers to agents in computational simulations rather than real-world deployments in the field. In addition, many multi-agent coordination algorithms have the potential to be applied to support task assignment of responder teams. Indeed, work by Tambe et al. [748, 303] has shown how humans may be able to implement plans computed as solutions to a Stackelberg game. While their solutions have been deployed with various human teams (e.g., guards at Los Angeles airport or security teams in the Boston/New York/LA harbours), they do not consider how such plans can be generated in real-time in collaboration with humans (i.e., taking into account human input dynamically) nor do they study how humans react to plans suggested by planning agents. Controlled experiments designed by the Human Factors community have sought to identify key aspects of human-agent collaboration [240, 587, 735, 788], propose transfer-of-control policies to shift control between humans and agents [682], and evaluate strategies of agent support for human teams [514].

Ramchurn et al. [640] built upon such results and developed an initial prototype [639] of a human-agent collaboration interface for field responders. In that prototype, a human commander worked with an agent-based planner (using decision-theoretic multi-agent planning algorithms) to deliver instructions to players of a mixed-reality disaster response game. The *interactional arrangement* between the human commander and the agent-based planner was such that the agent took control of which instructions to send to field responders on the ground. Results of field trials of the system showed that field responders on the ground were not always compliant with instructions sent to them as the agent was not aware of their level of tiredness, their preferences for tasks, or their preference to work with specific team-mates.

In [638] they go on to develop a new version of the planning interface that provides better control to the human commander and people on the ground. As such, the interface allows for a less rigid collaboration model, in the use of the autonomous planning agent to suggest plans that can be refined by the humans. This is further evaluate with both experts and non-experts in field trials to determine its effectiveness. Building upon this, in [811] and [174], an algorithm and a platform are specifically designed for the deployment of humans and UAVs working in collaboration. Their results show that the algorithm is able to efficiently recover targets from a dangerous environment by ensuring that UAVs identify threats lying ahead of paths taken by emergency responders. The platform then demonstrates how such a system can be deployed in the field with non-expert users in limited scenarios. They also do not evaluate the performance of human teams in terms of cognitive workload.

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