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Design in Engineering: An Evaluation of Civilian and Military Unmanned Aerial Vehicle Platforms, Considering Smart Sensing with Ethical Design to Embody Mitigation Against Asymmetric Hostile Actor Exploitation

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Anonymous: Sir Richard Grenville, unknown artist, a version at the National Maritime museum (Royal Museums Greenwich.

"*Never give-up, never surrender*." Captain J Nesmith.

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THANKS

Firstly I would like to mention Captain JRA Woodard ADC RN, BRNC, and Professor Alan Myers, Director of Studies BRNC, without whose support the initial application to CCW, and the project's entire enterprise, would have foundered at the start. I would also like to thank Professor Greaves, on behalf of Plymouth University's Faculty of Science and Engineering, for their financial support in this project. I am extremely grateful to Dr Rob Johnson, and the whole team at the *Changing Character of War Centre,* Pembroke College, Oxford, for the opportunities, and access to military related-resources critical to this academic engagement. Dr Johnson's help enabled me to progress much farther than I had anticipated in my passage from a scientific world-view to one embracing strategic, political, and international affairs. Face to face, on-line meetings, conversation, and emails with several of the other Fellows had their part to play, and I would particularly wish to thank Mark Sutherland for an introduction to military training, Will (Foreign Office) for terrorism-related issues, and Al Brown for just really interesting and helpful connection! At Pembroke I could not have done without the college IT and SALTO support afforded from Mrs Liz Robson, and during CV-19 visits live conversation! I am also indebted to Laura Cracknell in the McGowin library for help navigating the college library- I was noisy once. The difficulties of conducting this project during CV-19 were mitigated by the beautiful college quad environment, conversations with Richard the gardener, frequent trips to *Farthings Café*, and when necessary visits to the *George and Danvers* round the corner.

My thanks again to One and All.

[11] *The words of the wise are like goads, their collected sayings like firmly embedded nails—given by one shepherd.*

[12] *Be warned, my son, of anything in addition to them.*

Of making many books there is no end, and much study wearies the body.

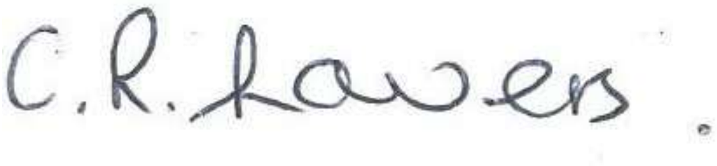
Ecclesiastes 12:11-13 New International Version.

OVERVIEW AND RATIONALE FOR THIS WORK

This report is written in part-fulfilment of personal output criteria for the Visiting Research Fellowship (Sir Richard Grenville Fellowship) at the Changing Character of War Centre, Pembroke College, Oxford, and the Centre for Sea Power and Strategy, Britannia Royal Naval College, Plymouth University at BRNC, Dartmouth. This was my first sabbatical since joining BRNC in 1993, and has proven extremely valuable, providing opportunity to focus on military UAV platform design and countermeasures to support my research and current taught platform-related courses.

There is a growing existential threat posed by modification of civilian Unmanned Aerial Vehicles (UAVs) or 'drones' by hostile actors in society, be they disrupted civilian air flights at airports, guerrilla operations, terrorist UAV IEDs, or conventional state warfare at the other end of the hostilities spectrum. The Fellowship arose from a concern that has been growing in my mind that readily available small Commercially Off The Shelf (COTS) UAVs could be modified for hostile actor operation in both conventional and urban warfare. In this regard I wanted to examine this proposition, explore and then propose *potential* platform design safe-guards which might be put into place to mitigate such threats. To support this objective I undertook an in-depth industry wide consultation from 'production line to user' across the UAV manufacturing industry, one does not always know the mind of those at the other end, and less so of countermeasures providers. We gain insights into the 'end to end' perceptions of manufacturer, user, and from a countermeasures provider's perspective. Although, countermeasures and drone tactics will be covered elsewhere outside the scope of this report. In this process I have developed interdisciplinary connections across the traditional humanities-science divide. The Fellowship, was spread across academic years 2019-2020 (Trinity term) and 2020-2021 (Michaelmas and Hilary terms). The report was written up during the 2020-2021 Hilary term, and helped me develop an emerging naval and maritime drone syllabus to include ethical exploration from design to operation. I consider possible embodiment of smart features: self-repair, fast-switching liquid crystal optical reflectivity modification, advanced materials, and embedded skin sensors, into the design process.

I have a unique position at the boundary between UK and Overseas military and civilian maritime activities. The Fellowship provided opportunity to develop links between Britannia Royal Naval College, the Dartmouth Centre for Sea Power and Strategy, and the Changing Character of War Centre, Pembroke College, Oxford, through which I have established a new professional network of personal connections. The project, report and related research papers were conducted against the challenging backdrop posed by the national response to CV-19.



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An Evaluation of Civilian and Military Unmanned Aerial Vehicle Platforms, Considering Smart Sensing with Ethical Design to Embody Mitigation Against Asymmetric Hostile Actor Exploitation

Abstract

In this report I undertook an extensive analysis of the maritime UAV platform systems sector of a wide range of upstream manufacturing industry and downstream end user stakeholders. I consulted a global range of military and civilian users, to inform discussions around civilian UAV platforms which could be modified by hostile non-state actors, with emphasis on the littoral maritime region. This has strategic relevance to the United Kingdom, being an island-state with over 10,000 miles of coastline, c. 600 ports, and nearly 300 off-shore oil and gas platforms. In addition the UK has 14 dependencies together with a combined EEZ of 2.5 million square miles, the fifth largest in the world.

This work followed developed protocols from previous space-based sensors research analyses including Airbus (2016-2017), and a wider evaluation from space-industry responses from a specifically designed 'questionnaire' method **[1].** I applied this methodology to summarise (2020-2021) UAV research findings, captured from a wide range of participants; I evaluated the *perception* of key design parameters in multi-dimensional platform design, and results are taken as representative of sector opinion. My analysis covered: the importance of persistency, all-weather, night and day capabilities, and other technical requirements. In 2011 John Vilasenor stated '*There will be imitators – crude at first – but better and better, and while reasonable people can disagree on how long it will take for terrorists, insurgents and other rogue groups to build or acquire weaponised drones that can be guided by video straight into a target, there is really no dispute that it is a question of when and not if. The day will come when such drones are available to almost anyone who wants them badly enough*' **[2].** It is this exploitation possibility I chose to investigate.

Nonetheless, I set some boundaries to the discussion, namely to **exclude** significant discussion of Lethal Autonomous Weapons Systems (LAWS), and Artificial Intelligence (AI) which although relevant to military grade drones are not a realistic short or medium term achievable for terrorists, guerillas, or insurgents. I also **exclude** underwater, and space, although some points relevant to UAVs do apply to one or more of these platform categories, with the greatest constructive alignment between space and air, for pseudo-satellite systems such as *Zephyr*.

I looked to develop a methodology and mechanism to facilitate users and manufacturers to express their thoughts on the embodiment of '*ethical*' values and design importance into civil platforms, and to integrate their workflows seamlessly through to countermeasures requirements if possible. The concept of Value Sensitive Design (VSD) was identified as the most relevant method for ethical embodiment within civilian UAVs, to evaluate and prevent non-state actors *easily* modifying platforms to their own drone purposes **[3]**. I wanted to examine if there was a Work plan that might be mapped out, a process put into place, to provide design safety protocols which limited exploitation. Questions arise when considering countermeasures, starting with what *are* the adequate measures, and those which may reasonably be put into place to detect, track and identify drones, and counter civilian modified UAV threats. However, this project report findings will focus on physical platform modification, whilst countermeasures will be discussed in a separate paper. Removal of the exploitation threat at the start of the design process would be the ideal pathway to follow if possible.

The key findings are that quantitative evaluation is possible with 3 dimensional analysis of: Endurance, Range and Mass, and could be used to limit platform exploitation. Respondent comments and Likert evaluation provides useful insight, especially with physical quantifiable factors. Likert evaluation is less consistent and clear for more abstract quantities. Improvements in robustness using smart composites: glass fibre, optical fibre with embedded sensors, or carbon nanotubes, is of more interest than 'green' materials in themselves.

The air domain offers key advantages within modern warfare, therefore it is important to look at what it is about COTS modified UAVs that make them an attractive option for terrorists, who today have unprecedented access to technology with an accelerating rate of changing technology. Past modified COTS UAV failure is no guarantee of continued failure, as first use of technology is rarely the most effective. As noted by Paul Scharre, '*the history of revolutions in warfare has shown they are won by those who uncover the most effective ways of using new technologies, not necessarily those who invent the technology first*.' [**4**].

We define a few key distinctive terms, namely: we will use UAV to include civilian platforms possessing *latent capacity* for weapons and payload delivery, and the term Drone if modified or existing military platforms. Other reports found that generic use of the word 'drone' is problematic, referring to different UAV systems designed for distinctly various purposes [**5**]. The military view of drones is they are mission systems rather than air platforms. Whilst, remotely operated UAVs in a military context are also known by the more frequently used term: Remotely Piloted Aerial System (RPAS), which was adopted in the UK to refer to a system or when referring to UAV platform only.

KEYWORDS: Unmanned Aerial Vehicle (UAV), Iterative Multi-dimensional Platform Design, Maritime Surveillance, Potential Tactical Operation, Insurgent Threats

CONTENTS

1. INTRODUCTION

1.1 The Changing Nature of Maritime Conflict and the UAV Threat Component

Maritime forces world-wide, are continuously engaged in modernising fleet capabilities and platforms; however in numerical terms Western naval forces have declined significantly since the Cold War, against the growing maritime capabilities of nations such as China. This situation is aggravated by increased operational tempo, which shortens the lifetime of ships, aircraft, and vital mission matériel. As such in attempts to overcome procurement pipeline problems the US Navy identified potential transformational leaps in platform technology, evidenced by vessels such as the Littoral Combat Ship (LCS), the DDG-1000 Zumwalt class destroyer, and the CG(X) next generation cruiser programs. However, the cost of these vessels is high and resulted in only three Zumwalt launches. US planners and others are also conflicted between the demands of major combat and those of existing operations. Maritime combat operations require high intensity sea control capabilities via. blue water ASW and AA warfare, and ballistic missile defence, carrying sea-based nuclear deterrence. Such operations are designed for combat with traditional symmetrical peer-to-peer competitors, not asymmetrical ones. By contrast stabilisation operations are often aimed at asymmetrical threats, which may require expeditionary warfare capabilities in brown water or littoral environments, to project naval and support forces ashore. These operations if they were to cease, may likely deteriorate local security very quickly. Stabilisation includes multi-layered maritime domain awareness, and it is into this complex sphere of often topographically constrained operations, that UAV platforms have measured appeal, to both conventional and unconventional forces. UAVs can impact several principles of war, namely their ability to swarm co-operatively, concentrating force to achieve decisive synchronised application of fighting power in offensive action, combined with the element of surprise. This was demonstrated in Nogorno Karabahk (Nov. 2020) with the augmentation of existing forces with weaponised and non-weaponised reconnaissance ISR UAV flights [6], supplied with Israeli Orbiter 1 'loitering munitions' and Turkish *Bayraktar-2* drones with an impact that was both swift and devastating. Turkish UAV capabilities have improved markedly since the 1990 Turkish Aerospace Industries' Inc. (TAI) UAV-X1 project. In 1995 an agreement was signed between the Ministry of National Defence and TAI for firing and tracking target drones as an air defence training requirement, to develop low-risk, low-cost and operationally flexible drones using advanced technologies. As a result the *Turna* firing target drone and *Keklik* tracking target drone entered service in 2001 [7]. Since 2004 Turkey developed the *Anka* (MALE), C*aldiran* (tactical) *Bayraktar* (fixed-wing mini) and *Malazgirt* (rotary-wing mini). Because of delays in *Anka* flight tests, MALE class *Herons* from Israel Aerospace Industries were purchased for border surveillance, signalling the start of a relationship which resulted in both nations supporting Azerbaijan. A *Bayraktar* TB2 has also been flown to Cyprus, claimed to '*protect ships drilling for oil and gas*', landing at Gecitkale airbase in Turkish Northern Cyprus, possibly motivated more by deteriorating relations with the West (December 16th 2019).

The ethical arguments and merits surrounding modified civilian UAV systems, or the potential benefits to asymmetrical actors from utilising captured military drones are discussed here, but it is beyond doubt that over the last decade (2010-2020), after 14,040 confirmed strikes, between 910-2,200 civilians were killed besides those individuals targeted by US drone strikes, demonstrating lethality **[8]**. For the past decade drones have helped fight enemies across the Middle East, transcending time, location and international borders. Much of the current debate about drones is whether their deployment to countries like Yemen and Pakistan is legal or ethical **[9]**. However, this is a mute-point as they WILL be used increasingly; the real questions are about *how* they will be used, and *how* their capacity for use might be more tightly constrained, ideally in my view at the design stage to prevent modification.

UAV technology developments have some drawbacks as they tend to be smaller than conventional aircraft, with limited fuel and energy storage capacity, and as such flight times tend to be lower than equivalent manned counterparts. In order to improve upon this shortfall, composite materials are taking a central role in the design and manufacture of UAV systems. Civilian, perhaps unlike military UAV platform design, should incorporate an integrated consideration of all philosophical, social and technological factors. However, there are major issues that must be addressed to design, and technologically embody ‘ethical’ platforms. The meaning of *Ethical* is not just ‘green low carbon design’, but one which reduces modification risk for ‘improper’ purposes. From a philosophical perspective we often reactive retrospectively to new game changing technology, considering new existential threats to the physical and psychological safety of military and civilians, and increasingly digital security and privacy. From a technological perspective we should incorporate ethics into design from the start, being proactive to integrate technology with better materials into our structural design, whilst considering equally practical issues such as: reduced environmental footprint, noise, and identification.

In terms of engineered products for humans they should be considered as social artifacts that generate new possibilities and risks; as engineers we must share responsibility for creating benefits, preventing harm, and avoiding unnecessary danger. Moral values, however poorly integrated into the design, will impact technological development. Personal ‘meaning’ and sense of ‘responsibility’ will still be present, even if a strict code of ethics has not been laid down. Hence the need for intentional design. Development of UAV/modified drone platforms presents a conflicted ethical dilemma in engineering. It has been said elsewhere that technological development warrrants cautious optimism – optimism, with caution. In this regard let us proceed to establish the perceived risk and what may be done to minimise this through ethical design: (*Ethics in Engineering Fourth Edition: MW Martin, R Schinzinger* ISBN 9780070540736).

Currently there is insufficient consideration, and lack of collaboration between ethics and platform engineering, combined with insufficient holistic consideration of the benefits and risks posed by modified ‘drone’ technology, and little exploitation of the emerging capabilities of newly available materials, for there to be a platform to be considered as truly an optimised ‘ethical’ drone. My project objectives were to explore, develop, and assess such UAV exploitation possibilities and propose solutions where possible, in the light of supporting evidence from research and the wider user community.

These objectives were:

1. To explore holistically, the benefits and risks of modified UAV and drone technology, framed from philosophical, social and technological perspectives, in part ‘capturing’ a snapshot of market opinion through our questionnaire and methodology. I focused on composite materials, self-sensing, healing surfaces and new structures exploring ‘known’ philosophical and societal risks in ‘ethical UAV design alongside ‘unknown’ considerations, integrating smart sensing technologies, and innovative structural material design. By ‘ethical’ I include reduced hostile exploitation design with environmental sustainability issues: green materials, natural woven fibres, minimal carbon footprint etc.

2. To utilise our questionnaire to provide qualitative and quantitative evidence-based metrics to formulate arguments about UAV technology developments which indicate their *realistic* perceived threat status. Ultimately this may allow us to proactively develop a ‘weighting’ to design ethical low exploitable UAV platforms for the civilian and military markets with optimum design based on chosen operating missions inputs, with focus on safety protocols, new structures and materials. Pro-active integration of ‘***low risk of exploitation’*** technologies at the start of the design process is desired.

3. To increase collaboration and dialogue between various key stakeholders: engineers, physicists, social scientists, military and civilians, and reflect on end-user aspirations for autonomous data processing in complex and ambiguous decision-making circumstances. In such situations platforms will be heavily dependent on machine-based learning. UAVs and Autonomous systems’ importance in hybrid warfare, blended with information age, smart technology will increase in coming decades.

4. To create validated design criteria that help stakeholders design ethical platforms to accepted standards without compromising competiveness, examining military and civilian *perception* of ethical design, sustainability importance, in industry driven by for-profit economics. To achieve this end designers must establish what criteria are available so philosophical and social considerations are embodied into platform design; and what impact these tools might have on product viability, e.g. would the imposed cost of a ‘safe’ platform upon civilian designers bankrupt the industry?

My thematic strategy to achieve these goals involved an appropriate iterated design questionnaire, looking with literature survey, expert witness conversations, and my primary research which supports design of an ethical platform. This requires an interdisciplinary approach; time spent on technological development as well as more philosophical/societal constructivist elements.

The questions that were asked to support these goals are given in **Section 5** with the full UAV Questionnaire attached at **Appendix 9.1**. Besides our responses from secondary stakeholders, and expert interviews, I also add my primary data where appropriate, as optical modelling and experimental data, to provide useful metrics, at how a small COTS platform may also be modified to be very low observable (optical).

1.2 Overall Research Methodology

The report research method followed is structured as follows:

A literature-based overview of the threat (**1.3**), covering hybridity and drone history (**1.4**), their benefits (**1.5**), and examples of modified UAV use (**1.6**). This is followed by a discussion of current UAV-related surveillance applications (**2.1**), details of application markets (**2.2**), current UAV platforms technical characteristics, classifications, and definitions (**3.1**), which precedes civilian and military platforms discussion (**3.2 - 3.3**). This is followed by a review of platform critical research trends (**section 4**) in terms of emergent technology, design factors and materials. Questionnaire design is discussed (**5.5**), followed by the completed/partially completed responses (**5.2**). Results and Findings are presented in **section 5.3**, with the summary in two parts, a practical list of recommendations (**6.1**), separated from the overall report conclusions (**section 6.2**).

1.3 The Modified Civilian UAV Threat

Widespread commercial and hobbyist UAV use has potential to dramatically alter not just civilian markets **[10]** but military ones as well, radically challenging traditional notions of security and safety with abilities to collect data, transport loads, and deliver ordnance. Such platforms are re-shaping surveillance, and the potential for exploitation by asymmetric warfare specialists. Commercial UAVs are typically built on small platforms, and use relatively cheap and readily available components from electronic shops. They have emerged primarily, but not exclusively, from UAV and quadcopter enthusiasts, and their creation has historically been subject to little scrutiny. Such platforms can carry multiple sensors, detectors, communications, and imaging equipment, and in an exploited capacity, ordnance. As modified 'drones' or Remotely Piloted UAVs proliferate they will change and challenge the military domain, and may be deployed for complex, hostile, and dangerous tasks [11]. Typical commercial UAVs are shown in **figure 1**. Currently battery life is the main limitation to widespread use, but for short duration activities, coupled with a lack of proper regulation (and inability of enforcement), they are advantageous to insurgent war fighters. Following deployment on global battlefields by various non-state actors, in weaponised and surveillance capacities, consumer platforms are now rightly viewed with security concerns. Consumer modified 'drones' have been deployed in: assassination attempts, transport of hazardous material and contraband, and imagery captured over sensitive sites **[12].**

Figure 1: Typical small commercial UAV COTS systems.

Due to advances in civilian markets consumer UAVs are developing in capabilities, with generational design *faster* than military developmental systems, in terms of intelligent flight, speed and manoeuvring abilities, which raises concerns around those deployed maliciously. Non-state actor operated drones include: modified COTS or self-constructed drones, which are increasingly present on battlefields **[13].** Drones have been deployed by various groups including Daesh, and Islamic State in surveillance gathering, in weaponised capacities dropping munitions and embedding them to later detonate (PKK and Hezobollah), to overwhelm enemy defences with small swarms, and to feature in propaganda **[14].** Recent successes in 'smashing' the centre of Syrian and Iraqi terrorist 'hubs' may only serve to disperse such technologies and attacks into a wider diaspora **[15]**. Remotely operated UAV implementation is not just a process of platform acquisition: it is a deeper revolutionary transformation of digital products, combining sensors inputs, with an enabling information architecture to develop coherent manned-unmanned 'teaming' to exploit the full potential of remote UAVs for maritime and littoral operations in real-time **[16]**.

Manned-UnManned Teaming (MUM-T) is now standard practice within the US Army. Teaming allows forces to maximise key asset use; the US Army operates its larger unmanned aircraft in combination with Boeing's AH-64 APACHE helicopter, feeding data to the manned rotorcraft for increased situational awareness. During MUM-T operations, the *Gray Eagle* or *Shadow* flies ahead of the APACHE assessing the risk status of the area before the helicopter enters it, minimising the chances of surprise attack **[17]**. MUM-T has led to development of the Unmanned or 'Loyal Wingman' Concept **[18]**. UK Qinetiq also demonstrated a manned helicopter and drone team operating for the first time in July 2020, over the British Army's ranges on Salisbury Plain, Wiltshire, UK.

Commercial and home-made UAVs have been modified and used by *Daesh* to conduct reconnaissance, filming, and direct attacks against Iraqi and Russian military bases in Syria. Concerns about the existential risks posed by such drones were further confirmed after the 4th August 2018 attempt to assassinate Venezuelan President Maduro at a military parade with two consumer DJI M600 COTS modified drones with 1kg of explosives. The remotely triggered C4-laden drone exploded mid-air, and was widely reported in the media **[19].** Was the event staged by sympathisers of the National Guard in Caracas who rebelled some time before, or survivors of the 2017 protests, where 100 people were killed, mostly by forces loyal to the regime? At this time no one is certain.

One drone in 2015 was fitted with a small amount of radioactive sand and landed on the roof of the Japanese Prime Minister's office, flown by an individual protesting Japanese nuclear energy policy. Unauthorised drones have been flow, largely with the aim of capturing imagery over sensitive sites, such as: the Colosseum, Eiffel Tower, White House, and various military bases **[20]**, with the UK reporting 37 security breaches in 2014 alone **[21]**. Alongside such drone deployment they have been used to great effect to disrupt transport infrastructure. In December 2018, Gatwick Airport suffered serious disruption for over 30 hours following report of a drone/drones over the airfield. At the time this incident impacted 140,000 passengers, and the unconfirmed platform operators continue to evade prosecution. Gatwick has since invested in drone counter-measures, the subject of a future paper. The cynical observer might consider that lack of evidence was simply a pretext to introduce countermeasures earlier rather than later. This type of drone-disruption is evident at other international airports: Heathrow, Chengdu, Lisbon, Tel Aviv, Delhi, Frankfurt, Wellington, Warsaw etc. In April 2019 circulated documents reportedly authored by the climate activist group *Extinction Rebellion*, detailed plans to deploy drones to disrupt operations at Heathrow Airport. Furthermore, the idea of targeting transport infrastructure with drones is founded on earlier disruptive planned attacks, such as the Japanese apocalyptic group *Aum Shinrikyo* who considered drone use, but in the end distributed sarin gas by other means on Tokyo's subway system **[22]**. Certainly Gatwick airport provided a critical point of reflection, and demonstrated the extent to which economic disruption at critical national infrastructure sites could constitute a national security risk. The US Department of Defence has looked to deter attacks against the Power Grid, but all infrastructural assets need to be compliant in this regard **[23]**.

Following disruption at Gatwick and Heathrow the UK government extended to 5km the area around airports in which flying of UAVs is prohibited. The Domestic Threat of Drones Parliamentary inquiry was a direct result of these events **[24]**. The session looked at ways in which the UAV-to-Drone (UtD) pathway is evolving, the UK's vulnerability to kinetic and non-kinetic drone attacks, and the effectiveness of counter-drone technology, with UK policy and practice. In the hands of an urban guerrilla or overseas trained terrorists, UtDs fit the mould of unconventional methods, allowing for specific targeting of political goals, attacks on government, media outlets, big business, as well as disruption, confusion, or assassination. Urban terrorists may employ drones to systematically inflict damage to authorities to distract, wear down, and demoralise a regime, sustaining operations and tactics without defending any recognised ‘bases of operations’. This tactic prevents conventional forces squaring off against them, a conflict in which they would almost certainly lose. However, with the essential element of surprise on their side, and acting for the shortest duration, with small swarms of drones, combined with local terrain knowledge, at speeds enemy ground forces will find difficult to match, drones may provide a potent guerrilla tactical advantage **[25]**. In deterrence, several UK military and civilian sites are being considered for testing counter drone technology.

Concerns have grown for the risk of biological and chemical attack, after recent chlorine gas dispersal over a political rally in Dresden, Germany September 2013 **[26]**. Such concerns were voiced by UK military forces and political leaders, with the British Army having assessed the 2012 London Olympics who thought it feasible a modified consumer UAV might carry poison and be deployed as a biological weapon in London **[27]**. Similar fears around radioactive material transported by drones into major urban areas exist for ‘dirty bomb’ style attacks **[28]**, although this is a low exploitation probability in practice due to lack of access to materials.

UAVs nonetheless, are being outfitted with a growing range of payloads. Besides cameras and sensors, some police and border force platforms have been fitted with pepper spray/tear gas (i.e. Israel and India), outfitted with flamethrowers (US and China), and grabbing claws (Japan). The likeliest exploitation route follows weaponisation of large agricultural pesticide fertiliser dispersal systems, weaponised for maximum terrorist activities. Enthusiasts have also added functionalities of fireworks, handguns, chainsaws, graffiti cans, paintball, flamethrowers and tasers in recent years **[29]**.

Figure 2: Throwflame - Introducing the TF-19 Wasp mini Flamethrower Drone https://www.youtube.com/watch?v=07rtBip9ixk

Consumer UAVs are available with in-built cameras or modular arrangements, allowing installation of various lightweight electronics devices [30]. Under current FAA regulations, they can only fly up to 400ft but typically require human pilot control in real-time during take-off and landing, as well as monitoring obstacle avoidance [31]. However, to insurgents or terrorists, there is little point going higher than this with modified COTS UAVS as the intent would be to send the drone under radar or visual cover, already with low Radar Cross Section (RCS), to exploit the element of surprise on unsuspecting enemies. Even UAVs not under enemy control are vulnerable in terms of navigation, to different types of GPS attack. *Spoofing* entails sending strong but false GPS signals towards a UAV, so it is 'hijacked' instead of following programmed directions **[32].** The UAV may be manipulated to crash, creating collateral damage, or flown to the attacker's location and modified. In the first instance it is possible for an innocent UAV operator to be held responsible for the consequences of a 'spoofed' UAV as it is hard to *prove* the origin of spoofed navigation signals, with significant disruption charged to an innocent party. The first successful UAV spoofing attack was achieved by the US Department of Homeland Security in 2014. Their controlled attempt was achieved with just US$1k of equipment. For now, military GPS uses encryption that renders UAVs invulnerable to spoofing, but are still susceptible to *jamming*. In a jamming attack, a UAV is overwhelmed with signals to its GPS receive antenna. Encryption ensures false signals are not mistaken for genuine ones, but real signals cannot get through elevated noise levels. Unintended collision may be a result in such situations. There have been several incidents that have caused losses without the owners of the jamming devices being found **[33]**. Besides attacks on UAV navigation, there is the issue of malign payloads, with the desire to design a platform so it cannot *easily* be modified to carry ordnance, by omitting weapons mounting points, as was the case of the UN Falco platform [34], and may be key to limiting exploitation. However, large unarmed civilian drones, with a mass of over 75kg falling out of the sky will be just as life threatening to civilian or military personnel as armed ones. Finally the cyber threat cannot be ignored, as today's drones require onboard computing systems, with on board and ground-based controllers vulnerable to malicious software or Maldrone (malware for drones) attack.

Technology Access

Two important individual-group technology characteristics shape tactical and operational decision-making, and constraining exploitation opportunities, namely: Access to and costs associated with modification of UAV technologies, and actor ability to develop expertise necessary to operate such 'bespoke' systems. For asymmetric attackers wanting to use new technologies, usually the technology sits elusively outside of their acquisition in terms of price, and lack of access via other actors (legitimately or from non state-actors). However, in the case of commercial UAVs, or 'bespoke' hobbyist systems, this is easy to achieve [35]. An actor's ability to develop their own expertise depends on the extent it focuses on the technology; this is easy to achieve as a nation state, less so for more dispersed but numerous insurgents, and much less so for smaller entities such as terrorist organisations or 'lone-wolf' attack. However, one successful attack even with minimal damage, falling short of planned fatalities, may still achieve significant propaganda or strategic goals regardless.

Inadvertent sale of such technologies should be avoided, and Non-proliferation is an issue raised since 2012 with the United States Government Accountability Office sponsoring a report to put in place information sharing with end-use monitoring of UAV exports [36]. The overall conclusion was the Departments of Defence (DOD), and the State, each conducted end-use monitoring of *some* UAV exports but not all, and differences in both agencies' programs *may* result in similar items subject to different scrutiny levels. In the contested space between Defence and Attack, the Defender often has to play 'catch up' and needs a long timescale of months to years to adequately put into place a process from non-proliferation through counterterrorism intelligence, law-enforcement, detection of terrorist activities, and both active and passive defence. In the event of an attack there is a need to detect and warn, and with an analysis of any successful attack with forensics, and other methods **[37]**. Whilst, the Attacker has greater flexibility in planning and staging, through surveillance and targeting, and has enhanced ability to escape the scene of the terrorist act entirely.

The unpleasant fact today is armed militant Non-state actors, can access capabilities, that were until recently, largely within the control of sovereign governments only **[38].** However, in most circumstances more effective alternative attack modes are possible than the modified UAVs can provide, due to practical limitations**.**

My Pembroke CCW Centre *Grenville Fellowship* focused on developing a 'strategic' overview of small civilian and potentially captured military platforms, for near to mid-future implementation (0-15 years). This project will help develop current advisory capacities in countermeasures support against drone attacks. Such attacks are increasingly of an asymmetric and hybrid nature, and although hybrid rule-changing warfare is not new, perhaps traced to the Peloponnesian Wars (431- 404 BC) in the writings of Thucydides, contemporary Athenian General. It is in the context of the modern digital information age that it is now seen as a decisive factor in achieving successful outcomes for military, paramilitary and non-state actors. The Peloponnesian War, by modern standards, was a small-scale conflict closer to modern asymmetric guerrilla-scale warfare, of a kind well suited to UAV tactics. The UAV, like its predecessors, the plane and tank provides mobility, speed and versatility. It introduces an abrupt paradigm shift with future potential for autonomous software-mediated war-fighting on multi-sensor platform 'swarms', is set to accelerate this type of warfare. Certainly, the time to field accessible new technology is less for terrorists with a 'try and see approach' rather than the long procurement timescales of DOD or MOD. In 'Countering Irregular Activity within a Comprehensive Approach,' **Rear Admiral Chris Parry**, **RN**, notes that '*hybrid warfare is conducted by irregular forces that have access to the more sophisticated weapons and systems normally fielded by regular forces'*.

One of the earliest often quoted uses of unmanned platforms was during the first Italian War of Independence in 1849 when the Austrian Army used unmanned balloons armed with bombs controlled by timer fuses, developed from manned military reconnaissance platforms from the Napoleonic era (L'Entrepremant at the Battle of Fleurus, June 26,

1794) during the French conflict with Austria. This usage followed just 11 years after the first flight of the Montgolfier Balloon, Joseph-Michel and Jacques-Étienne, in 1783, manufacturers brothers from Annonay in Ardèche, who engineered the first transparent paper manufacturing process. After 160 years of unmanned platform use we now see rapid proliferation of military and civilian applications, and between them via technology transfer. Most of these systems until recently were largely in the hands of governments, and private companies, themselves mostly Government funded by expanding surveillance and law enforcement. This activity has increased markedly during the global COVID-19 'lockdown' response, with civilian modified drones used in numerous ways **[39 - 40]**, following the lead provided by China's civil surveillance of minority groups such as the Uighur **[41 - 42]**, with wider implications for civil liberties today **[43]**.

However, the route to battlefield deployed drones was similar to developments of the balloon and especially the airplane, which began as a supportive role in World War I, in terms of artillery guidance and forward gun observation. The airplane was developed by two bicycle inventor brothers, Wilbur and Orville Wright, (1903), who were the first to achieve powered sustained and controlled flight, with the first practical airplane two years later. The first steps towards UAV systems was probably Elmer Ambrose Perry who combined auto-stabilisation, remote control, and autonomous navigation in the Curtiss Sperry aerial torpedo delivered by a powered unmanned aircraft in 1918, following earlier radio research by Nikola Tesla. Between 1930 - 1952 the Radiophone Company was instrumental for driving forward unmanned flight; founded by English actor and amateur aviation enthusiast Reginald Denny in 1939, with over 15,000 radio-plane drones used to train American anti-air gunners by the end of World War 2. The company was acquired by Northrop Grumman in 1952. In the 1950s the USAF and Army developed general surveillance drones, e.g. the SD-1 *Observer*, and in Vietnam 23 versions of the successful *Ryan* AQM drone flew 3435 sorties. The Gyrodyne *QH-50 DASH* was the first UAV launched and recovered at sea. DARPA's *Boeing Condor* became the first aircraft to make a fully autonomous flight, including take-off and landing, flying 51 hours at 55,000 feet in 1986. Whilst in the 1990s General Atomics developed the low cost *Gnat* system, followed by the *Predator*, which in January 1994 demonstrated the first 40 hours Endurance drone. By overcoming aviation problems encountered during

World War II, and driven by innovations within fields such as: rocketry, aerodynamics, propulsion, and electronics, the creation of the Air Force as a separate branch of the Armed Forces became possible. The overwhelming force multiplier of airpower matured in World War 2 through the wide range of missions in tactical, operational, and strategic environments it could provide. Air power allowed forces to strike effectively and decisively, penetrating the heart of enemy states for the first time. After World War Two the ability to maintain continued Allied air superiority was of great concern, and was operationally transformed by two key parameters:

Firstly a synergy of new technological innovations, tightly coordinated in time to provide decisive optimal applied power (e.g. the first synchronised wave of stealth aircraft in the First Gulf War within a 5 minute window), and

Secondly the consequent nature of modern air warfare changed the 'war fighting footprint' to the point today that there are no clearly defined battlefronts, nor distinguishable combatants. The distinction between 'civil and military' has all but vanished, with enemies embedded amongst local populations, putting war fighting into the public battlespace as never before, and with non-state aggressors able to hide amongst the civilian population. Saddam Hussein could hide his aircraft in an 'urban' context but military aircraft found amongst housing or under a flyover are NOT ambiguous targets, regardless of the ethics of whether they are targeted. However, today this is the domain of the 'urban camouflaged' guerrilla, and UAV platform deployment hides well within such an environment. Such platforms combined with small scale conflict 'Skills' gained in Syria and Iraq by Al Qaeda and ISIS, creates deadly camouflaged urban landscape threats. The effectiveness of small wars preparation in this regard is evidenced in the hybrid lessons as far back as the French and Indian War (1756-1763) which provided ample opportunities for future key War of Independence actors like Washington, Arnold, and Stark to 'gain their spurs' and later become 'Game Keepers turned Poachers' from a British perspective **[44]**.

The Case for Drones

General Charles Horner argued that the capacity of friendly and enemy forces, aims and their political goals, and environment, directs war. Air power *may* help achieve these ends by generating a disproportionate outcome for the level of force applied, to achieve strategic objectives from considerable stand-off ranges. Military power may be both a sharp and blunt instrument of national power, as well as an instrument of national strategy. Air power today combines military and civilian components, and is influenced by and influences in turn, politicians and society. The rise of autonomous platforms without human direction on the ground is incongruous with Clausewitz (**1832**), who argued war must be considered an instrument of policy, established with 'boots on the ground', and not an autonomous remote function. The use of coalition forces drones against Al Qaeda in the Arabian Peninsula had limited success in degrading their hierarchical structure, and only a temporary disruption due to elimination of some senior leaders **[45]**, or the recent Airstrike that killed General Qassem Soleimani, the head of Iran's elite Quds force at Baghdad International Airport 3rd January 2020 **[46]**.

Attempts to qualitatively assess Al Qaeda 'success' in this regard were inconclusive on whether drone strikes helped *or* hampered their initial objectives, due to the consequences after strikes took place, with potential further radicalisation and political fallout from collateral damage. In fact use of drones systematically, particularly by the Americans, in the Syria and Afghanistan theatres a) denigrated the hubs of the groups and b) forced dispersal into local insurgencies, which are hard to defeat using existing doctrinal orthodoxy **[15]**. However, the ability today to apply force at great distance remotely with long range weapons, e.g. the **Pegasus X47 B**, launched from an aircraft carrier, is a potent warning to potential aggressors. Until recently few would have considered drone power as providing more than assisting conventional war-fighting, with forward observation etc., but in the wake of the recent Armenian-Azerbaijan conflict, military planners and politicians are more aware of the war winning potential of drone systems, albeit in a small-wars context. Strategic effects cannot generally be expected to bring down political regimes, but the spread of UAVs will radically *remodel* the rules under which they operate and expand their arsenal.

The existential risk of civil war today provides some angst in both the France, and the USA, lent further pessimistic credibility by a recent interview with now retired French

General Pierre de Villiers, the former chief of staff of the French Armed Forces **[47]**. Any presumptions that this could never happen, should bear in mind the American Civil War, with the appearance of Southern urban guerrillas in the North, and the consequent Counter-guerrilla movement, such as the Unionist regiment Tennessee Cavalry under Colonel William B. Stokes **[48]**. The distinction in such circumstances between 'patriots', civil-war guerrillas, and insurgents is a difficult one, and typifies the difficulty today in distinguishing between terrorists and insurgents on the other hand **[49]**.

Further evolutions in technology, especially AI, may trigger a revolution in military use. The *nature* of air power may not change with adoption of UAVs, although its *characteristics* will. UAVs are a summation of previous incremental technological revolutions and system 'developments', but their *utilisation* and *exploitation* together may be considered an evolutionary shift **[50]**. The fundamental change that revolutionised air power upon which the Pegasus X47B relies, namely the birth of the aircraft carrier, synergistically combined manned fighter aircraft with a warship landing platform, and can now project maritime power offensively and defensively.

Irregular war, conducted against terrorism, and *by* terrorism with UAVs, has limitations; they do not survive well in contested airspace- a weakness still exploitable, by air defence, although of limited success in Nogorno Karabakh (2020), and they cannot yet be used in defensive counter air operations. As stated by the Vice Chief of the Air Staff of the United States Air Force noting these limitations in 2011, '*One has to remember that the current ISR fleet… is absolutely a permissive fleet… The Predator, the Reaper, the Global Hawk will not fly in contested (airspace) and will certainly not fly in denied airspace.*' The missing element of UAV survival in contested space with defensive posture may be achieved with AI methods, launched from autonomous surface combatants, may reach this point of revolution, of air war-fighting singularity.

Policy makers and military experts endorse the idea of drones revolutionising air power because it changes how the character war is conducted, transforming tactics, doctrines, and concepts which they may for a while seek to capitalise upon before a new 'equilibrium' is restored. Drones also reduce collateral damage when combined with precision, providing detection, relayed communications, sensors augmentation, and other capabilities. Future threats will determine the strategic, operational and tactical platform developments and contribute to future air power. 'Swing role' performance, where platforms can perform different tasks in single sorties, creates greater flexibility in mission assignment, and better value for money reducing the assembled force package required. This combination of capabilities within a single UAV will make them a game changer in air power implementation in multi-role modular designed missions on limited budgets. However, as quoted by RAF Squadron Leader Joe Doyle, who analysed RPAS operations in Iraq and Afghanistan between 2001 and 2010 he concluded, '*The limited and context-specific extent of this UAV "revolution" should warn against the premature replacement of manned capabilities in Western force structures and doctrine.*'

Drone or modified UAV systems contain several key elements, firstly there is no human operator on board, removing humans from a conflict or the danger to life zone; the platform operator may be remote to the battlefield. Secondly, civilian and most military produced systems are designed to be recoverable and reused where possible. However modified UAV systems, e.g. IED drones may be considered as a one off kamikaze system and costs should be kept low as a consequence. In this regard a 'certain' degree of hysteria was generated with the '*Slaughterbot*' Autonomous Killer Drones Technology video which role-played a terrorist organisation using UAV swarms with IED warheads to kill lecture halls of students **[51]**. Although, the main role of autonomy is to exploit the available high level of automation to reduce operator loading, allowing him to concentrate on specific tasks, whether to deliver lethal or more often non-lethal payloads: ammunition, blood **[52]** etc., or perform activities such as reconnaissance to achieve military strategic objectives. Nonetheless, '*The proliferation of inexpensive, small drones around the world is the most concerning tactical development, since the rise of the improvised explosive device in Iraq'*, remarked Marine General Kenneth McKenzie recently (Feb 10, 2021), amplifying concerns that dependable countermeasures do not currently exist.

From World War 2 the shift from large-scale forces to smaller, flexible, and adaptable forces works well with RPAS in new war fighting environments. Developments in Global Positioning Systems (GPS) has led to inexpensive and wide-spread precision navigation with low cost civil GPS receivers. Furthermore, UAV secure Beyond Line Of Sight (BLOS) relay communications is possible through reliable satellite networks, e.g. 5G-Starlink's, revolutionary network composed of thousands of NEO satellites. Use of modern digital software has led to reduced size and power requirements of military equipment, ideal for UAV platforms in terms of fuel requirements.

1.5 Benefits of UAV Technology Platforms

Traditional UAV designs are cheaper to develop and manufacture compared with manned aircraft. Furthermore, with less military personnel exposed to danger, and not jeopardising high value military assets, policymakers have greater freedom to respond to crises or react to challenges. By removing a key restraint of warfare, namely the risk to one's own forces, drones make conflict easier to conduct and military operations more likely, whilst eliminating the political pressure of not sustaining warfare, having a much lower threshold to conduct such activities, which is not necessarily a good thing. Conflict thresholds should remain at the highest possible level, leaving conflict as the method of last resort, if all other avenues of resolution fail.

Non-traditional or unconventional war fighting performance may lack accountability of action, especially when things go wrong, with unclear distinction between war and not war, the so-called *grey zone* **[53].** In the fight against terrorism this has implications. Professor Rosa Brooks (2015) argues '*there is no such time as peacetime*' anymore and that the '*forever war*' is here to stay. Many hostile measures and countermeasures - actions like sabotage, disinformation, and political destabilisation, - are Measures which fall Short of conventional War (MSW). State activities other than conventional or nuclear war may be applied against other states at any moment to gain advantage and reduce that state's capabilities or stability. Asymmetric war generates asymmetric needs and in as much as the UAV is a weapon for dealing with unconventional adversaries. It is also a potent tool in the hands of unconventional forces. UAVs will revolutionise air power in wars by and against terrorism, insurgency, or those involving guerrilla tactics. Pan-national terrorism, which crosses state boundaries with impunity, could turn an entire country into a digital-real world battlefield, and requires new countermeasures. According to Michael Evans '*The possibility of continuous, sporadic, armed conflict, its engagements blurred together in time and space, waged on several levels by a large array of national and subnational forces, means that ... war ... is likely to transcend a neat division into distinct categories*' **[54].**

Limitations of UAV Technology Platforms

The fallout from a downed UAV has reduced political consequences is less impacting than dead combatants. There is huge psychological difference between media and propaganda viewed at home showing dead bodies of USAF helicopter crewmembers dragged through Mogadishu streets (1993) and the surviving pilot beaten **[55]**, compared with the more recent USAF UAV shot down by Iranian forces in 2011, which resulted in Iranian claims that with reverse engineering they would soon copy US technology. There are a range of limiting issues relevant to deployment of modified UAVs, namely small size and weight, limited lifetime energy sources, available drone models, payload limitations, and restricted levels of autonomy, which we will discuss in the Questionnaire responses.

1.6 Examples of Modified UAV Use

Lone Wolf attack

In Sept 2011 a 'Lone Wolf attack' by a 26-year old man was arrested by undercover FBI agents planning to fly explosives-laden model aeroplanes into the Pentagon and US Capitol with rigged mobiles phones to detonate IEDs. In January 2015, an off-duty employee of the US National Geospatial-Intelligence Agency lost control of a friend's DJI Phantom quadcopter, which crashed onto the White House Lawn. Four months after this another man was arrested for trying to fly a *Parrot Bebop* drone (cost £700-900) over the White House fence.

Terrorist organisations

As early as August 2006 Hezbollah launched three small *Ababil* drones, some allegedly carrying explosive payloads, with intent to attack Israel military targets. The drones were shot down by Israeli F-16s. In October 2012, Hezbollah allegedly flew a small *Ayub* drone 35 miles into Israeli airspace to undertake reconnaissance on a nuclear reactor. In 2014, during Operation Protective Edge, Israel forces shot down a potentially armed Hamas-control *Ababil-1* UAV (Al Qassam Brigades), with a *Patriot* surface-to-air missile, with Israeli airspace incursions following, with the announcement in July 2015 that the Al-Qassam Brigades captured an Israeli *Skylark* 1 that came down in Gaza. They claimed the drone had been repaired and again operational. To Hamas, the small drone size was irrelevant– it was instead a subversion of technological dominance, kudos and victory over a high-tech 'Goliath' **[56]**. A statement from the group claimed '*this is a great achievement… and a gift to the Palestinian people… this demonstrates the strength of our people and its resistance,*' **figure 3 [57]**.

Figure 3: Hamas video aired on Aqsa TV purports to show a captured Israeli drone. Screenshot/Aqsa TV/Ynet.

Islamic State is also known to have modified a DJI *Phantom* UAV platform from reported imagery in Fallujah, Iraq in early 2014 for propaganda purposes, it can provide ISR and target acquisition to Islamic State **[58]**, with video released of UAVs used for reconnaissance and battlefield coordination during assault on the Iraqi Baiji oil refinery complex **[59]**. Islamic terrorist threats are not just a Middle East issue, *Boko Haram* according to the Nigerian Army, regularly uses drones in war fighting, and is recruiting foreign jihadists **[60]**. US drone use to downgrade terrorist leadership strategies to increase the probability of terrorist organisation failure or disruption, has been arguably partially successful in this aim **[15]**, the effect is diminished when used against a highly networked organisation such as Al Qaeda or IS. However, the same technology approach used by the US drone strikes in Yemen which markedly increased after 2010, can also be conducted by terrorist groups in response, e.g. use of a drone in Yemen to disrupt and kill senior military personnel at a very public parade **[61]**, **figure 4.**

Figure 4: **YEMEN Parade UAV attack.**

Insurgent groups

Donetsk People's Republic's (DPR) militias in eastern Ukraine reportedly possess and deployed sophisticated Russian-made *Eleron*- 3SV drones for its ISR campaigns. The Ukrainian military used a range of modified and tailor-made hobbyist UAVs for ISR support, and their militias experimented with GPS spoofing countermeasures and signal jamming against Ukrainian drones. An unconfirmed report from as early as August 2002, stated that a Colombian Army unit had discovered a number of remotely-controlled aeroplanes during a raid on a Revolutionary Armed Forces of Colombia (FARC) camp. The intended use of the aircraft was unclear **[62]**.

2.1. Review of Potential Littoral UAV-Related Maritime and Surveillance Applications

Surveillance can support different maritime activities. This section summarises current and potential UAV applications of maritime surveillance technology.

***ISR**:* Intelligence, Surveillance and Reconnaissance encompasses multiple activities, relating to systems planning and operations that collect, process, and disseminate data in support of current or future military operations. Land, sea, air and space-based platforms have critical ISR roles supporting littoral operations. ISR systems include UAVs, satellites, as well as other air, ground, sea or space-based assets.

Piracy: Maritime surveillance plays a part in reducing potential hostile takeover of ships or oil rigs. The worldwide threat of terrorism and piracy in international waters is increasing, and the need for immediate solutions is paramount. Countries with substantial coastlines in Southeast Asia, the Gulf of Guinea, Caribbean, and the Horn of Africa region have had high piracy incidence that threatens international trade and the maritime shipping industry. For piracy surveillance, and considering recent Iranian terrorist UAV attacks on Saudi shipping (2018) satellite-based vessel detection integrated with conventional information streams to extend surveillance information to Coastguard, police force, naval, customs and excise agencies, intelligence services and border guards may be augmented by a network of UAV Systems. Satellite imagery provides a unique overview of what happens around hijacked ships, monitoring the movement of mother ships and swarms of smaller associated craft. However, the time delay inherent in such satellite updates without persistency, and the generally poor detail would be improved by 'loitering' UAV systems, perhaps preventing some attacks before they happen. These initiatives may benefit from UAV operation conducting safe surveillance at long stand-off ranges without those observed knowing they are under observation.

Illegal Immigration and Border Control: In recent years, illegal immigration, through maritime borders, has attracted attention in the EU and is arguably the most topical challenges to maritime border security of Member States. Maritime surveillance plays a key role in ensuring efficient border security and control, and is unlikely to change even with an increasing range of existential threats. Expanding immigrant pressure from Africa and its consequences, notably the high death toll of unsuccessful sea crossings, was the focus of this attention. In 2019-2020 120,000 irregular migrants and refugees arrived in the EU, mostly by sea with Greece receiving the greatest increase **[63]**. The EU-funded SEABILLA (Sea border surveillance) project aimed to tackle security by adopting early warning systems and sharing information on asylum seekers and natural disasters. Illegal immigration was one identified priority, as well as drug trafficking and illicit activities in the Atlantic and Mediterranean Seas, and the English Channel.

Pollution and Oil Spill Surveillance: Remote sensors, be they on UAV, manned aircraft or satellite, detect pollution on water surfaces through water properties such as colour: reflectance, temperature, or roughness. Oil slicks are distinctly visible in Synthetic Aperture Radar (SAR) imagery as dark areas (day or night). Most slicks are caused by ships emptying bilge before entering port. Satellite-based optical with SAR capability are relevant for oil spill detection, providing all weather, day and night, wide-area coverage, and it would difficult to provide the same large-scale with UAV systems. A single satellite image can capture over 100,000 km^2 of sea surface at once, making this an efficient means to check for oil spills. CleanSeaNet identifies and traces oil pollution on the sea surface from ships and offshore installations, and monitors accidental oil pollution at sea during emergencies **[64]** and *may* benefit from UAV monitoring. Transport Canada uses satellite surveillance to detect illegal discharges at sea across vast swathes of ocean in the search for oil-like signatures, but in port facilities and near inhabited coast UAVs may provide a cheaper and targeted near real-time option to confirm spills, identify their sources, or gathering evidence for prosecution. Satellite-based SAR systems support European operational oil spill monitoring, vessel detection and tracking.

Ice Monitoring: SAR data is valuable in monitoring seasonal or permanent ice-covered ocean in the Arctic, Antarctic, Baltic and Bohai Seas, or Sea of Okhotsk to military and civilian vessels. UAV systems are unlikely to provide added benefit in this area to satellite-based systems in the immediate future.

Illegal Fishing: Illegal Unrecorded Unregulated (IUU) fishing persists as authorities cannot survey all the seas simultaneously to stop it and protect marine species worldwide. London Economics **[65]** reported in 2015 that 1 in 5 fish are taken illegally from the oceans, costing the global economy est. £15.2B per annum. Fishing vessel behaviour monitoring is critical to tackle this problem. Australia has engaged with partners to combat IUU fishing under *Operation Nasse*, a multilateral maritime surveillance operation involving France, New Zealand and the USA. The operation lasted 3 weeks, involving air surveillance, sea inspections and maritime intelligence sharing. The Canadian government utilises RADARSAT-1 data regularly to decide deployment of aircraft to catch illegal fishing operations, coupling SAR data with AIS information to provide a comprehensive picture of what is available. In the UK, a prototype Information Analysis Platform was developed to analyse fishing vessel behaviour, and may potentially combine UAV data with freely available satellite data from providers such as NovaSAR, and Sentinel-1. This data could be used by Defra, the Fisheries

Departments and other authorities to inform of illegal fishing in UK waters. However, AIS systems may be switched off, so that UAVs provide the necessary 'loitering persistence' need to monitor and catch illegal fishing in the act.

Search and Rescue: Maritime surveillance technologies support search and rescue missions, detecting distressed vessels or missing aircraft or ships. Recent maritime operations have changed priorities, providing an effective approach to mass rescue operations highlighted by the Mediterranean crisis, and development of new search and rescue technology. In 2013, an Italian Coast Guard plane in a Frontex joint operation detected a rubber dinghy in distress with migrants on board. The Italian Coast Guard identified two patrol boats and one merchant vessel who were directed to the area. 84 migrants on board an overcrowded dinghy were taken on board the patrol boats and transported to Lampedusa Island Italy **[66]**. In 2014, the Australian Strategic Policy Institute made the case for an Australian observation satellite in the wake of the loss of Malaysian flight MH370 emphasising the fact Australian search and rescue covers nearly 1/10 of the globe, rendering satellite the **only** technology that can effectively monitor such large areas. Although global Search and Rescue is not possible with current UAV technology, this has not stopped the UK RNLI trialled several potential UAV Search and Rescue platforms in 2018 **[67]**.

Illegal Trading of Goods: Maritime security threats include illicit activities under the guise of regular shipping activity, such as smuggled goods, or drug trafficking. In the EU large amounts of contraband is smuggled from China at a cost to the EU economy, West. 10Bn Euros annually, whilst drug smugglers use sea transport containers as a simple, convenient, and cost effective mode of transport **[68]**. In this regard UAVs may prove useful for remote ship observation.

Anti-Terrorism Activities: Recent concern has arisen over the possible impact of maritime UAV-launched terrorist attacks. Ships and seaports may facilitate terrorist activities in different ways: using ships or UAVs as 'bombs', in narco-terrorism, or weapons trafficking. Operation Active Endeavour is a maritime surveillance operation led by NATO's where ships patrol the Mediterranean and monitor shipping to detect, protecting against terrorist activity. The operation evolved following terrorist attacks against the United States after September 2001, consisting of surface units, submarines, and maritime patrol aircraft; monitoring, with UAV and countermeasures, would be of benefit.

Port Security: Port security refers to the defence, law and treaty enforcement, and counterterrorism activities that fall within the port and maritime domain. Electro-Optical and Infrared Systems are used for various applications, including protecting ports and harbours by monitoring port facilities, storage areas or container depots. Systems operate by scanning and observing all land and maritime zones for unauthorised activities. If intruders are observed, the system continues with identification and intruder tracking, to direct security forces, with the recent addition of the SPYNEL -X and –S thermal imaging sensor for drone detection **[69]**. Such systems could benefit augmentation with UAV systems aloft, providing wide area persistent stare (e.g. Zephyr) **[70].**

Off-shore Platform Security: Typical threats to offshore operations involve hostile intruders using surface craft, diving gear or small submarines. Added security risks through internal theft, uninvited fishermen, and sabotage from contractors and employees pose threats. If national security forces guard sites, hostile actor attackers may outnumber them. Current security surveillance of offshore platforms includes spotlights to watch areas close to platforms, night-deck patrols, electrified fences, and coordination between a rig and towing vessel, sharing information on possible responses. UAV systems may provide earlier warning of such incidents. Increasingly, electronic security plays a key part in securing platforms, such as: short-range radar to identify vessels approaching a platform; vectored pan-tilt-zoom video cameras; situational awareness software; remote two-way marine radios; and stand-off access-denial systems (including water monitors or acoustic devices). Forward-Looking Infra-Red and AIS are used to protect offshore resources. Spynel systems from HGH are set to provide all-weather, 24/7/365 real-time surveillance. The Spynel solution is built for maritime based wide-area surveillance, 360^0 Field Of View, day/night imaging combined with long-range intrusion detection and tracking, considered suitable as a standalone perimeter security system for oil and gas platforms **[69]**.

Navigation Of Autonomous Boats: There are potential applications for autonomous boats, including detection and prevention of illegal trading; immigration route surveillance, or coastal enemy surveying. Rolls-Royce believes there will be remote controlled unmanned coastal vessels and ocean-going ships by 2035 and also leads the Advanced Autonomous Waterborne Applications Initiative (AAWA). Real-time remote monitoring is key to bringing technology to the autonomous surface fleet market. The project received EUR 6.6M from the Finnish Funding Agency for Technology and Innovation, and brings together universities, ship designers, manufacturers and societies to produce the specification and preliminary designs for the next generation of advanced ship solutions. The Maritime Unmanned Navigation through Intelligence in Networks, a collaborative project co-funded by the European Commissions under its 7th Framework Programme ended in 2017, aimed to develop and verify a concept for an autonomous ship, defined as a vessel primarily guided by automated on-board decision systems but controlled by a remote operator in a shore control station. Plymouth University is currently developing its first full-sized autonomous unmanned due to sail across the Atlantic in 2021 celebrating on the 400th anniversary of the Mayflower voyage, fuelled by renewable energy with leading-edge technology **[71]**.

Land-based Applications: As well as using UAV surveillance technology to gather information to support maritime-based activities, UAV can provide benefits in observing and supporting land-based military activities. Other civilian applications may include:

Agriculture: UAV used for agriculture can provide data for economic and environmental benefits to farm management processes.

Forestry: high resolution UAV imagery can provide detailed information on forest acreage, estimating fire, storms, and extreme weather damage and mapping deforestation, amongst other activities including fire-fighting.

Risk Management: UAV imagery can support land use and environmental monitoring.

Disaster Monitoring: using UAV to monitor areas affected by disasters, e.g. tsunami, is critical for timely disaster relief efforts, allowing for rapid response to priority areas captured in satellite images, and may require military as well as civil authorities response.

Early Warning of Infectious Diseases: satellite-based risk maps of haemorrhagic fevers, such as Ebola, help health officials anticipate outbreaks and take timely actions for disease control and prevention, could be followed up by local UAV applications in China or elsewhere, e.g. CV-19 surveillance.

2.2 UAV Market Assessment

This section provides a brief overview of current key UAV technology users in listed activity, with available cost information, presenting figures of global market size in relation to UAV maritime surveillance, and security, covering: Security- Airport and Marine Security, Maritime and Border Security; Maritime Reconnaissance and Surveillance - Maritime Patrol Aircraft; Pseudo-Satellite and Satellite Industry, and the Security and Surveillance Radar Platform Market.

Recent reports provide findings on maritime security. The drone industry is projected to be worth £17B by 2025 by Goldman Sachs **[72]**. The market is broadly divided into fixed wing, rotary blade, and hybrid drones for varied applications: military, agriculture and environment, media and entertainment, energy, government, construction, archaeology, others, divided by geographical region. The Association of Unmanned Vehicle Systems International predicts '*that in the first 3 years … more than 70,000 jobs will be created in the USA with an economic impact of more than US$13.*6B **[73]**, and that by 2025, the organisation forecasts 100,000 jobs will be created with an economic impact of $82B in the US alone.

Other reports show markets in these sectors growing rapidly. Global expenditure on commercial drones in 2014 was $700M, with DJI being the market leader, followed by Parrot and 3DRobotics **[74].** In Australia between 2015 and 2022, the global commercial drone market expects to grow from A$5.95B to A$7.47B. In addition, the DIY market is fast growing, with sales primarily in components**.** UAV market size in related services is predicted to match hardware sales within the next few years. UAV costs range from a modest US$50 for micro drones, the standard DJI Phantom, US$699, to the high-end Intuitive Aerial *Aerigon* costing US$250k for shooting high-resolution film production video. This wide price-range represents the diversity of capabilities in commercial platforms. In 2016 analysis of 202 commercially-available drones listed on the comparison site **SpecOut.com** revealed listed UAVs had an average flight time of 18 minutes, an average range of 1400 m and median price of £390, all metrics that sit well for urban operation, except remote control in complex built up areas which may be obstructed**.**

The importance of international trade by sea, with increasing maritime threats, and growing awareness of maritime security are driving all aspects of the maritime market including the UAV sector. Key-country actors are: UK, USA, Israel, Japan, Canada, EU, India, South Africa, South Korea, Brazil, Nigeria, and the UAE, with a market-value exceeding US$6.8B. This is a fraction of the overall maritime surveillance market size: Security- Airport & Marine Security value of US$53.84B 2016, Maritime and Border Security US$15.32B 2015. Surveillance: Maritime Reconnaissance and Surveillance: Maritime Patrol Aircraft US$53.84B 2016, Satellite Industry US$208B 2015, Security and surveillance radar market US$6.08B 2014, SAR Satellites US$6.8B 2016, and EU Expenditure on Maritime Surveillance € 237.32M 2016 (limited data).

Further details of the **Security and Surveillance Market Share** are given in **Appendix 9.2.**

3 CURRENT UAV PLATFORMS

3.1 UAV Technical Characteristics

Technical characteristics sit at the heart of defining UAV and drone operational performance.

Endurance - is the main performance parameter for COTS civilian and military UAVs, and is a measure of how long a UAV can stay in the air. It may be measured as total flight time or the time a UAV can stay persistently over station. Endurance varies between UAV designs. High endurance UAVs typically have long narrow wings and streamlined fuselages to minimise drag. High endurance small UAVs may use propellers for improved efficiency, e.g. the military *ScanEagle* has endurance over 24 hours and an internal combustion engine, whilst the electric powered *Puma AE*, has endurance of over 3.5 hours (AeroVironment). Most electric-powered COTS fixed-wing small UAVs have endurance 60 - 90 minutes **[75]**. Importantly for COTS-modified drones smaller military UAVs don't have substantially greater endurance than civilian ones. As a general design rule UAVs comparable in aerodynamic design, size, and technology generally achieve similar performance. Unlike aeroplanes, multi-rotor UAVs have reduced endurance due to their powered lift rather than aerodynamic lift designs. Most COTS configurations have endurance typically 20 – 30 minutes. Endurance may be increased by modification, e.g. sacrificing payload for extra batteries, but this has drawbacks depending on the application **[75]**.

Range - This term may refer to two different measures of UAV performance: namely, aircraft range or data-link range. Data-link range is the maximum distance a UAV can maintain communications with a Ground Control Station, and depends on several factors. The most common sense, and the one taken here, is platform range refers to the maximum distance a UAV flies in a given configuration and in a particular flight condition. Many variables affect range, including altitude, aerodynamic efficiency, battery / fuel capacity, propulsion efficiency, speed, weight, or wind parameters, which we investigate in the questionnaire. The range for most small COTS UAVs is between one - tens km. However, in some UAV operations data-link range may be the main constraint. Civilian UAV users have less RF flexibility, and often use higher frequencies due to path losses, namely environmental loss factors, such as water content.

Altitude - Maximum UAV operational altitude is constrained more by payloads and operational choice than performance. Lift and thrust are negatively affected by low density air caused by elevation or temperature. This problem may be addressed by decreasing General Take Off Weight (GTOW), resulting in reduced fuel weight or payload. Payloads may be constrained by maximum range or sensor field of view, limiting maximum altitude at which a UAV operates. Small COTS UAVs fly from ground level to c. 400 m altitude. Military users may compromise between payload performance and reducing detection probability. Hobbyists or commercial operators are constrained by regulation to avoid other air traffic. However, non-state actors do not respect regulations or restrictions to achieve their goal, unless keeping to anticipated flight paths support their objective, e.g. appearing to be a commercial UAV until the last moment.

Speed - Fixed wing UAV speed is selected and adjusted to deliver optimum performance for a particular phase of flight. Certain speeds permit maximum range and endurance, and are considered the most important. Speed varies with weight, design, propulsion, and other factors, but are typically 10 - 50 m/s for small fixed-wing UAVs. High speed is not usually a priority for most COTS users, but is possible with optimised aircraft design, e.g. jet or pulse-jet engines. Rotary wing and powered lift UAVs, by comparison, typically achieve low flight speeds, 0 - 15 m/s, for COTS models. As with fixed wing design, faster speed is achieved with specialist helicopter or multi-rotor aircraft designs.

Payloads - Sensors, especially cameras, are the main payloads carried by small COTS UAVs, most have a camera on-board for piloting purposes or secondary objectives. They are used for Intelligence, Surveillance, Target Acquisition, and Reconnaissance (ISTAR) missions. Camera and other sensor payloads on small COTS UAVs vary significantly, primarily dependent on: application, size, and budget. The simplest and lowest-cost aerial video systems use COTS analogue cameras rather than digital. Video is usually sent to a monitor on the ground via a wireless link operating in amateur radio bands.

Payload Capacity - Payloads may be installed at multiple points on even small UAVs. Most are near the nose or the centre bottom of an aircraft's fuselage, external to or within the fuselage, allowing camera and sensor payloads to have a clear Field Of View (FOV). Internal payloads benefit from weather protection, reduced aerodynamic drag, increased endurance, range, and speed. Sensors may be fixed to moveable mounts called gimbals, whilst fixed sensor payloads require a UAV to manoeuvre to adjust its FOV. Gimbals permit payloads to move independently of the UAV in 2 or 3 axes. Payload capacity varies dependent upon UAV design, but I observe a general rule that: **maximum payload capacity is 10 - 20% of UAV GTOW**, which applies to all small UAVs regardless if they are multi-rotor or aeroplane. Larger small COTS UAVs have maximum payload capacity > 5 kg. As with other UAV platform design and operation, payload weight can be adjusted for performance.

For small UAVs, it is usually a single unit comprised of the hardware and software needed for: Stabilisation; controlling orientation, position, speed and course; and controlling sub-systems, such as payload.

Autonomy The degree of autonomy is a system's ability to execute a task without human intervention. Sub-systems like payloads may be controlled separately from UAV platform controls. However, with small UAVs, where weight, space, and power are limited, designers try to integrate several functions into one on-board unit. Some UAVs or autopilots are 'completely autonomous'. Semi-autonomous autopilots control some functions at all times during operation, and others at the operator's discretion, upon command from an operator. When a UAV is fitted with a fully autonomous autopilot, operator influence decreases. An operator provides parameters, e.g. reaching a certain destination at a certain time, or finding and tracking targets of a specific type, and the autopilot controls the UAV to complete the set task. When this definition is applied, few operational autopilots are truly *fully* autonomous**.**

Most autopilot systems control flight stabilisation and functions to reduce pilot workload, including altitude, course, and speed. When an autopilot manufacturer speaks of a 'fully autonomous flight', they often mean mission data is pre-programmed for the autopilot to execute; Some autopilots have a manual control so pilots directly control the UAV with joysticks, ideal for a hostile actor. Manual control flight, especially with mobile phone view technology, can be an effective means for small UAV piloting. Autopilots rely on hardware components readily available through advances in consumer electronics and automobiles, requiring one or more microprocessors and an ability to measure flight parameters: acceleration, angular velocity, orientation, position, and platform health (battery voltage or fuel reserves). Some military UAVs operate with old technology because of strict qualification requirements. Civil users, especially those not bound by CAA regulations, are more likely to move to new technology as it becomes available because of increased capabilities, or to use the latest components.

Communications- the pathway between the UAV and ground is known as the 'data-link'. It is common to see separate command, telemetry, and video data-links on a single UAV. This is due to RF interference issues and lack of integrated 2-way data-links. Manufacturers use wide frequency range diversity when employing multiple data-links, to prevent interference. Some small COTS UAVs use cellular and satellite communications. UAV development programs by Alphabet and Amazon's Prime Air service will use cellular networks as their main communications platform.

Propulsion - Small COTS UAV propulsion systems are dominated by propeller driven systems with internal combustion or electric motors. Multi rotors and many small fixed-wing UAVs use DC brushless motors built for model aircraft. They are available in multiple power ratings from various global manufacturers, and require an electronic speed controller connected to the UAV's control system. Some have conventional jet engines, whilst others use ducted fans driven by electric motors. Internal combustion engines are found on larger UAVs, especially when greater endurance is a mission requirement. These engines are often developed for aircraft, but owe their development to power tools like chain saws. Gasoline engines are more common, but diesel and kerosene engines are now available. Controls are more complex and typically require mechanical control to actuate levers for power setting or fuel mixture control. Another propulsion option is the pulse jet, used by fixed wing aircraft. Today's pulse jets are similar in operating principle to those used by unmanned German Vengeance weapons. Small pulse jets and planes are available worldwide, and used by experimental hobbyists due to their particular operational characteristics which may include difficulty to start as well as significant heat. They offer an affordable alternative to jet engines for high speed flight, but not for Non-state actors likely who would likely employ small COTS UAVs for attacks where high flight speed may provide a significant tactical advantage.

3.2 Civilian UAV Platforms

High-end commercial UAVs are equipped with cameras which view over a kilometre away, as well as infrared sensors, thermal imaging systems, loudspeakers, and spotlights. The mass produced commercial nature of such technologies has driven the cost of accessing them down. One of the main civilian UAV suppliers is Da-Jiang Innovations (DJI) China, accounting for 50% of the North American market in 2016. DJI dominates the drone market above $500 USD, whilst below this limit there are numerous competing companies. COTS drones are easy to modify, allowing rapid developments in capabilities. Innovation and new designs offer insights into how guerrillas may employ COTs drones, with gun firing and mounted flame thrower operation demonstrated **[76].** The commercial and public sector maximise productivity using UAVs in certain tasks more efficiently, or reduce workplace risks. The extent of the UK drone industry can be found in a comprehensive database of UK civilian and commercial drone players [77].

Civilian UAV Types and Classifications

Fixed Wing - on aeroplanes, these develop lift from fixed aerodynamic lifting surfaces. A fixed wing aircraft is comprised of a fuselage, tail, a single wing and one or more engines for propulsion. In small COTS UAV designs it is common to see a variety of wing configurations. Most fixed wing COTS UAVs use a single engine in the nose or tail. These engines take the form of electric motors or internal combustion engines with gasoline, diesel, or kerosene fuel. Fixed wing COTS UAVs can be launched and recovered in several ways. Those with Gross Take-Off Weight (GTOW) under 10 kg can be hand-launched. Heavier UAVs may use purpose-built catapults powered by bungee cords, or tension lines anchored to the ground. Recovery is achieved via parachute, deep stall or skid landings. A deep stall landing occurs when a UAV is flown in at low altitude and the nose pulled up quickly to below stall speed. It loses aerodynamic lift and falls to the ground. A skid landing is similar to a conventional landing, although many UAVs do not have landing gear.

Civilian Multi Rotor Frame - These achieve lift through rotation of an aerodynamic surface known as a rotor (see **figure 1**). Many rotary wing aircraft have a single main rotor to produces lift and thrust for horizontal motion. The main rotor produces a torque reaction which must be countered, usually with a tail rotor, or tandem rotors whose rotations counteract each other. However, most small COTS UAVs using this design are a coaxial configuration. Small rotary lift aircraft use electric motors or internal combustion engines to power the rotors. Rotary wing aircraft have both Vertical Take-Off and Landing (VTOL), and can hover. VTOL allows operation in areas where fixed wing aircraft cannot, whilst hovering permits a UAV to maintain station, an advantage in surveillance. These advantages come with a practical trade-off, however, as loss of power means loss of lift. Under some conditions, rotary wing aircraft can auto-rotate for safe landing. These abilities and limitations make helicopters hard to pilot. Combining this with their mechanical complexity, relatively high cost, and lower endurance and top speed, makes them less popular for small COTS UAV operation, and to hostile actors who will likely lack the experience of committed hobbyists.

A large percentage of small COTS UAV designs use multiple rotors to generate lift, each controlled by an individual motor or engine, arranged around the outside of the UAV, and are called ‘multi-rotors’. Total platform thrust is controlled by varying the power setting of each motor to produce lift in the desired direction. Most multi-rotor UAVs have a common design principle where motors tilt, balancing torque to provide stability and control. The number of motors is determined by the UAV mass, with more motors allowing greater GTOW. Multi-rotors are exclusively powered by electric motors due to low weight and ease of integration / operation, although there are designs with internal combustion engines for greater endurance, power, and payload. Multi-rotor UAVs offer similar benefits to rotary wing designs with regards to VTOL and hovering, however there are differences. They cannot auto-rotate, so inflight power failure can be catastrophic, especially with quadcopters. Compared with other rotary designs, multi-rotor endurance and speed tend to be less. Despite drawbacks, lift UAVs have become more popular than rotary wing aircraft in this market, seen by the success of large commercial manufacturers specialising in this UAV type.

The frame is an important part of the platform because it must be light enough for a UAV to take off but strong enough to provide support and not break in a minor crash. UAV’s have their own flight dynamics and structural integrity that must be met and it can be hard to establish empirically what exactly is required.

There are many frames to choose from; the commonest is the Quadcopter, but for heavier loads there is the Hexacopter or Octocopter. A Tricopter is a UAV with 3 arms with 120^0 between them. A Quadcopter has 4 arms, and is the most popular design, and the easiest to construct. If one motor fails the UAV will most likely crash. It is possible to add more motor sets on a quadcopter. If a Hexacopter motor fails others can make up for it (redundancy). Using more motors creates more lift allowing UAVs to lift heavier payloads, but a drawback is they are more expensive. An Octocopter can lift heavier payloads again and may survive a faulty motor unlike a Hexacopter. Rotor UAVs are very popular, and research teams often prefer: ‘*Small multirotor drones with cameras.’* **Prof. T,** Portsmouth.

The potential of UAV for earth observation is clear in terms of application, cost, and flexibility. Contribution from different communities: photogrammetry, robotics, computer vision, artificial intelligence, space domain, electronics, navigation, etc. have advanced data processing with a combination of terrestrial and aerial techniques. Common applications include: Urban monitoring (heat losses, change detection, city modelling, etc.); General surveying and mapping; Environmental monitoring (fires, energy fluxes, natural hazards, etc.); Archaeological documentation; Agriculture / forestry inventories and monitoring.

Civilian UAV advantages

Civilian UAVs have the following characteristics: they are powered aerial platforms without carrying human operators. They use aerodynamic forces to provide vehicle lift, and fly autonomously or piloted remotely. They are designed for recovery, and may carry lethal or nonlethal payloads. UAVs include those components to control the platform and may fly everywhere and under regulatory control, responding flexibly with on-board installed sensors; reduced costs compared to traditional devices, but with technological and legislative problems and some limitations.

Civilian Classification According to Range and Endurance

Very low-cost close range - UAVs have 5 km range, 20 - 45 minutes endurance, and cost c. US $10k (2012 est.). UAVs in this class are similar to model airplanes.

Close range UAVs - includes those with a range of 50 km and endurance of 1 - 6 hours, and used in reconnaissance and surveillance.

Short range UAVs - these include UAVs with a range of 150 km or greater, and endurance of 8 - 12 hours, mainly used in reconnaissance and surveillance.

Mid range UAVs - This class includes UAVs with a high speed and working radius of 650 km, and used in reconnaissance and surveillance, and gathering meteorological data.

Endurance UAVs - These have an endurance of 36 hours and working radius of 300 km. They can operate at 30,000 feet altitude and used in reconnaissance and surveillance.

3.3 Military Drone Platforms

Military Drone Classification

Defence agencies have their specific standards, and civilians their categories for UAVs. UAVs are classed according to the Range they travel, and their Endurance in the air using sub-classes developed by the US military: Very low cost close-range, Short-range, Mid-range, and Endurance UAVs. In the UK the MAA regulates operation of military manned, unmanned and remotely piloted aircraft through regulation. **Table 1** shows MAA classification categories together with their NATO equivalent. According to NATO, common taxonomy and the starting MAA category, UAVs sit in 5 categories, shown in **Table 1:**

Maximum Take Off Weight	NATO Class	Common Taxonomy	Normal Operating Altitude (ft)	Starting MAA Category
< 200 g	Class I	Nano	<1,200	Class I(a)
200g – 20kg	Class I	Micro < 2 kg Mini 2 – 20 kg	<3,500	Class I(b) Class I(c)
20kg – 150 kg	Class I	Small > 20 kg	<18,000	Class I(d)
> 150kg	Class II 150 kg – 600 kg	Tactical > 150 kg	<18,000	Class II
>600 kg	Class III > 600 kg	Male/Hale/Strike	>18,000	Class III

Table 1: UAV NATO class.

Some key definitions:

MALE - Medium-Altitude Long Endurance (MALE) UAV is an unmanned UAV which flies at an altitude of 10,000 - 30,000 feet for extended periods, typically 24 - 48 hours e.g. China's CAIG Wing Loong, and Turkey's Bayraktar TB2, and

HALE - High-Altitude Long Endurance (HALE) UAV is an unmanned UAV which flies optimally at altitudes up to 60,000 feet, capable of flights which last for very long periods of time without needing to land, e.g. Airbus' Zephyr.

Very Small UAVs with dimensions up to 50 cm length. Insect-like UAVs, with flapping or rotary wings, are a popular design: small, light-weight, and useful for spying. Larger ones use conventional aircraft configurations. The choice between flapping or rotary wings is down to maneuverability. Flapping allow perching and landing on small surfaces, e.g. the Israeli IAI *Malat* Mosquito (wing span 35 cm and endurance 40 minutes, the US *Aurora* Flight Sciences Skate (wing span 60 cm and length 33 cm), as well as the Australian Cyber Technology *CyberQuad Mini* (42 × 42 cm), **figure 5**.

Mosquito

Figure 5: Very Small UAV

Small UAVs This class applies to UAVs with at least one dimension over 50 cm and under 2 m. Designs are based on fixed-wing models, and most hand-launched e.g. the 1 m long *RQ-11 Raven* (US Aero Vironment 1.4 m wingspan), or the *RS-16* (American Aerospace). The *RS-16* crosses the boundary between small and medium sized systems (**figure 6**). Some UAVs in this class are based on a rotary-wing design.

Figure 6: Small UAV en.wikipedia.org/wiki/Bayraktar_TB2#/media/File:Bayr

Medium UAVs These are too heavy to be carried by one person but smaller than a light aircraft, with a wingspan: 5 -10 m and payloads: 100 - 200 kg, e.g. medium fixed-wing UAVs, like the Israeli-US *Hunter* and UK *Watchkeeper*. The *Hunter* has a wingspan of 10.2 m and is 6.9 m long, with GTOW 885 kg at takeoff (**figure 7**).

Figure 7: Medium UAV

https://en.wikipedia.org/wiki/Thales_Watchkeeper_WK450#/media/File:Watchkeeper_Remote_Piloted_Air_System_MOD_45156635.jpg

Large UAVs This class applies to large UAVs used mainly in military combat, e.g. the US General Atomics *Predators* and the US Northrop Grumman *Global Hawk*.

Figure 8: Global Hawk Large UAV

https://upload.wikimedia.org/wikipedia/commons/9/9d/Global_Hawk_1.jpg

Lightweight Target Designation Equipment and Precision-Guided Munitions

Prior to development of precision-guided munitions or 'smart bombs', there were 2 ways aircraft could attack ground military targets. One was to deliver inaccurate weapons from high altitude, roughly above the 15,000-feet limit for anti-aircraft artillery. Since each weapon had a low probability of hitting the target, multiple aircraft must carry large payloads. Or alternatively an aircraft could dive-bomb, descending briefly to lower altitude to deliver accurate bombs; this required highly manoeuvrable aircraft invulnerable to anti-aircraft gunnery or small-arms fire. Development of precision-guided munitions and lightweight laser target-designation systems were revolutionary, making it possible during the Gulf War for small aircraft, flying straight and level at Medium altitude (i.e. over 15,000 feet) to deliver munition accurately with minimum collateral damage. UAVs perform these missions well.

Types of Armed UAVs

Many armed drone systems can fly long distances, e.g. the Iranian *Ababil* or *RQ-7 Shadow*, others are constrained in operation to locations within LOS of ground stations, typically tens of miles. In most military cases UAV ISR data is within 50 miles of the location. Whilst Predators flying in support of US troops in Afghanistan are usually controlled from Nevada, but they can be controlled from Afghanistan. Landing, one of the hardest parts of Predator operation, is always locally controlled. Where needed to operate a drone from a distant base it requires a satellite link. An important problem is that drones designed for short-range use (e.g. Bundeswehr, German Army, *Luna X 2000)*, cannot receive command or transmit data from long distance, but used on one way missions, could be used as fully automated long-range cruise missiles. An aspect of reusable armed drones are generally easy to shoot down—so, whilst attractive to states that enjoy air superiority, they are of limited use for forces that cannot protect them during employment in contested air space.

Long-Range, High-Technology: This group includes systems like the *MQ-1 Predator*, and *MQ-9 Reaper*, and the *RQ-7 Shadow* similar to the Predator, both proven in combat. Although the technology for keeping the *Predator, Reaper, and Shadow* in the air is fairly simple, the mission systems that allow them to impact ground combat are more advanced and not widely available, including: gyro-stabilisation, laser designators, synthetic aperture radar, and precision munitions. Some are available in civilian versions, e.g. Hollywood action films also use gyro-stabilised cameras mounted on aircraft. UAVs like the *Predator, Reaper, and Shadow* are used in conflicts where they have air superiority, but can still be shot down with old fighter aircraft. There are stealthier drones such as the *X-47B Pegasus*, with more sophisticated technology than *Reaper*, but these are only built by high-end military forces.

Long-Range, Low-Technology: one example is the Iranian *Ababil* which uses basic radio remote control to achieve unmanned flight and video recording. All the key technology to build this class of armed UAV is available at electronics shops world-wide. Whilst these UAVs include high-resolution cameras, they usually lack stabilisation systems for high accuracy steering, and more advanced sensors. Such systems are once again easily shot down by Allied systems, and because radio links are vulnerable to jamming or interception, it is not regarded a major threat to the USA or its allies when operated as a reusable armed UAV.

Short-Range, High-Technology: Many American and overseas companies have developed comparable small systems for various uses, such as law enforcement or commercial photography. Low cost has permitted them to be widely used. However, large-scale use was delayed by regulatory concerns, especially regarding flight safety resulting from poor situational awareness. These UAVs usually cannot detect aircraft in their immediate vicinity, making them vulnerable to collisions with manned aircraft. The technology in these systems is inherently dual-use. For example, very small UAVs use microelectromechanical inertial navigation units, technology used in commercial products, such as toy helicopters and Wii controllers, making them likely states hostile to the USA or UK will acquire them in the near future. They may be used to suppress internal threats, or support ground combat units, as the US does. This is not an insurmountable threat to US operations. However, current US doctrine for short-range air defence is mostly concerned with defeating attacking helicopters with missiles rather than UAV attacks, which sit in this category. The UK should develop new defensive systems as the threat from small UAVs grows, especially when applies to small, short-range individually controlled UAVs. Small, loitering or persistent aircraft operating autonomously in enemy territory are suitable for '*swarming use*.' These systems may incorporate aspects of the same technology as small commercial UAVs.

However, the requirements for high-end target recognition for successful attack mean these may only be manufactured by a technologically advanced military nation. High-end small UAVs operating deep in enemy territory are still vulnerable to ground fire, but harder to target, due to the military expendable nature, and better described as loitering munitions.

Short-Range, Low-Technology: Radio-controlled model airplanes have been available commercially for decades, and now includes quadcopters etc. In principle, they may be used as weapons of terror, delivering small payloads to sensitive sites. Recent plots include a 2011 planned attack on the Pentagon and a 2013 neo-Nazi plot in Germany. A successful attack hasn't yet been achieved, but this doesn't guarantee continued failure! Cheap GPS improves the UAV ability to find targets, with the inherent problem of recovering a UAV in the presence of stronger air defences making their use as reusable systems unattractive by powers lacking air superiority. This category represents the most immediate modified threat.

Comparison of Reusable and Expendable Drones

Armed or unarmed, otherwise reusable drones may conduct a one-way '*kamikaze*' mission. Just launching a military aircraft and crashing into a target is easier than launching it and landing it again safely, as is the case with commercial UAVs. When survivability is less an issue, small systems may be launched from covert locations. Weak state and sub-state groups have employed such systems in the past. Hezbollah used them against Israel in several previously unsuccessful attacks, notably April 25, 2013. As in previous incidents, the IDF detected the drone on radar and dispatched F-16 fighters to destroy it. The poor success rate of Hezbollah's UAVs contrasts with the effectiveness of ballistic missiles fired from Gaza. It is important to recognise that Israel's success against expendable, low-technology UAVs, results from the Israeli generally highly vigilant alert state maintained at all times, including its proactive rules of engagement. In the more-relaxed approach the USA guards its airspace, it is possible a terrorist group might launch an expendable armed UAV attack from Canada, Mexico, or from within the United States own borders.

Technologies that make reusable UAVs such as *Predators* attractive are largely irrelevant in expendable applications. GPS navigation makes it easier for an expendable

UAV to hit a specified target—particularly for a surprise attack in which the defence is unable to take precautions like jamming the GPS. However, if one is *mostly* concerned with terrorist Weapons of Mass Destruction use, it is not clear that precise target location is important. Delivering chemical munitions to a random location within a large city may be sufficient to satisfy a terrorist's objective. Although the technology that is important to successful operation of long-range drones is employed with manned aircraft, drones are nonetheless preferable for many missions for one overwhelming reason: they can be made smaller and at reduced cost. This advantage is meaningful when mission equipment is much lighter without crew accommodation, as is the case with drone platforms smaller than a Predator. And no hostile actors are at direct risk of injury or death. For a terrorist in the field and for practical logistics, there is limited interest in UAVs much larger than a Reaper in the near future. If an aircraft is large, the advantages of having it unmanned diminish, e.g. it is harder to set up and launch, requires increased manpower etc., and in cases where they require a datalink to perform missions, if security and protection of data links may not be assured.

Impact of Air Defence on Armed UAVs

Reusable armed UAVs such as the *Predator* are effective in the role of hunter-killer,' in which they fly and search for targets. When targets are found, they may engage them or pass cues to other systems that can, whilst continuing their surveillance role. Searching for targets may require flying for extended duration. Systems like the *MQ-1 Predator* and *MQ-9 Reaper* operate at medium-to-high altitudes to maximise survivability and minimise the probability of detection. In most of the world, systems coordinated by the International Civil Aviation Authority who track aircraft at other than very low altitude. The main purpose of the system is to prevent collisions amongst civil aircraft, namely airliners and general aviation. If a Predator were loitering at 15,000 feet in Mexican airspace, Mexican ATC would know—and if the Predator had not filed a proper flight plan, they would be concerned. The Mexican Air Force could shoot the drone down. A technologically advanced nation might destroy or hijack a civilian radio-controlled UAV with non-kinetic technologies such as jamming or spoofing, with real fears today of UAV attacking aircraft near a major international civilian airport (**figure 9**).

Figure 9: **UAV view over civilian aircraft approaching airport.**

4. PLATFORM CRITICAL RESEARCH TRENDS RELEVANT TO FUTURE UAV SYSTEMS

4.1 Emergent Technologies

These are characterised as immature technologies in the 'proof of principle' stage, some of our own emerging work for potential UAV platform-embedded sensors fit in this category **[78 - 79]**; whilst mature technologies are those where novel defence applications have been identified. I will list these areas and expand on this **Emergent Technology** in more detail in **Appendix 9.3,** stating why they are so important. Current areas of military concern cover advanced electronic and optical materials, autonomy, bio-inspired technologies, communications, data information, quantum technologies, energy and power, future computing, high power technologies, human focussed technology, medical advances from biological science, micro and nanoscale technologies, and microelectronics.

4.2 UAV Design Factors

Although geometric modelling of UAV rotor and fixed wing aircraft design is well established **[80 - 81]** proliferation of interesting new functionality materials and embedding them into such platforms is generally less well documented. Appropriate material selection may significantly increase *functionality* afforded by future UAV platform air frames, which in discussion with user communities at the design stage, may incorporate desired, as well as preventing undesired features which might otherwise benefit potential asymmetric warfare actors. This may be addressed with greater ease through an iterative design process **[82]**.

Good platform design must include robustness, which describes how reliably systems will likely function under adverse conditions common on a battlefield. A robust invention is designed to work *despite* problems; if failure is inevitable a platform or component should fail controllably. Robustness can be built into platforms to include: strength, redundancy, simplicity, self-healing, and managed failure.

Robustness: through strength includes the ability to withstand extreme short-term loads, especially cumulative effects of wing loading or wear that cause structures to fail through fatigue **[83]**. Commercial planes, which experience pressurisation and depressurisation cycles, are designed with an understanding materials *will* fatigue after repeated stress. Part of the robustness of military aircraft design comes from strict maintenance schedules that require parts to be replaced *prior* to anticipated failure. Historically adding mass was the only way to make a manned platform stronger, however this increases fuel cost, reducing endurance. New materials such as carbon composites are replacing aluminium, and are less expensive, stronger and more resistant to fatigue and wear.

Redundancy and graceful degradation: involves having multiple 'back-up' systems so if one fails another will take over. Whilst redundancy increases cost and the hardware required, it greatly increases a system's robustness against sudden catastrophic failure. The probability of failure in ALL systems simultaneously is much less likely. In planes redundant systems are mandatory; if there is a failure in a mission critical part of the avionics there **must** be a backup. Failure adds avoidable force losses, which is poor for morale. Redundancy is what makes distributed communications architectures like Link 16, AIS, and Bowman, so robust with all nodes connected through multiple distributed pathways; if one path is blocked or destroyed, another will be found.

Simplicity: the simpler a system the less often it *should* go wrong, whilst the more complex a system, the more may be expected to fail. In mechanical design, simplicity may be achieved by having reduced moving parts, hence the move towards overlapped coverage phased array radar systems which do not rotate **[84]**.

Self-healing: such systems achieve robustness through their ability to repair themselves. Certain polymer materials can be engineered to change state and restore broken polymer cross-links after battle or stress induced damaged. One example of self-healing is development of carbon-fibre composites used in modern vehicle structures: UAVs, fighter aircraft, racing boats, and bicycles, as carbon fibre has a high strength-to-weight ratio. However, one problem with these materials is a tendency to separate or *delaminate* when large impacts cause cracks which form *parallel* to the surface. Researchers at Switzerland's *Ecole Polytechnique Federale de Lausann*e developed a novel technique to make composite material self-repairing **[85]**. Their technique involves impregnating a composite with thousands of small bubbles filled with liquid monomer molecules and smaller bubbles filled with a catalyst. When the composite is subject to impact, fibres in impacted areas compress, lowering the light level passing through them and sensing a specific damaged area. Shape-memory wires are then triggered to contract as monomer and catalyst bubbles are ruptured by the impact, reducing the delaminating region size and allowing monomer to flow into, bond and repair it. In addition, actuators are made from shape-memory alloy, a metal that contracts when electricity is passed through it, combined with sensors made of optical fibres embedded in the composite mesh. In this way failure is managed achieving a measure of robustness which fails gradually rather than catastrophically, on landing 'temporary' in-flight repairs may require replacement.

Key Material Drivers

There is great interest today in composites made from two or more different materials which when combined possess qualities such as increased strength, hardness, or flexibility. Carbon fibre composites have revolutionised aerospace progress, with UK companies like Airbus and Rolls-Royce optimistic about the future of composite platforms, with promising research and industrial developments.

Common Hobbyist UAV Materials

Current materials used for UAV and drone airframes include aluminium, which although a lightweight metal, and easy to work or mould, is heavier than materials like carbon fibre reinforced for composite frames. Carbon fibre has high strength, low density and high stiffness. Industrial UAVs prioritise performance over weight with some homemade platforms using wood. Carbon fibre is widely available with screening advantages to impede Radio Frequency signals probing the platform, whilst Printed Circuit Board has the same structural properties as fibreglass. Plastics lend themselves towards 3D printing with thermoplastics having good strength and low density. Thermoplastics include nylon, polyester, and polystyrene, and are easily injected into moulds. Generally a 3D printer creates perfectly shaped plastic frames, idea for small drones, and epoxy-laminate G10, which is a fibreglass variant often used as it is a less expensive alternative to carbon fibre, but more expensive than wood, aluminium or plastic **[86]**. Recent doctoral work by Simon Weait, Plymouth University, into the '*Design of an UAV for Extreme Environment Operations Using Heat Resistant Ceramic Coating Fused Deposition Modelled Materials'*, shows great promise with 'ethical' green materials: GreenTec Pro and Durabio, combined with 3D printing.

4.3 Commercial Composite Materials

One of the most important composite characteristics is mechanical strength. A composite is a material made of two or more constituent materials (a matrix or binder, with fibre reinforcer), **figure 10**.

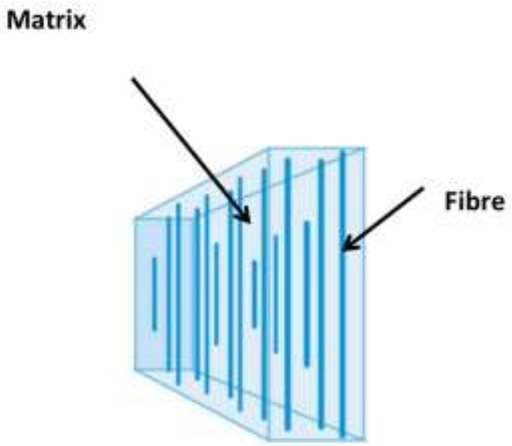

Figure 10: Composite of matrix and fibres.

When such materials combine, the new material has different characteristics from its constituent components. Composite construction is old- *wattle and daub*, has been used since antiquity as a composite method for making walls or buildings, in which a woven lattice of wood strips, wattle, is daubed with a combination of wet soil, clay, sand, animal dung and straw. Wattle and daub is still an important construction method. Many historic buildings include wattle and daub construction, and the technique is again popular today as a low-impact sustainable building technique. In modern materials the load is carried by fibres (70-90%) whilst rigidity and shape is provided by the matrix which transfers load to the fibres, stopping or slowing crack propagation by isolating fibres so individual fibres act separately. Composite materials have been used in the aerospace industry since the 1940s when Glass Fibre Reinforced Polymers (GFRP) were first used in the maritime industry. In 1944 the first US aircraft composite fuselage was a modified *Vultee BT-15*. In the 1960s composites consisting of Fibre-Reinforced Plastics (FRP) impregnated with epoxy resin. Airbus has now increased composites use from 25% to 53% in the *A50 XWB*, with Boeing doing the same in its 787 replacement of the 777, with composites at 50%, up from 12%, with reduced corrosion and fatigue risk **[87]**.

Today UAVs are designed in simple modular fashion with wing and tail plane preformed by traditional modeling techniques –bonded balsa wood, plywood ribs and spars. Subsequently, a system may be bonded with balsa wood skin. Composite parts can be made by hand lay-up lamination, followed by vacuum curing. Skin laminations (wing, plane, or fuselage) may be fabricated in negative moulds, produced by milling, or lamination of a master mould. Ribs and spars are milled from composite panels.

Corrosion poses a substantial economic burden which may result in severe safety or environmental hazards. A recent study estimated the total annual cost of corrosion in China at over US $310B, 3.34% of China's GDP **[88]**. Amongst corrosion mitigation measures, organic protective coatings and composites may be used, adding 2.3% of all anti-corrosion expenditures. Protective organic coatings are essentially polymer composites with complex chemical compositions and heterogeneous surface interfacial properties, coupled with the requirement to detect corrosion or cracking as early as possible. We developed an optical surface monitoring method which detects and quantitatively assesses metal surfaces in a marine environment over long timescales which could be used for UAV skin monitoring **[78]**.

4.0 FUNCTIONAL MATERIALS

Functional Fibres

Carbon fibre reinforced polymer composites are used in industries such as the military, aerospace, and energy sectors, primarily due to their attractive properties: good stiffness, specific strength, and anticorrosion response in operational environments. But there are also applications where smart functional composites would benefit engineering and UAV platform surface fabrication. To this ends smart multi-walled carbon nanotube based composites, which change mechanical properties (flexural strength and stiffness) or electrical properties (resistance and conductivity) by direct and indirect stimuli **[89]** are valuable. Stimuli may include temperature changes, onset of fracture, or pressure and strain variations under load, where a fracture directly affects a composite's electrical properties. Carbon NanoMaterials (CNM) electronic functionality may even replace rare earth metals, as strategic stocks are increasingly controlled by China. A recent study argues CNM may potentially substitute 14 metals found on the EU Critical Minerals list, or listed as a conflict mineral by the US Securities and Exchange Commission. Richkard Arvidsson and Bjorn Sanden, environmental systems analysis researchers at Chalmers University of Technology, Goteborg, Sweden. They state CNM are potential substitutes for rare-earth metals, enabling transition from scarce metals to CNMs such as: graphene, carbon nanotubes, or fullerenes **[90]**, allowing greater potential semi-conductor dependent operations, fibre strengthened composites, and carbon based functionality/sensing.

Graphene, (**figure 11**) first isolated in 2004, as single plane of sp^2 carbon-bonded atoms in a hexagonal honeycomb lattice, is the thinnest material, the strongest, the best virtually transparent electrical conductor, and the best heat conductor.

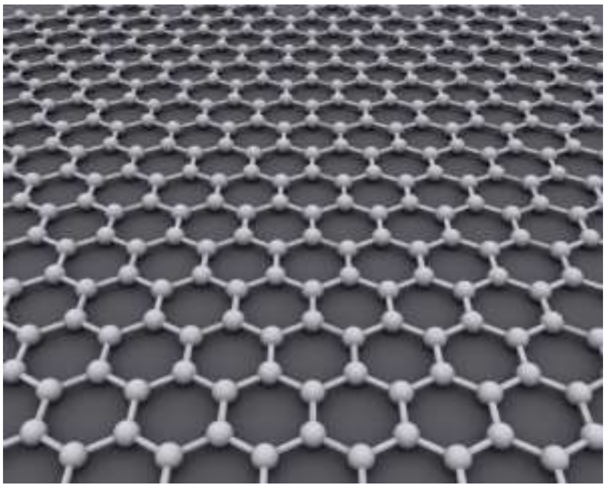

Figure 11: Graphene sheet https://upload.wikimedia.org/wikipedia/commons/9/9e/Graphen.jpg

There are now over 200 companies producing graphene for applications in: batteries/supercapacitors, plastic/polymers, structural material, additive/3D printing, automotive, thermal management, rubber/synthetics, lubricants, magnets, sensors, electronics, semiconductors, water filtration, transparent conducting electrodes, optoelectronics, transistors, touch screens, photodetectors, spintronics, optical modulators, hall effect sensors, barrier films and coatings, conductive ink, aerospace, energy generation, electrochemical, corrosion resistance, medical applications, waterproof coatings, plasmonic/metamaterials, quantum composites, piezoelectric, hall and pressure sensors, and sound transducers.

There is also interest in materials which heal cracks or act as structural load-bearing materials which minimise crack growth use self-healing mechanisms in smart protecting coatings **[91]**. Scientists at the University of Colorado **[92]** recently developed 'living' structural materials, creating a 'scaffold' out of sand with a water-based gel for bacteria to grow into specific shapes, so they could proliferate and mineralise in a process similar to seashell formation. The team looks to add more functionality, such as detecting or extracting toxins or air pollutants. I anticipate 'biologically active' composites will revolutionise smart composite manufacture, and with it UAV / drone technology, enabling platforms to possess a range of dynamic 'sensory skins'.

Self-healing coatings, inspired by biological systems, are able to repair physical damage or recover functional performance with little or no human intervention. Autonomous healing mechanisms may be enabled by embedding polymerisable agents or corrosion inhibitors in a coating matrix. For non-autonomous mechanisms healing is induced by external heat or light which triggers chemical reactions, or physical transitions needed for bond formation, or molecular chain movement. One of the most difficult aspects of the technology is designing capsules that are brittle or frangible enough to release their contents when needed but are strong enough to withstand the pressures normally exerted on them **[93]**. CNM and fullerene capsules may also encapsulate active elements, glues etc. for self-healing.

Shapeshifting Composite Functionality

A further UAV development is radical change or 'morphing' of wing shape (**figure 12**). Wings and other components (e.g. inlets, or nozzles) could change shape in flight to give UAVs an ability to take off from shorter runways or loiter over targets longer (**persistence),** or attack or sprint at high speeds to engage new threats or evade enemy fire. Morphing structures may improve fuel efficiency and extend flight time. The technology would make UAVs more versatile, providing greater operational capabilities **[94].** Wing materials use Shape Memory Polymer (SMP) stretched over joints.

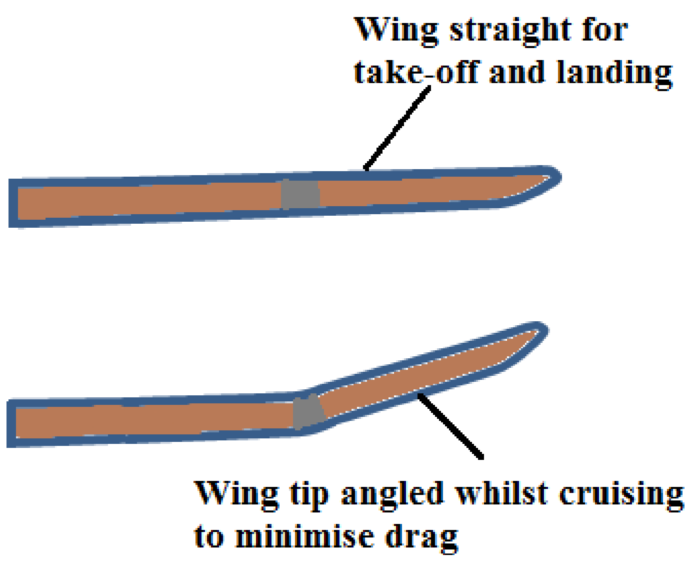

Figure 12: **Morphing Wing Shape.**

The material softens and stretches to a wing's new shape when activated by heat, hardens, and returning to its '*memory*' shape when cooled. Actuators inside wing 'skins' of flexible silicon are controlled and synchronised by computer.

The Future of UAV Composite Design

According to *Composite World*, the market was set to produce 738 metric tons of composite airframes by 2018. As UAV market share increases in civil and military applications, the demand for more maneuverable, payload effective UAVs will increase, with composite materials playing a key role in new platform development. Additive manufacturing techniques such as Fused Deposition Modeling and Laser Sintering, combined with composite materials permit more effective drones for security and military purposes. Introduction of environmentally friendly composite fibres may grow significantly; current bast fibre research, with the structural component of plant stems, are composite materials having low density, yet possessing similar specific modulus and strength to glass fibres. As such they are widely perceived to be *more sustainable* than synthetic fibres. Bast fibres are ligno-cellulose systems with similarities arising from their similar roles in nature **[95]**. Bast fibres are proposed in numerous applications including marine vessels constructed from composites.

Superlight aerogel materials are proposed in UAV manufacture. Given composites were introduced into UAV, vehicle, and consumer electronics devices because they are light, reduce fuel consumption, and keep costs low it is no surprise that a breakthrough in aerogel manufacture, the world's lightest solid material, may reduce costs by a factor of ten, will figure prominently. Composed of up to 99.9% air by volume aerogels are the best thermal insulators. Boston-based *Aerogel Technologies, LLC*, developed a new manufacturing process to produce aerogels in its *Airloy* ® range with large-scale plastic-like durability, opening the possibility of aerogel as lightweight structural material for a range of UAV applications. Aerogel Technologies claims replacing *Airloy* ® in 10% of the plastic interior of a Boeing 737 would save an airline like Southwest $500M-$1B a year in fuel costs **[96]**.

Future Composite and Material design: over the last 20 years the ability to create, manipulate or modify existing materials at the nanoscale resulted in rapid innovation in many fields. Materials at the nanoscale have different properties from their macroscale counterparts, such as increased permeability, strength, chemical resistance, and increased conductivity. Nanomaterials have improved functions and decreased the size of military energy sources, and how long they last, converting solar power to useful energy on the battlefield and improve military equipment. Military research is incorporating nanomaterials to enhance functionality of existing applications [97]. For several years, there has been increased investment in military and civilian nanomaterial use and since inception in 2001, nearly $4B has been invested in nanomaterials by the US National Nanotechnology Initiative. Commercial nanomaterials help manufacture scratchproof eyeglasses, crack resistant paints, anti-graffiti coatings on walls, transparent sunscreens, stain repellent fabrics, self-cleaning windows, and ceramic coatings for solar cells. Combining nanomaterials with emerging technologies may provide added force multiplying leverage.

Electro-optic materials such as liquid crystals are proposed with potential for reflectivity modification, due to their relatively low power requirements. However, the most likely route for liquid crystal use is in low power platform elements to REDUCE passive optical reflectivity for stealth, rather than increasing it for improved detection. We explored liquid crystal low active power camouflage stealth concepts in a recent paper arising from this project [98].

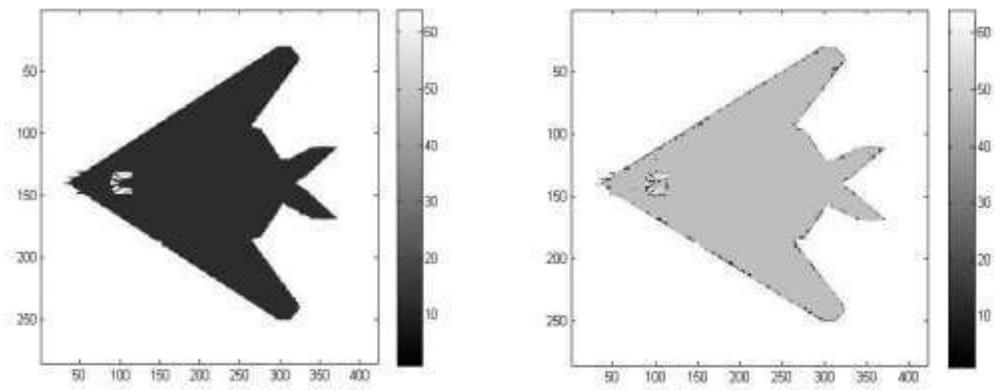

Figure 13: a) Ambient Reflectivity Simulation 0 V applied b) 12V applied [98].

5. QUESTIONNAIRE

5.1 Questionnaire Design:

To underpin the arguments of this dissertation, and suggest potential platform security design safeguards, I consulted with a wide range of stakeholders, potential customers, and interested entities. In this context, I valued opportunities to engage with various individuals around this research and to hear their 'voice'. I was keen to establish their thoughts around: Civilian and military UAV surveillance requirements particularly maritime, activities in the surveillance and security domain, new materials, sustainability, sensors and energy sources, technical requirements for UAV-derived surveillance, and future cost expenditure for surveillance and security, and how much they communicate ‘upstream’ and ‘downstream’.

The purpose of the questionnaire was to collect accurate, unbiased and relevant information, provide structure to guide interviews and discussions, for a systematised response to facilitate data processing and analysis with narrative. I designed a questionnaire focusing on the key information required to support my analysis. The questionnaire was written to provide clear analytical outputs. I focused first on the respondents’ capacity to provide accurate information. To mitigate against the risk of error, I tried to design unambiguous questions with clear instructions. The main questionnaire ethical considerations were: respondents provided informed consent, respondents knew *how* the information would be used, why it was being collected and by whom; and that their participation would not jeopardise their own, nor others, safety and security. This required: identifying assessment objectives and information needs, deciding on the sources of information, data collection technique, drafting the questionnaire, structuring and formatting it, and field testing with several groups of students to review the questionnaire (10 times), and finalising the Work Flow plan analysis. **In the report quotations are provided, but limited attribution about respondents is given to avoid compromising participant safety.**

5.2 Stakeholder Questionnaire Consultation

We built upon several years of ongoing questionnaire-related investigations with various maritime professionals, with input from Middle East countries particularly amongst maritime and land-based professionals in the UK, EU, and USA. We engaged as wide a range of stakeholders and interested parties in conversation to establish their thoughts around: UAV surveillance requirements, particularly the maritime and littoral environment; current and future activities in the surveillance and security domain; the technical requirement for UAV maritime surveillance, and associated applications. A questionnaire was developed to best facilitate responses from *different* stake-holders, and served as the basis for recorded responses from conversations. Consultations took place via a combination of face-to-face interview (impacted by CV-19), telephone consultation, email conversation and questionnaire, and online conferences/events to stimulate stakeholder engagement with the research. During the research, I received responses from over 140 stakeholders replied with a potential for c. 22,000 possible responses. However, there were about 10 000 data entries in practice. In order to provide the most coherent narrative, not all question findings are reported here. Most will be discussed in future publications. Section **5.3.2** summarises and overviews engagement with these stakeholders, and some of the tabulated responses. It is noted most stakeholders could not provide all information, especially financial data, partly due to national security and competitive corporate reasons. Several open and closed questions helped facilitate discussion, and qualitative assessment with a 1-5 Likert Scale.

Some exemplar areas we explore in conversation are given below:

1. What are the perceived 'ethical' drone design technology benefits, and drivers, of manufacturer and end-user, e.g. are they purely financial ones?
2. What sensors capabilities may *realistically* be incorporated into platform design, and what are their relative importance and *implications* for: power consumption, increased data handling, growing requirements for in-platform computer processing, and autonomous AI algorithm analysis of multiple sensor data fusion in real-time operational scenarios?
3. Is there user *demand* for increased payload capacity from lower mass materials, e.g. superlight aerogels, carbon fibre, ceramics, GRP etc., rather than laminate hardwoods? And what opportunities for technology transfer to space-based and underwater platforms exist? Does increased payload capacity user demand off-set improvements in achievable manufacturers' reduced composite mass?
4. Are ethical designs *necessarily* cheaper? Will manufacturers more likely commit to 'eco-friendly' platform design if they are less expensive? If assets have reduced cost, or increased efficiency, will focus shift towards increased tactical, or swarm use? And if platforms are cheaper are they more likely to be deployed 'sacrificially' in high risk areas, where authenticating human data streams may experience reduced availability?

5. What importance do manufacturers and end-users place on drone use, persistence, night and day availability, all weather capabilities, endurance, simplicity, redundancy, self-healing, managed failure, etc.?

6. Further philosophical engineering design aspects exist, namely: what ethical responsibility is there on engineers to design civilian drones differently to military drones, e.g. to ensure human welfare, or privacy? Is modification of civil platforms to create 'bespoke' military platforms acceptable practice, or should it require a legally enforced framework? Is there evidence military drone use *detrimentally* impacts civilian drone uptake, or increases public mistrust? There are also ethical military and civilian surveillance dilemmas for sensitive information system design, i.e. what do we mean by a 'responsible human decision' process, and how do we embed such responsible non-human ethical decision making values near real-time into AUV on-platform signal processing?

Fundamentally, what differences exist between 'ethical' designed platforms and 'normal' designs given UAV Value Sensitive Design *applications* in agriculture, search and rescue, and disaster monitoring may be a good model to use for the likelihood of exploitation**.** It is hoped this approach at least provides some credible prevention against simple platform modification undertaken by non-state actors.

Key Set Questionnaire Questions.

1 Respondent Details.

2 Details about the UAV applications the organisation uses/provides.

3 The UAV applications the user / provider is interested in and what are their required frequencies (e.g. daily, hourly etc.)?

Most questions related to the use of the Likert format, where 1 is 'not important' and 5 is 'very important' to incorporate the following into UAV design: 5 Specific platform operational roles, 6 Platform Sensors, 7 Energy sources, 8 Payloads, 9 Materials, 10 Advanced Materials, 11 Design Characteristics, 12 'Self-healing materials', 13 Various design requirements and benefits. 14 Ethical Design, 15 Various platform temporal attributes, 16 The responsibility for engineers to design civilian UAVs *differently* to military drones, welfare, safety, and privacy, 17 Questions related to any legally enforced framework to prevent modification of civil platforms into 'bespoke' military-grade platforms, 18 Perception of drone attacks or military use negatively impacting civilian UAV uptake, or increasing public mistrust, 20 Likert Questions related to embedding responsible non-human ethical decision making (near real-time) into your UAV platforms?

And 21 As an end-user/manufacturer are your 'ethical' drone design technology benefits, and drivers purely financial ones? **Not** Likert.

And further Likert scale questions: 22 Design Concepts How important are the following military design factors, 23 Threats and Countermeasures: civilian UAVs are designed to exclude potential military sensor payloads, 24 Military data acquisition systems might undertake kill decisions automatically, 25 What are your organisation's core competencies in the field of UAV development. 28 (a) What mission benefits do your UAV systems provide for earth observation? (b) The costs to build and operate systems. (c) The history of the development of systems.

5.3 Research Findings and Discussion

5.3.1 Record of contact with shareholders

Although many stakeholders engaged with us, it was not always appropriate for them to disclose information due to security reasons or future organisational plans. Nonetheless, **figure 14.** provides the geographical distribution of 'open' question respondents, with a breakdown by global region. Over one hundred and forty stakeholders provided answers to some, or all the questionnaire questions.

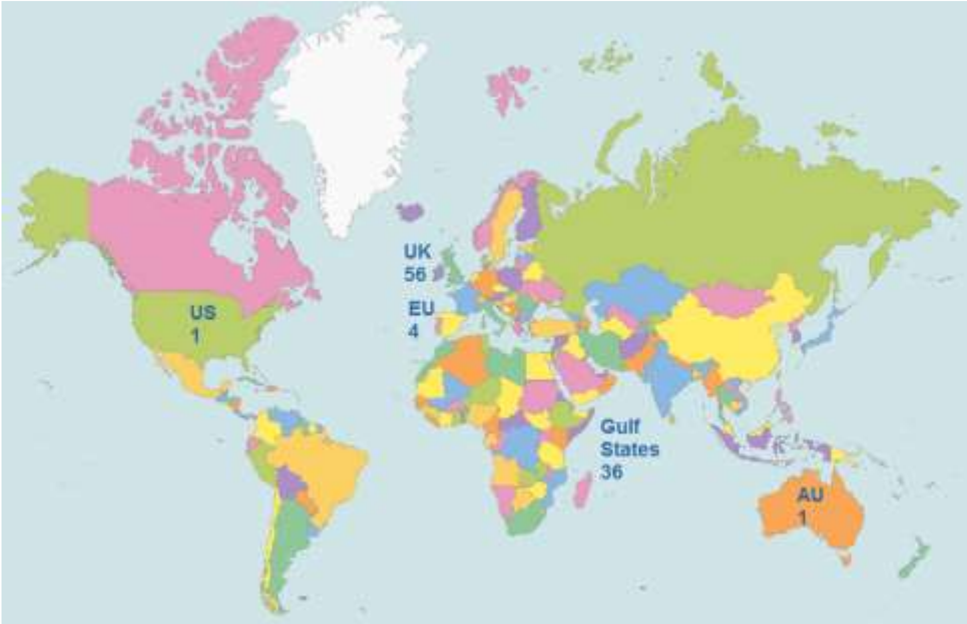

Figure 14: 'Open' Global Distribution of Stakeholders Views. 98 Open Responses.

5.3.2 Findings from Stakeholder Consultations

In summary responses given in this report came from questionnaire and informal discussions with upstream UAV manufacturers, data providers and users, mostly: UK, US, European Union, Kuwaiti, Qatari, and Saudi Arabian maritime professionals (the downstream sector). This section presents some of the key findings from our primary research. Analysis of the questionnaire results, together with information received though conversations, revealed the types of UAV platform service to participating organisations, with weighted importance, differing by nation as well as between upstream and downstream. *The most pertinent questions are discussed with the key findings given here.*

Surveillance technical capabilities

Responders were asked technical requirements related to UAV platform sensor systems. The questionnaire asked respondents to indicate how important specific UAV system capabilities were to them. Respondents rated the importance of: 'night and day', 24/7 capabilities; 'all-weather' surveillance which can operate in all-weather conditions including cloud cover, and 'persistency', i.e. ensuring longevity of service, on a scale of 1 (not at all important) to 5 (very important). The importance of surveillance technical capabilities depends on the user and may be summed up by: '*Primarily land based focused and orientated towards detection. The primary objective of enemies, their tools incl. weapons, IEDS, supplies, their activities. Also patterns of life*.' **Lt Col, British Army**.

2. Applications and Cost

The appeal of small COTS UAVs lies mainly in their wide range of applications, and availability for multi-role and multi-sensor payloads, and cost. This last point is an important one, combined with the age of mass consumer goods. Widespread platform exploitation is partly cost driven, it *must* be affordable. Just as the use of satellite Arctic sea ice monitoring provides a financial gain UAV can also provide financial benefits in other areas. **'***It is important to expand the use of the drone, (it) saves time and money'.* **Colonel, Kuwait Navy** and, **'***We have used the DJI Mavic pro 2 drone (with thermal and night vision capabilities) to detect the illegal fishing activities in the Kuwaiti bay and around Failaka island*', detecting activities such as illegal fishing, anchoring in coral reefs locations may have net financial gain. *'Regarding autonomous action, algorithm analysis, multispectral analysis, and multiple sensor data fusion cost IS NOT everything, but is still very important*,' **Lt Col**, British Army.

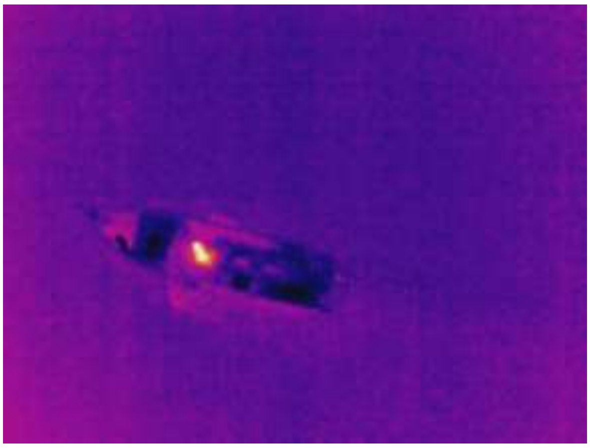

Figure 15: ***Kuwaiti UAV*** **Thermal image monitoring illegal fishing.**

A point equally applicable to the civilian research scientist: *'Simultaneous multispectral scanning & LiDAR would be great, but is generally not feasible because of UAV load limitations.'* and, '*The applications identified above are used by University of Portsmouth* *researchers in a number of fields, but especially in environmental disaster response.*' **Prof T.** Portsmouth**.**

5. Navigation–related sensors '*For navigation, we typically relied on other sensors, but using UAVs for things like SAR/CSAR meant quicker deployments in time of crisis and less risk to our own aircrews, which we would traditionally perform SAR/CSAR via manned helicopters.'* **Ex - *US Navy***, *Intelligence.*

Speed of deployment and safe navigation is critical. There are also UK concerns about navigational communications security, not least of which is the 'return to origin', as this command could be hacked**.** In March 2019 it was relatively easy for Amat Cama and Richard Zhu, to exploit a weakness of the infotainment system browser in a Vancouver Tesla Model 3 to input their code and take control of the system **[99]**. Similar 'attack surfaces' on autonomous platforms offers ways to break into various smart platforms **[100]**, or even in location critical placement: *'One of the problems we have faced is when flying the drone from the ship, the problem was when returning the drone to the home location, the ship was not at the exact location as before the drone took off so we had to use the manual landing, this could lead to loss of the drone in the water if the controller was not good enough or when in windy weather,***'** **Colonel Kuwait**. How much more likely are civilian and military forces to lose a drone if errors and deliberate interference are factored in? From the perspective of the 'Return to Origin' if a fault is detected by the autopilot this may not always be the best policy: *'Generally yes, but it may be (*best to go to a*) to preset location to avoid compromising the pilot's location,'* **Lt Col, British Army**. The level of issue links to human decision making, *'if AI decision making is compromised,* (consequences) *entirely depends on the function in question and the context of operation*.'

Sensor 6. Chemical Biological, Radiological or Nuclear (CBRN)

Interestingly for all the emphasis being given to CBRN risks today (**figure 16**), the results of 44 maritime professionals are split equally between VIS/NIR, Thermal, and Explosive detection capability, with CBRN trailing far behind. *'The prospects of politically violent non-state actors utilising CBRN weapons has captured the imaginations of not only public officials and the news media, but also a sizeable group of scholars who have sought to better define and characterise this apparent threat'* **[101].** However, across questionnaires when specifically asked to review typical response to chemical threats it is regarded fairly highly (**figure 17**). This apparent contradiction may be explained by the fact that although a broad spectrum recognise the value of these specific sensor types it is considered low compared with everything else that a mission platform must do, relying heavily on VIS/NIR and thermal sensing. Overall costs and practicalities preclude the use of chemical/biological/radiological/and gas sensing capability except in immediate niche requirements. No platform can detect everything, nor fulfil every mission objective. The strongest response is, Visible with Near Infra-Red, followed by TIC, and then explosives.

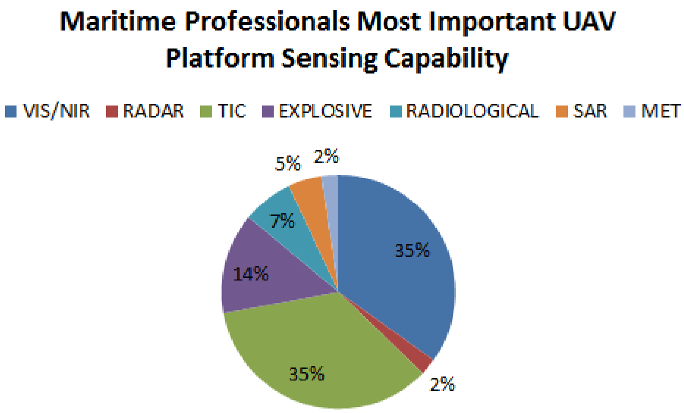

Figure 16: Most important perceived UAV platform sensing capability.

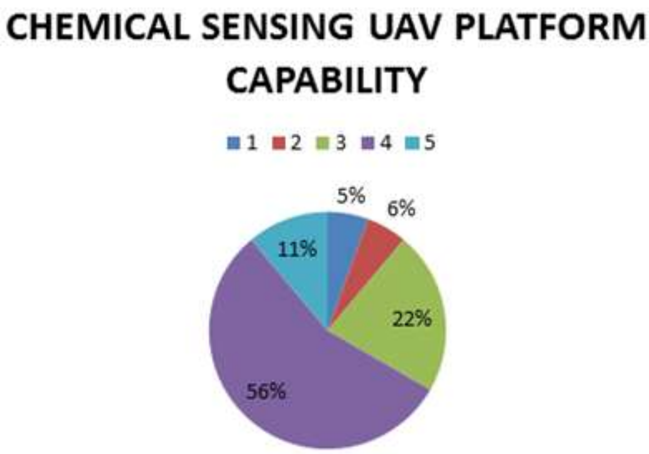

Figure 17: Importance of Chemical Sensing as a UAV platform capability.

The responses in this category was somewhat disappointing with only 18 replies, but 77% in categories 4 – 5, and 89% in categories: 3 – 5 shows that from those who replied it was something they were taking seriously.

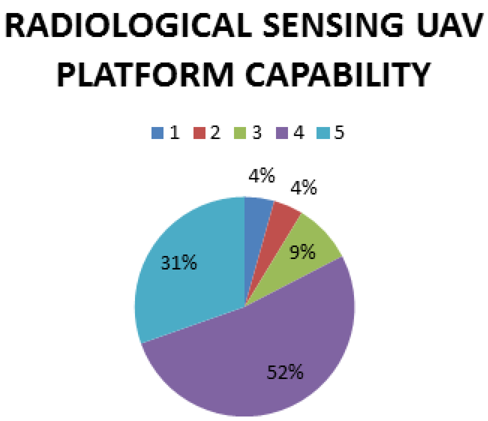

Figure 18: Radiological Sensing UAV Platform Capability.

Clearly radiological sensing is perceived to be extremely important (Category 4 - 5 83%), further increased to 92% in categories 3 – 5, but we should also look at atmospheric sensing of the most important air *quality* monitoring gases which are: CO, CO2, NOx, SOx, O3 and CFCs, with UAVs already designed to detect such gases **[102].** In addition to these it is also useful to record temperature, humidity, and dust levels. However, as a question of priorities over gases, is monitoring the electromagnetic spectrum. In this regime the following statement is common: *'As both a civilian and prior military, our emphasis on drones is focused on collecting and examining the RF spectrum.'* **US Naval Intelligence Officer.**

There is a wide range of motives that might make acquisition and/or use of CBRN weapons attractive to terrorists, and certainly many terrorists have considered CBRN use. Technical and knowledge-sharing innovations make it potentially easier for terrorists to achieve CBRN capability, which could facilitate them to pursue weapons for potential UAV platform delivery. The higher the level of technological development in an organisation's host country, the *greater* the likelihood of pursuing CBRN capabilities. However, in current thinking, the more embedded an organisation host country is in the world economy the less likely an organisation will be to pursue CBRN capabilities and jeopardise their economy by sanctions versus gain of some sort of dubious CBRN status.

Ironically, the more authoritarian the host country, the lower the likelihood organisations will pursue such capabilities according to one author **[101]**. However, such authoritarian regimes are likely to develop their own technologies, as over 80 countries now have drones in their military arsenals **[103]**, with about 35 owning major systems **,** though fewer possess weaponised versions (principally the USA, UK, France, China, Russia, India, Israel, Pakistan, Iran, Iraq, Nigeria, Somalia and South Africa **[104].** Israel has long overtaken the USA as the worlds' leading manufacturer of UAVs, supplying >60% of the globe's requirements **[105].** Pakistan, spurned by the USA when it looked to obtain armed Predators, has rapidly developed its own *Burraq* combat drone **[106]** which it first used to kill 3 senior militants in September 2015. Analyst assessments of Pakistan capabilities are largely based on China's *CH-3* drone, one of which was previously obtained by Pakistan. The *CH-3* is an all-weather MALE platform with an 8m wingspan, 2400 km range, and maximum 80 kg payload **[107].** This acquisition route is familiar to Nigeria, Iraq, Saudi Arabia, the UAE, and Egypt **[108],** and none of these are likely to relate to CBRN deployment.

Chemical weapons, radioactive use, Weapons of Mass Destruction etc., are for terrorist groups "*comparatively unlikely to get its hands on anything truly devastating. Groups harboring such extreme goals would probably be small and poorly resourced..... Such WMD attacks as they are able to mount would thus be of a far more modest 'homebrewed' kind and therefore within the limits of containability*' **[109].** The most likely future homemade UAV terror threats is a combination of 'everyman' drones and mobile IEDs, rather than CBRN. The knowledge, resources and technical skills to produce such drones is now available freely. According to Cohen and Schmidt, a drone with camera and Wi-Fi connection carrying a homemade bomb on its undercarriage to produce a whole new level of domestic terror is '*just around the corner'*, without the accessibility issues posed by CBNR **[110].** What is certain is that sensors have already been fitted to UAVs for radiation monitoring and mapping of contaminated land at Fukashima in the range 0 - 6 micro Sieverts per hour using LIDAR **[111].**

7. Reduced power consumption

With growing diversity in the range of mission capabilities and associated requirements for more advanced technologies mentioned, designing modern UAV power systems is challenging. In particular, increasing reliance on the electrical power system for delivering key platform functions, electrical and mechanical, requires a systems-approach to be employed in their development, to maximise output for MALE systems to loiter over station. In terms of this power system modeling. *'A balance will have to be struck between time on station performance, and the benefits of adding such systems'* **ex-RN**, and allied with this is the energy source limiting endurance.

7 Energy sources and proven consumption (41 responses) 73% categories 4 - 5, 90% (3 - 5). Finding new efficient sources of fuel is important as current fuel consumption is generally high, and single source. *'Our drones were either turbo-prop or jet engine drones, so we relied heavily on jet fuel.*' **Ex-US Naval intelligence.** In this regard the use of solar powered systems like Airbus' Zephyr serves to provide long duration flight, has much attraction.

8. Sensors Payloads

UAVs to deliver life critical medical products on the battlefield, have been explored by RAND Corporation, who investigated and produced a fleet design tool for autonomous UAV blood delivery to assess small UAV designs critically centred around: **Range, Cruise Speed, and Payload [112].** General battlefield medical support and dual-use civilian emergency UAVs may provide essential life-saving materials quickly and safely **[113 - 114]**. According to Emily Aasand **'***The American Red Cross released a study detailing how UAVs can help first responders could improve disaster relief efforts.*' UAV can collect data before during and after disasters, provide aerial data in areas too hazardous for humans, deliver supplies, and relay emergency Wi-Fi and cellular phone services when normal communications may suffer outages, just when needed the most **[115].** There are several companies providing critical and lifesaving products, e.g. Zipline which launched services in Rwanda and Ghana [2019] **www.flyzipline.com/**
Similarly UAVs used in a wider humanitarian relief context have been the subject of other recent reports **[116],** or to monitor movements of armed groups in relation to local population, prior to use of UN force, and to record incidents where peacekeepers are using force to protect civilians. This helps with the accountability of peacekeeping, an area to research in itself **[117].** In terms of terrorism the effects produced by most modified UAV delivered payloads, or even 'captured' military drones, notwithstanding comments raised regarding CBRN above, do not stand out as high risk as there are

better and simpler ways to deliver more potent payloads to the target. However, UAVs enable air attack, for adversaries that may otherwise not have ability to attack from the air, and against superior ground forces without immediate access to airpower at all, might prove decisive, even with modified COTS drones **[118 - 119].** Today it is possible to modify a basic drone for visual inspection, surveillance and reconnaissance where it might otherwise be difficult or dangerous for humans to go, or with ability to 'sniff' for various chemicals, gases, and even radiation.

With practical considerations in mind regarding the last few Likert-style questions, each criteria has impact on other aspects of design. E.g. the greater the number of sensors the higher the platform power requirement will be, with a reduced primary payload capability, and increased cost etc. Designers must remain focused on the primary platform purpose, any benefits in other areas must not come at an unreasonable expense of the primary design parameter.

9. Sensors Materials

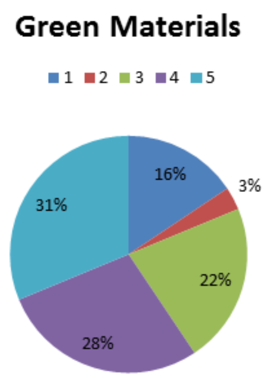

Figure 19: The Importance of Green Materials in UAV Platform Design.

I received 32 responses in the Green Materials criterion with 59% in categories 4 - 5, and 81% in categories 3 – 5. There is much focus today and moralising on use of environmentally sustainable materials. Much work on sustainability and 3D printing is taking place. **'***The project is centred on sustainability of the materials used not only for the development of drones but also of FDM 3D printing.* ***SW*****,** Plymouth Uni. However: *'A small UAV is unlikely to have a huge carbon footprint. Environmental sustainability must balance the immediate carbon footprint with the total lifespan/ hours of service of the UAV. Long-lasting but, superficially, less environmentally-friendly components might have a better net benefit over the long term.'* **Prof L,** Portsmouth**.** This is particularly relevant if platforms are designed to undergo radiation exposure, heavy fire, or used expendably. Green sustainability is outweighed by other factors: *'Like the previous comments suggest, few if any specific materials, or components have an inherent moral value. Moral benefit-like performance or operational benefit – emerges in the relative merits of the speed, endurance, functionality, cost,* (and) *total environmental harm per hour of use,'* **Prof L,** Portsmouth Uni. And rightly frames the issue of sustainability as balanced against much more important mission critical issues such as endurance, range and payload. This linking of design to cost is not a mute-point, as in terms of Low cost design: It: '*Depends on the role, and if it needs to be disposable or built quickly with limited materials…'* However, a more 'frangible' or 'crumpling' platform made of sustainable materials, is one way to reduce deliberate impact damage. Recycled materials also align with sustainable ones, but require much processing at cost. An expensive 'sustainable' platform destroyed on a mission is not as useful as two platforms costing ½ unit cost, although 'Recycled materials are under scrutiny: *'Recycled plastics are being addressed by INdiGO, Interreg projects with Preventing Plastics Pollution, also Interreg PPP also relevant'.* **Prof S**, Plymouth Uni.

There is certainly a need to develop innovative environmentally friendly gel-coating technology for composites in marine and wind-turbine applications to reduce Volatile Organic Compound (VOC) emissions, processing time and cost. Gel coats are applied to fibre-reinforced composite materials for aesthetics or protection. Styrene is an essential part of these gel-coats. Styrene emissions during processing may cause irritation or neurological effects and there can be an odour nuisance at factories. In the USA styrene is listed as '*reasonably anticipated to be a human carcinogen'*, as a result styrene emissions are limited. Although most composite parts production is closed mould, some is undertaken under open-mould conditions. Further information is available at www.ingect.eu. In practical terms however, use of green materials e.g. Green Tec Biopolymer, Durabio etc., natural woven fibres, recycled plastics, minimal Carbon footprint '*all are desirable features, but if they clash with the overall requirement to conduct EOD safely and successfully less green (but not horrifically toxic) alternatives are likely to be considered more important,*' **Lt Col, British Army.**

Sensors 10. Aerogels, Carbon Fibre etc.

Heat resistance is of practical interest on the battlefield. It is an increasingly important factor for several applications, not only related to fire-fighting, a topic covered in more detail under **ethical design 14.**, but even regarding overheating is important. '*I will emphasise heat resistance, but we didn't use ceramics in our drones. Heat resistance was important to keep the sensors and avionics at operational temperatures during lower altitude operations when cool air was not available to pass through to the fuselage*.**' US Ex Naval Intelligence.** However, reduced mass may bring its own problems as: '*reduced mass/aerogels may compromise stability*', **Prof S, PU.** Basically the lower the mass the less stable the platform may be.

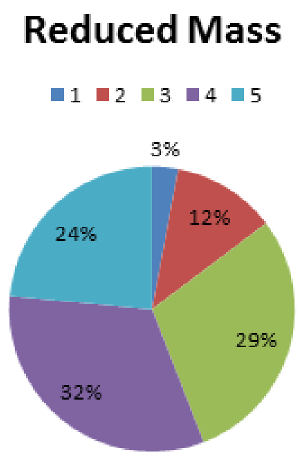

Figure 20: The Importance of Reducing Platform Mass.

Clearly reduced mass **(figure 20)** is regarded as moderately important to most respondents 56% in categories 4 - 5, and 85% in categories 3 - 5 from 92 respondents. The lower the platform frame mass the more sensors, or ordnance, possible. '*The project is investigating FDM 3D printed polymers coated with a ceramic coating. The coating will provide a thermal barrier enabling the drone to directly firefight and enter burning buildings if required. Currently there are two materials being considered: GreenTec Pro-PLA and Polyester Biopolymer, DuraBio, Polycarbonate Biopolymer*'. **Simon, PU.** As for superlight aerogels, carbon fibre, ceramics, GRP and polymers, from a military user perspective '*we are relatively agnostic about the inclusion of specific materials, materials are selected for the* ***value*** *they add vs the costs (monetary, endurance, secondary hazards etc.*)' **Lt Col, British Army.**

Certainly a great deal can be learned from existing use of UAVs for wildland fires, and improvements in drones for fire-fighting applications will have reverse civilian to military benefits as well **[120]**, including the strategic maritime Babcock Light Unmanned Aircraft (*Lua*), developed by the group's Spanish innovation team with a 7kg payload, capable of several hours autonomous flight, providing a role within the data system to help emergency services direct fire-fighting assets, feeding data into real-time simulation to predict the behaviour of a fire, which is its key innovation **[121]**.

Reduced mass platforms now allow small platforms to carry useful payload size such as the May 9th 2020 consignment of medical supplies, which was the first to be carried by UAV across the Solent to the Isle of Wight, with its cargo delivered to the Pathology Dept at St Mary's Hospital. The flight was part of an innovative trial by Solent Transport, the University of Southampton and Windracers to use UAVs to assist the hospital in its response to the CV-19 outbreak **[122].** These innovations may seem new, but the SDU UAS Center has flown blood samples and medical equipment by UAV between Odense, Svendborg and Aero for over three years, saving the Danish health care system some SKK 200M p.a., under project Healthdrone **[123].** Medical military benefits of drones/UAVs are also important to civilians in conflict zone deployment. Since 2014 the UN has used UAVs in the DR Congo conflict zone, and recently in Mali and CAR to gather information, potentially directing peacekeepers to people under threat **[124]**. Mass is not just a key factor for civilian payloads, or firefighting, but also for hostile actor use, it is an important factor in determining the potential attack payload. According to Walker-Roberts and Hammoudeh in written evidence submitted to the Parliamentary enquiry **(DTD0003)** '*Drones are technologically limited as to the weight that they can carry, and in general are not capable of highly sophisticated attacks by terrorists unless assisted by a very capable actor, probably a nation state*' **[125].**

11. Endurance This is the main key to enhanced UAV for long endurance military surveillance capabilities, alongside this range and platform mass are the critical mission 'triangle'; all of which rely on power. Various military and civilian platforms can be categorised in conventional tables, but for the first time we plot here small COTS UAVs alongside small military drones as a 3D scattergram plot in Matlab, as a function of Endurance, Range and GTOW mass (**figure 21A**). This visualisation shows that military and civilian drones clearly overlap for the smaller categories although there is divergence for military long range and endurance systems such as Predator (**Figure 21B**). The visualisation method strongly indicates that concentration upon intrinsic platform data: e.g. endurance, etc., lends itself to further deductive work, namely exploring any empirical mathematical relationships which may exist between factors such as endurance and platform mass, based on quantitative data using the scientific method first elucidated and developed by Bacon (*Novum Organum)*.

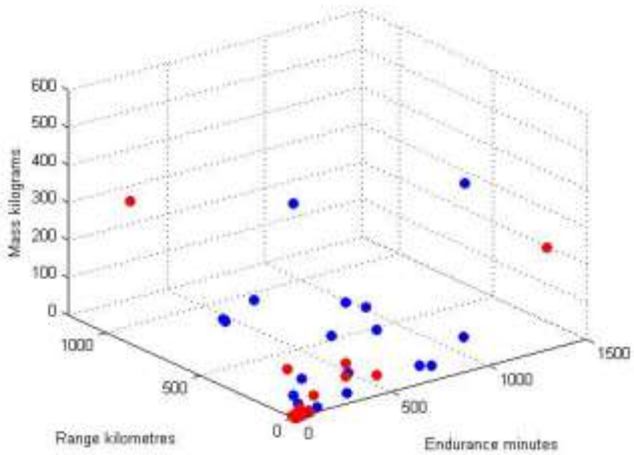

Figure 21A: Small and Medium Civilian UAVs (Red) and Military Drones (Blue).

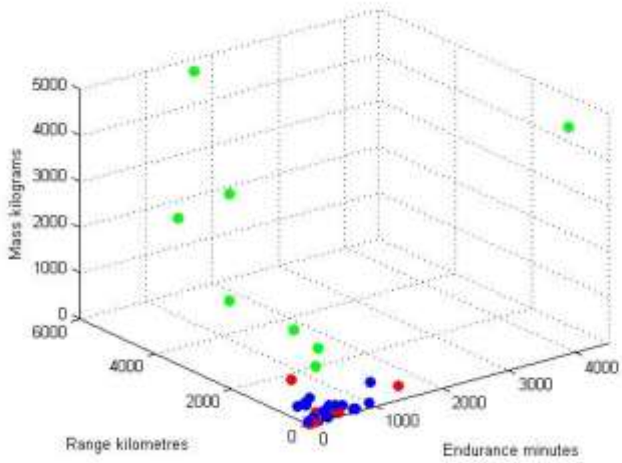

Figure 21B: Small and Medium Civilian (Red), Small and Medium Military Drones (Blue), Large military drones (Green).

From this 3D visualisation perspective, the proposed use of civilian solar powered aviation, e.g. Zephyr, given that Cruise is the longest phase of any such mission is important to civilian endurance, is unlikely to satisfy military requirements **[70].** *'Endurance is an important factor as the greater the endurance the longer the range and the more time the UAV can be conducting recon or supporting with its payload,'* **RN,** and **'***Endurance is the most important as it is the factor all others rely upon. A massive range, altitude, persistency or ability relies on the endurance to achieve these***,' RN.** The table for these UAV parameters is given in **Appendix 9.4.**

Several strategic military responses are interesting from the perspective of long range detection. '*It is very important to have long range. Identifying targets when they are close can limit reaction times. Early warning is vital to obtain***.'** This is especially relevant in the maritime environment, but other wider considerations also apply, *'The ability to remain in the air working for long periods of time will provide the most up to date battlespace picture for the longest time,'* and, whilst '*UAVs are so valuable because they can act as surveillance for long periods at time and don't have the same limitations as normal aircraft. The longer a UAV is aloft the more time it is performing its role.'* ***RN ANON****.*

It is with this characteristic of endurance that the Tactical and Surveillance Airbus Zephyr variants will provide passive surveillance across the electromagnetic spectrum (listening over wide-area), combined with high resolution: optical, infrared and radar (more focused detailed eyes), provided via local area secure networks, with potentially sub-surface imaging. Airbus *Zephyr* weighs in at 30 kg, speed of 30 knots, and a 25m wingspan slightly less than the Airbus A320, with Wyndham, in Western Australia, the world's first operational launch site **[126]**.

Zephyr isn't the only platform to provide high altitude long endurance surveillance. In September 2018 another Airbus platform, the *Perlan 2* glider, achieved an altitude record of 76,000 ft, higher than a U-2 spy-plane, '*touching the void*' straddling both troposphere and stratosphere, and may be used in a pseudo-satellite role **[127]**. Although high-altitude airships may fulfill tactical surveillance roles better, as a potential solution to a noted lack in US Army combat operations in Afghanistan 2001, and Iraq 2003, where ground forces lacked adequate intra-unit communications. Tactical satellites are also demonstrated as a suitable solution **[128]**. However, tactical satellites are costly, and potential alternative platforms are solar-powered high-altitude UAVs like Zephyr, or airships above 65,000ft **[129]**.

Furthermore regarding **Endurance** for small COTS modified drones: '*The most problem we have faced is the endurance of the flights, both drones we used was 20 minutes this has added some limitations and difficulties. Also one of the problems was flying in military areas as the drone could be lost. We have faced that in Qarou island, several parts of Boubyan Island and some parts of Failaka island'* **Colonel Kuwait**.

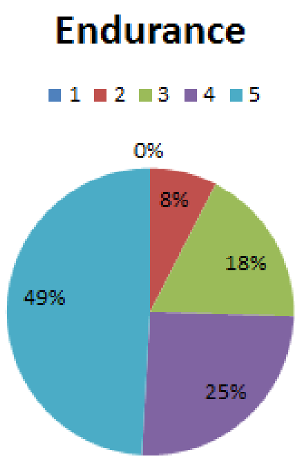

Figure 22: The Importance of Endurance in UAV Design.

There were a total of 106 responses from manufacturers to end users in this category. Clearly Endurance is very highly regarded with 74% (categories 4 - 5) as a key operational platform characteristic, rising to 92% in categories 3 - 5.

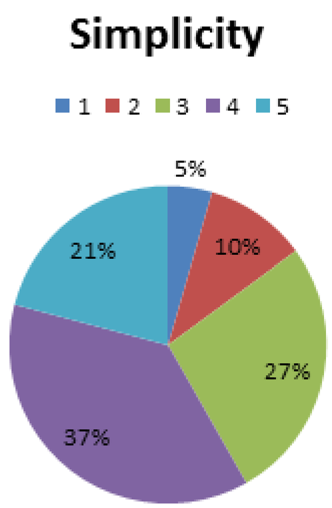

Figure 23: The Importance of Simplicity in UAV Design.

There were 67 responses in total regarding Simplicity, with 58% in categories 4 – 5, rising to 85% in categories 3 – 5. It was expected that **Altitude** would also be highly regarded in this study (**figure 24**). This expectation was borne out from looking at the results, with an identical number of responses, and 64% in categories 4 - 5, rising to 82% in categories 3 – 5. Allied with Altitude was a pertinent optical/RCS stealth comment, **'***UAVs are designed to operate without detection and should not be vulnerable at a low height. This is why I think it is the most important factor in UAV design. Stealth and avoidance from shoot-down are achieved with altitude,'* **ANON.**

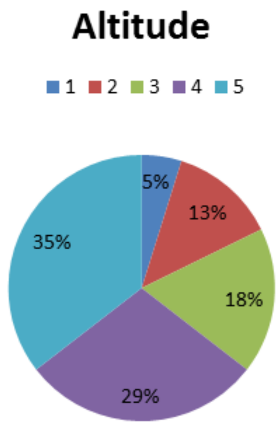

Figure 24: **The Importance of Altitude in UAV Design.**

Another 77 respondents also considered Range (**figure 25**) as a key factor, with 68% in categories 4 - 5, and 93% (categories 3 - 5).

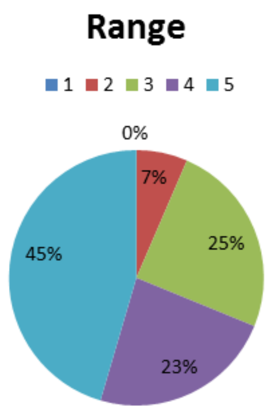

Figure 25: **The Importance of Range in UAV Design.**

Payload and Redundancy

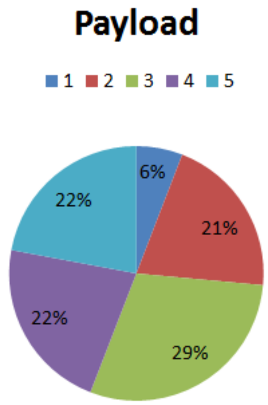

Figure 26: The Importance of Payload in UAV Design.

There were 68 respondents to this question, with only 44% in categories 4 – 5, and 73% in categories 3 - 5. This is a strange response overall given that a platform's ability to carry and deliver a payload is its primary purpose. When considering the typical mass distribution of an average platform (**figure 26**), the empty weight of the platform is related to wing area. With regard to payload, a rule of thumb payload can be estimated at 10 - 15% GTOW, which is a useful metric.

'The Payload of a UAV is its primary function, whether that is sensors and imaging or bombs/missiles. This has to be the most important to fulfil its primary role. ***RN,*** and *'It is crucial to be able to carry the appropriate weaponry for the mission, as this can significantly hamper the types of operations you can do,'* another **RN ANON**

Without adequate payload capacity UAV and drone operation is futile. Consequently commercial hobbyist UAV could be designed to provide as little spare capacity as possible to minimise exploitation opportunities. Given the typical Payload is 10 - 15% of overall platform mass, perhaps to prevent exploitation the ability for **spare capacity should be 10 - 15% of the payload mass/mass design rule?**

Clearly all respondents recognised the key importance of redundancy, and building in a robustness in terms of avionics and operational mission capabilities (whether military or civilian) received 68 respondents, and is highly rated (**figure 27**) with 68% (categories 4 - 5), and 90% in categories 3 - 5. This criteria is also allied closely with Simplicity, already discussed.

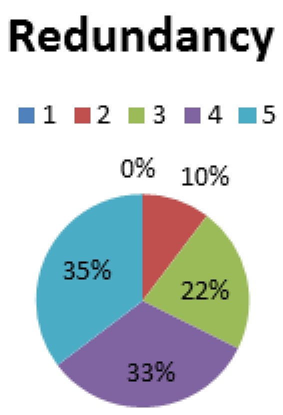

Figure 27: The importance of Redundancy in UAV platform design.

Night-Day capability

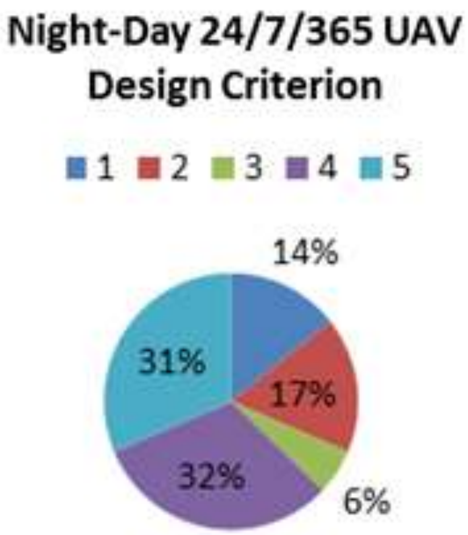

Figure 28: The importance of Night-Day 24/7/365 in UAV platform design.

The overall response to this question seems a little strange if it is taken in isolation from all other considerations. Several typical questionnaire responses are helpful to make better sense of this question: *'Because you want a safe coast you have to work night and day and in all weather conditions.'*, and, *'Our mission has to be done 24/7 partial coverage* *would not offer the operational capability requirement.'* and *'It is part of my job to protect the coast of Qatar so sensing capabilities are very important in all conditions.'* ***Qatar Coastguard***. In conclusion Night/Day capability cannot be undertaken independently of weather capabilities.

All Weather Capability

Military maritime users have a practical interest in the requirement for all weather capabilities: *'Unless it can operate in all conditions it is a useless asset as it will just be sat on the ground. The future nature and locations of warfare are unknown so a UAV has to be adaptable as intelligence/surveillance will definitely be increasingly important in warfare.'* **RN.** There were 35 responses to this category with 83% in categories 3 – 5 emphasising the importance of weather for operational activities. *"Weather is always a limiting factor,'* states another **RN**, and**:** '*All weather ability is vital for the RN because when we are on operations at sea the weather can change so quickly if it was unable to perform in bad weather it would be no good*!' **RN.** The practical problem is weather, on land or sea, and is never the same. **'***Weather at sea is rarely constant, poor weather can appear quickly. UAVs grounded due to high winds wastes money.* (It) *Doesn't matter how good the sensors are if it never flies***,' RN.** The following typical response of all-weather UAV capability importance and value is made clear, '*It will manage the coastal area and offshore area in bad weather when small boats cannot go offshore*' **CoastGuard**.

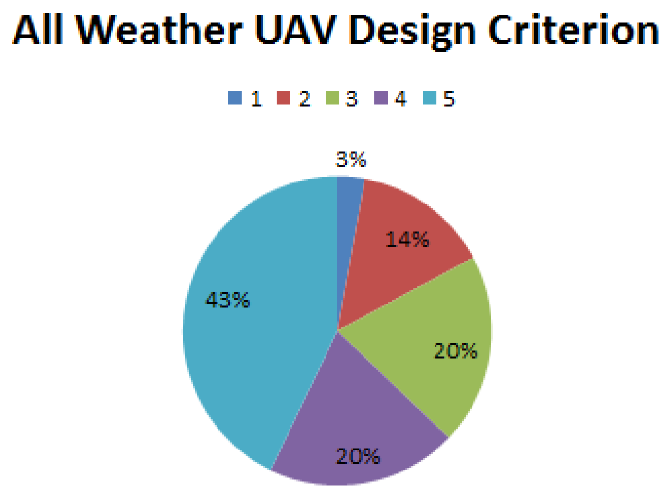

Figure 29: The importance of All Weather Capability.

Persistency

Regarding UAV persistency, typical comments include: *'The persistent system would be required in the event of a piracy incident, enabling surveillance of movement of hostages', although knowing how to deal with the data acquisition, transmission, and storage of a persistent system extracting the useful data in a timely manner is less clear'* **RN.** In this regard the ARGUS-IS System **[130]** (or DARPA's Autonomous Real-Time Ground Ubiquitous Surveillance Imaging System contracted to BAE Systems), is a powerful indication of what technology in this area has already achieved. It is an advanced camera system that uses a mosaic of 368 cellphone cameras, providing video with auto-track of moving objects with Persistics software developed by the Lawrence Livermore laboratory. It can cover a 15 square mile area in detail but retain the wider perspective with a 1,800,000,000 pixel data stream. This is too much information for a human being to process, and presents significant digital storage and data retrieval issues. *'A valid problem of persisting without AIS algorithms in a truly persistent system would provide too much data for use to meaningfully interpret.'* **RN**, and as far as monitoring acts of piracy, and search and rescue needs are very rapidly emerging phenomena it has been said of their requirements: *'This is a fundamental factor of why a UAV is designed. If it is not over a target for the maximum amount of time, it is not fulfilling its role,'* **RN.**

There was a total of 54 respondents to this question, with 66% of the responses were set in categories 4 - 5, rising to a total of 80% in categories 3- 5.

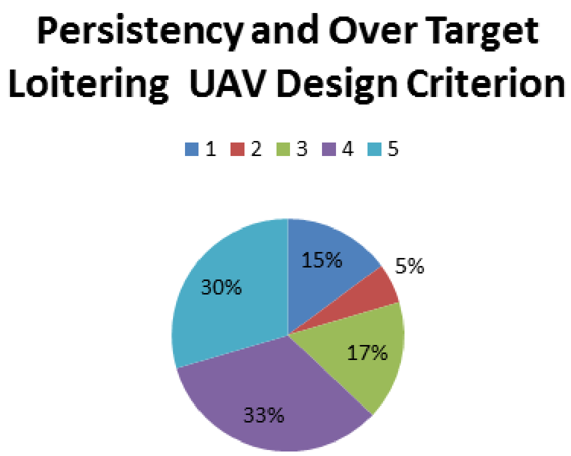

Figure 30: The importance of Persistency and Over Target Loitering in UAV Design.

Graceful Degradation

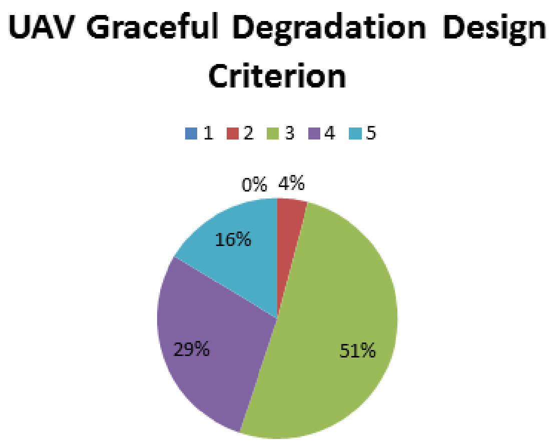

Figure 31: The importance of Graceful Degradation in UAV Design.

As far as graceful degradation goes 49 respondents yielded a resounding 96% in categories 3-5, and this criterion is closely allied with the importance of redundancy, as already discussed. Redundant systems will more likely provide graceful degradation so this should not be a surprise. Graceful degradation rather than catastrophic failure provides the very strongest overall positive responses, also allied with redundancy and graceful degradation is simplicity.

Water-related criteria

Water-related criteria, namely water resistant design and de-icing ability, are important parameters in discussion with operators of both UAV and manned systems, to avoid weather-related platform failure, although the number who could give definitive answers in this area, especially from the military was limited.

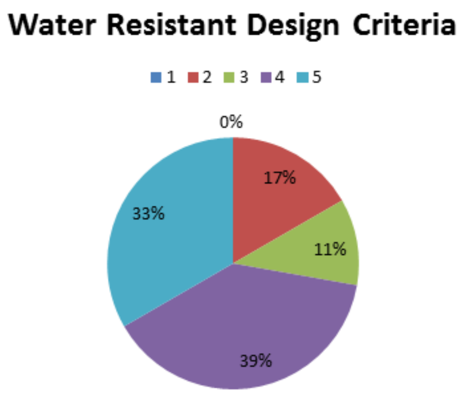

Figure 32: **The importance of Water Resistance in UAV Design.**

There were only 18 responses, with 72% in categories 4 – 5, rising to 83% in categories 3 – 5, with 72% in categories 4 - 5. In the past aerial missions, especially stealth platforms, were limited to night and good weather operations (e.g. ideal conditions in the Nevada desert training and the Iraq War), but not all operations are so close to the ideal training conditions (e.g. Bosnian conflict).

Deicing Ability

One of the greatest constraints to operational use of RPAS is the effects of weather, according to the UK Ministry of Defence. The Ministry stated it is particularly a problem for lighter aircrafts to manage in certain environments, such as areas suffering from high cross winds, icing, or lightning strikes.

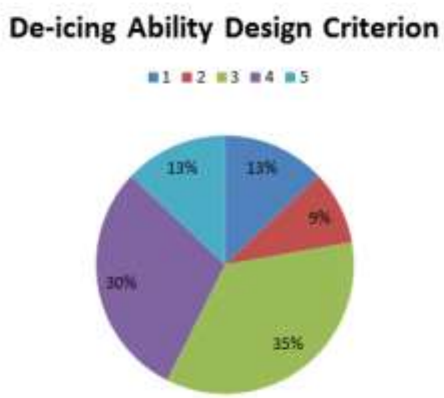

Figure 33: **The importance of De-icing Ability in UAV Design.**

There were 54 respondents to this question. There was an improved overall response in comparison with the previous question. 88% of responses fit in categories 3 – 5. Yet the responses were broadly similar in overall (3 - 5) distribution.

Icing is a major problem for nearly all platform wing surfaces and is an old phenomenon, and thus highly rated (88% in categories 3 - 5). Extreme icing is a known cause of aviation mission failure, but impact can be mitigated. The solution is not new, as microwave communications networks and relay stations in the hostile Northern Canadian Arctic environment frequently experience severe rime icing on microwave relay towers (**Figure 34**) with ice over 1.5 metres thickness **[131]**. However, specialist coatings developed by ESA, working with automotive and aerospace companies like Daimler-Benz have developed ice-phobic properties preventing ice and snow accretion. Icing is not just a problem of global latitude, but altitude as well, affecting platforms from North America to Africa**,** *'De-icing is a common problem encountered at high-altitude world-wide. Each of the above answers should actually be 'it depends'. Everything is driven by the task of combination of tasks that are required. Desert functioning will not need de-icing but mountain rescue searches in Scotland will. Self-maintenance and simplicity will be important in developing parts of the world (I was once an engineer for 2 years in Zambia). For volcano study, cheap and disposable might be best. Altitude and range only helps if flight rules allow them to be used.'* **Prof. L,** Portsmouth Uni.

Figure 34: **Rime Ice on Communications Towers [131].**

Icing spoils aerodynamic characteristics at best, and in a worst case scenario, may cause the loss of the UAV. De-icing capability is required in many parts of the world, in terms of fluid or electrical de-icing. Besides the icing threat are other 'failure-modes', such as bird strike which may damage structural integrity (e.g. a civil Airliner windshield) or impair equipment functionality. Similar to bird strike are the impacts of hail or stones thrown up near runways. Another factor often associated with hail is lightning strike which requires a protective structure against strike, usually with copper foil or mesh. Crashing must be avoided at all costs as UAV crash conditions are very different to manned fighter aircraft, designed to eject a pilot, and often piloted until out of the maximum crash risk zone. A data base of drone crashes is found at the drone-wars website **dronewars.net/drone-crash-database/**. UK MOD is not exempt from accidents having disclosed that two of its 10 General Atomics MQ-9 Reaper MALE UAVs were involved in serious accidents since 2015, with one aircraft decommissioned, and another placed in long-term **repair [132]**. According to the database the loss of the two Predators in June 2011 was because of bad weather and lightning strikes.

12 Self-healing, as an inflight mechanism, is an interesting potential attribute, and is: '*Not only important for UAV's but aircraft as a whole*' RN. Use of embedded glues was discussed earlier: whilst **'***Self-healing will be considered in this project but not at the expense of endurance and capability.'* **Simon, PU.** Even in a project largely focused on sustainability and the hot environment of maritime/ land fire-fighting, **'**(it) *Could be very important for operating in harsh environments,'* **Prof. L** Portsmouth U.

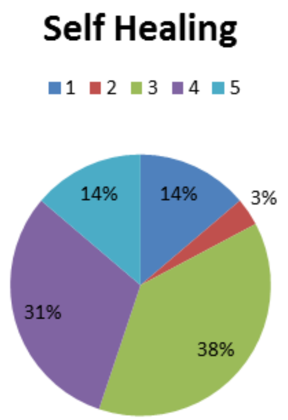

Figure 35: The importance of Self-Healing in UAV Platform Design.

Respondents regarded this category as of high significance 83% in categories (3 - 5), and 45% categories (4 – 5). A useful reflective comment covering all these design materials and platform attributes so far is the importance of recognising synergies between them, '*there is a direct correlation between endurance and loitering for example. Equally there is a relationship to range. It should also be emphasized that these are 'aggregate' assessments of* features I'd be interested in. Variance across different platforms for **different** functions is not just likely, but probably desirable,' and '*For example a long endurance loitering UAV that is helping pattern of life studies and/or providing wearing of people digging in IEDS we would want designed entirely differently from a disposable UAV whose function is to drop a shaped charge on an IED component in a controlled explosion approach to bomb removal. The former will undoubtedly be optimised for higher altitude flight, almost certainly fixed wing, light body, minimal sensor based payload. Contrast that with what will probably be a rotary wing, smaller UAV able to fly very accurately and either land, drop or fire a disruptor of some description. It may also be desirable for it to be cheap so if it lost the loss is easily absorbed. We may even want it to be expendable, do the disruptor integration and cooperation is controlled as part of the system*.' **Lt Col,** British Army.

Overall quantitative evaluation with 3 dimensional analysis of: Endurance, Range and Mass, may be used to limit platform exploitation. Considering various material parameters and factors such as: strength and redundancy, and possible green materials, improvements in robustness using smart composites: glass fibre, optical fibre with embedded sensors, or carbon nanotubes, with encapsulated glues, are of great interest. Such integrated smart functionality may provide several mutual gains, rather than targeting introduction of 'green' materials *per se*.

13 (a) Autonomy and Artificial Intelligence related factors There is a general level of understanding today as to the important role of Autonomy and AI in augmenting naval situational awareness, in an environment historically strongly dependent on trained human decision making. According to Greg Allen, Artificial Intelligence and National Security, however, '*AI's role as (an) innovation supercharger (could) deliver a strategic, and perhaps permanent, economic and military advantage to a country that develops a significant lead in exploiting AI applications. Because of this recursive-improvement property, and because AI applications also facilitate the automation of labor, it is possible to imagine a breakaway economic and innovation growth… which then* *guarantees it will be the first to discover the next generation of innovations,'* etc. However, at a more immediate and practical day to day military tasking level, naval operations see it at a much more superficial level. '*Artificial intelligence should always be, like cruise control when driving, an intelligent addition to, not replacement of human decision making.'* **RN** comment. Loss of a pilot can be avoided and risk to life minimised, and '*As in many cases the point of a UAV is the removal of a human from danger, so by having an increased range such UAV would do that.'* **RN ANON.**

13 (b) Power consumption etc.

Power is also a critical system parameter, as the minimum level of power defines the least fuel consumption, with minimum power expended to achieve the maximum flight time. This is achieved multiplying the drag for minimum power conditions by velocity, also in the minimum power condition. Standard equations for velocity and drag in minimum power conditions are available **[133].** Similarly for quadcopter power requirements UAV platforms have a clear relationship between energy requirements and total UAV weight**.** In a similar manner Range, the total distance an aircraft flies between takeoff and landing, is limited by fuel capacity, calculated elsewhere **[134]**. In practical terms: '*Endurance is very important, the ability to give the target a sustained 'staring at' is often invaluable in successful EOD work. That is why energy matters to us. That said, I'm pretty agnostic about what the source is. I'm more interested in its outputs,'* **Lt Col,** British Army**.** Future work will look to establish civilian and military platform empirical relationships dependent upon intrinsic platform properties.

13 c) Tampering and Jamming

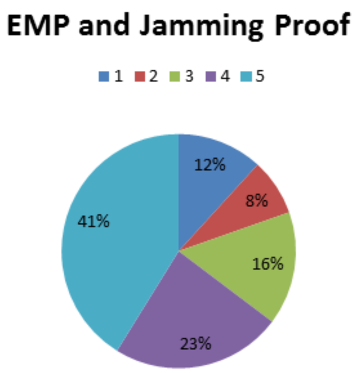

Figure 36: The importance of EMP and Jamming Proof UAV Platform Design.

There were 51 respondents, with 65% in categories 4 – 5, rising to 80% in categories in 3 – 5. Tampering and Jamming sits well in consideration with tamper proof Software and Hardware. They are also similar in the number of responses provided. The requirement for, and understanding of cyber security is clear, with the requirement for future countermeasures.

Software and Hardware Tamper Proof

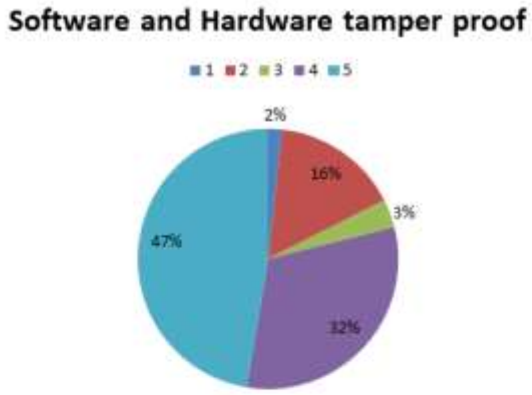

Figure 37: The importance of Software and Hardware Tamper Proof UAV Platform Design.

There were 57 respondents to this question, 79% of responses sit in categories 4 – 5, with 82% of the answers in categories 3 - 5. This is interesting as responses are clearly firmly in either the 'very important' or 'not important' camp.

13 Legislation: Fitting AIS/GPS Legislation may ensure certain platform technologies are required, or banned, one route for a Government to determine what industry would otherwise develop proactively according to market forces. There were 55 responses to this question, with 69% of respondents in categories 4 – 5, rising to 77% in categories 3 – 5.

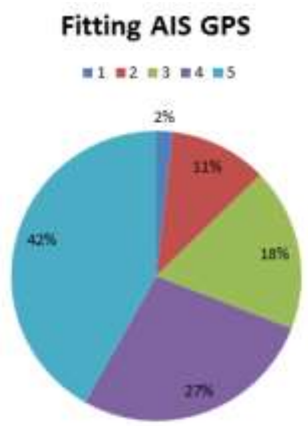

Figure 38: The importance of Fitting AIS and GPS in UAV Platform Design.

To some extent legislation already exists and is determining actual payload limits: *'The design of the UAV has not yet been established but it will be restricted to 20 kg all up weight due to CAA UAV legislation'* **Ex-RN.** Certainly the majority favour legislation for AIS and GPS, whereas GPS benefits the terrorist, AIS does not. But usually someone else is expected to 'make it happen'. The reality is there are already several laws in place, such as the 2006 Terrorism Act, Sect. 5, outlawing preparation for acts of terrorism, which make the act of attaching a bomb to a drone illegal. Or Sect. 57 of the 2000 Terrorism Act which makes *possessing* such items illegal. Or Sect. 58 of the same Act, which makes *teaching* others how to build, acquire, or operate such a device illegal. Since things like this *are* already illegal, what future laws or frameworks will be proposed to counter those who have little or no intent in abiding by them?

Legislation has commercial implications, adding AIS/GPS will carry a cost, one a large platform drone supplier can 'absorb' into overall unit cost with little difficulty, a smaller hobbyist manufacturer on the other hand may not be able to do this due to practical load limitations, or at a cost increase which prohibits most of his sales, effectively forcing the business out of the market.

13 Mandatory Compliance? Allied to issues of legislation is actual compliance with civil regulations, which is an enforcement issue. Currently Air Traffic Controllers (ATC) rely on voice communications, which would be impossible with UAVs as they rely on data links for control updates. Besides the risk of terrorist hacking there are also a growing number of UAV-related injuries. The importance of Drone Infringement Safeguarding was raised recently with Nov. 2019 the focus of a NATS Airspace for All report author Steve Hutt, who provided several key conclusions to problems **[135]**. Namely, ADS-B broadcast from a test drone via transceiver could be detected under most circumstances, but not at ranges beyond 10 nm from ground-based receivers. It could be detected by General Aviation transceiver fitted aircraft, to give ATC increased confidence in a drone's position which is otherwise difficult to see even when a pilot is warned a drone present and the traffic display advises of the drone's position. Visibility is impacted by the look angle, and variable low contrast background. In most case pilots were highly unlikely to see drones unless very close against a plain high contrast background. At 5 nm range pilots with sufficient reaction could avoid drones. There are grounds for 'tightening up' this area after notable public events such as the Aug. 2013 drone footage crash at the Great Bull Run, Virginia where 4 spectators suffered minor injuries, and the 2014 April Triathlon crash, Geraldton, Australia, where an operator lost control of a drone, which hit a runner in the head, causing minor injuries, besides other incidents **[136].** The low visibility of most small COTS UAVs combined with low Radar Cross Section (RCS) materials, e.g. GRP, make drones or UAVs hard to detect at the best of times. Our own work with liquid crystal display coatings show it is possible to make a potential military high-end platform harder to detect **[98].** In the UK, a programme called ASTRAEA is underway to provide the necessary technology and standards in order for the Civil Air Authority (CAA) to certify safe UAVs use in non-segregated airspace alongside general air traffic, which includes sense and avoid technologies to allow UAVs to avoid collisions and communicate with ATC. ASTRAEA is concerned with securing the code to the UAV so no one can tamper or hack it, and develop a system of autonomy with its remote controller for example:

i. '*Should I do X?'*

ii. If there is no response, 'Unless you say otherwise, I will do X'

iii. If there is then no response, the UAV does X on its own **[137]**. However, *'Man-in-the-middle attacks from skilled hackers, -can remotely down or hijack a drone if the C2 signal is not secure.'* **Ex US Naval intelligence,** And as such mandatory AIS and CAA legislation are important to push, as is maritime environment drone AIS, and securing against cyber-attack or identified drone use. A terrorist may wish to crash a small drone into the cockpit or undercarriage of a large passenger jet, especially on take-off when loaded with fuel, or slowing on landing. 'Mingling' between unmanned/manned platforms is disturbingly easy, see **figure 9**.

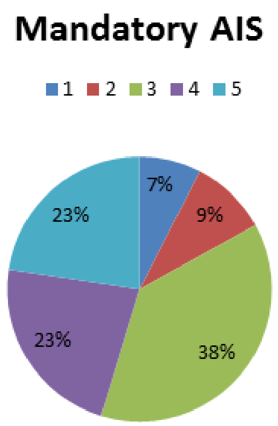

Figure 39: The importance of Mandatory AIS in UAV Platform Design.

Following on from the previous question, there were 59 respondents to this question with 46% in categories 4 - 5 but rising more dramatically to 84% in categories 3- 5. This question should also be viewed in the light of the next question looking at CAA Legislation.

CAA Legislation

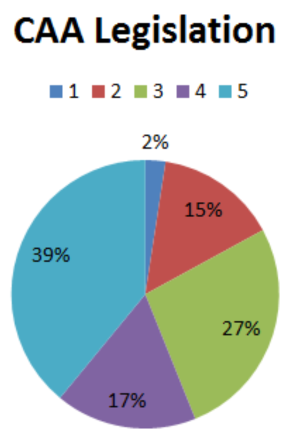

Figure 40: The importance of CAA Legislation in UAV Platform Design.

There were fewer responses to this question, specifically 41, but closely similar with 83% in categories 3 - 5. These two factors are strongly supported by the respondents. Equally, fitting AIS/GPS is seen as an important factor and if GPS is platform available AIS should be fitted, so asymmetric actors cannot simply benefit from GPS data.

Privacy

This issue is a growing concern, especially in the realm of civil liberties, and since widespread use for civilian monitoring during CV-19, with a range of visible, NIR, and thermal cameras, loud speakers, disinfection equipment etc. has vastly expanded. Even before CV-19 it was widely recognised privacy-related legislation in the US, UK, and EU, and current regulatory mechanisms do not adequately address privacy and civil liberties. A recent paper by Finn and Wright, argues that a combination of top-down legislated requirements, and bottom-up impact assessments are needed urgently to adequately address privacy and civil liberties **[138]**. Other liberty minded organisations such as **BIG BROTHER Watch** advocate for restraint on the ever-extending outreach of the state, assisted by new technologies, into diminishing citizens' rights **[139]**. A 2014 technical report found 93% of US adults opposed drone use to monitor people's daily activities around their home. Whilst the legal debate surrounding UAV use by law enforcement agencies continues to be established as the US Court tries to keep to the plain intentions of the Fourth Amendment and the Founding Fathers of the US constitution **[140]** most respondents to a US drone survey opposed drones for monitoring people at work (77%) and in daily activities in open public places (63%). For surveillance in **both** public and private places, opposition to drone use was highest amongst persons with lower incomes and those who preferred government to focus on individual rights over public safety. High levels of agreement were found in people's Aerial Drones, Domestic Surveillance, and Public Opinion Survey of excessive surveillance of Adults in the United States **[141]**. A repeat of this survey in the aftermath of CV-19 would be most interesting to see how public perception may have changed.

14 Ethical UAV design is summed up at the start with the comment of "*Any newly engineered concept or product has a responsibility to be ethically created and its life cycle environmentally analysed to ensure minimum impact*." **SW, Plymouth U.**

It is necessary to study the ethical dimensions of a technology and establish the extent to which it is designed for good practice, increasingly as we have the power to control how a UAV 'thinks' and acts, and to 'create' the right kind of value system. In the same way autonomous drones need ethical design considerations so they behave according to societal expectations, and as far as the ethics of warfighting goes is required to operate in a reproducible manner, potentially more consistently than humans. According to Elizabeth Quintana several key enabling tasks currently undertaken by a pilot on a manned aircraft must be reallocated for an unmanned vehicle with a range of functions including: sensor and other information fusion, communication management, optimal path planning, collision avoidance, trajectory motion and path following, target identification, and threat evaluation, engagement decision, weapons deployment, abort decision making/response, task scheduling, and cooperative tactics **[142]**. Extensive work by Luppicini and So concluded there were various Technoethical constructs arising from commercial UAV use, notably: ethical, political, socio-cultural (e.g. privacy, malfunctioning), economic, privacy, unethical action, safety, morality, and legality **[143]**, which lack real scrutiny, due to the emergent nature of UAVs, in my view has much commonality of new ground to be explored alongside comparative military platforms.

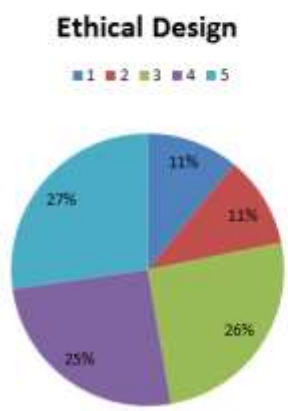

Figure 41: The importance of Ethical Design in UAV Platform Design.

There were 55 responses to this question, about half of the maximum number of responses to many of the questions set. However this factor still seems to be strongly appreciated and valued by both military and civilian responses, with 52% in categories 4 – 5, again rising to a high value of 88% in categories 3 – 5. Ethical design for fire-fighting applications has attracted much recent interest. '*The idea of a swarm of firefighting drones came from the news about the Grenville high rise building disaster. Having been trained in shipborne frefighting and damage control methods I quickly realised drones could have potentially saved lives by firefighting and supporting human firefighters. My project to me is about improving the opportunity to save lives as our population is growing and available housing land mass is decreasing. This means high rise buildings will become more common.*' **SW, Plymouth.** Such drones fabricated to survive harsh operating condutions using heat resistant materials would also be of interest to the military as well. It is certainly clear that drones used for various aspects of enforcement are now used routinely with at least 1578 US state and local police, fire and public safety agencies having acquired drones in recent years **[144].**

Omission of Mounting Points

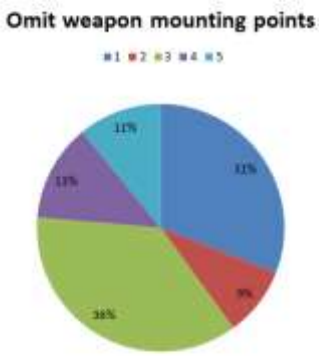

Figure 42: The importance of Fitting AIS and GPS in UAV Platform Design.

Overall this was perhaps the most puzzling response of all the questionnaire responses and yet perhaps the one that would have provided the most clear division! There was only a small number 24% 'valuing' the omission of mounting points, rising to only 60% in categories 3 – 5. This unexpectedly low figure may be due to the military tendency to think it is good to have the ability to attach extra materiels (e.g. ordnance), whilst civilians may be less aware of the risk of potential weapons mountings. This is an area for further follow up, and the cognitive dissonance between upstream/downstream and military/civilian users, would be one area manufactures and users should discuss together. *'My concerns with 'ethical UAV design' is that it is extremely broad as a term and different aspects of it wil be of varying effectiveness. For example, a commitment to use ecologically friendly materials in UAV manufacture could be both laudable and effective. The ability to 'design' UAVs that cannot be used for nefarious purposes on the other hand is much harder to achieve, although different measures will have varying diffuculties to bypass. 'Stopping' hardpoints or explosives being added to the UAV is almost impossible. Putting elements into the design that increase radar reflectivity on the other hand may be much more difficult for a criminal or terrorist to remove.'* **Lt Col,** British Army. Which leads into consideration of mounting points.

The fitting/omission of mounting points also raises some wider discussions about multirole capabilities of small drones vs larger platforms. *'But as multirole possibilities often drive cost up, and size, and complexity, and servicing demands, they make much less sense for other functions. A cheap and cheerful quadcopter to look around the corner or over a compound wall for an infantry section is better being cheap, light and small than being bigger, more expensive and able to do 'other jobs ' too. Even fitting hardpoints to that small device radically changes its endurance as they are a high percentage of the ovrall mass of the UAV,'* ***Lt Col***, which is of course radically different to the opportunity cost of fitting an equally small hardpoint to something signifcantly larger like a Global Hawk. And furthermore '*a MQ-9 Reaper can be a remote controlled 'close air support' platform, providing air support weapons to ground combat, or it can fly for much longer without weapons as purely a surveilance platform*.' **Lt Col**. That makes total sense as a multirole capability, and practically once ordnance has been delivered such a platform is still capable of continuing in a surveillance role for some time after, even to help evaluate the effectiveness of the mission.

16. **Design differently.** There was generally little response or tendency towards designing a platform differently. *'The concerns are rather different, but the problems they create are the same: personal data security and OPSEC',* **RN ANON** <u>*and*</u> *'Given the differences in use this is an important topic. Consideration also need be given into how the public perceive drones as negative technology. UAV design safeguarding welfare, safety*

and privacy of the public needs to be highlighted to the public to help promote their acceptance, **SW,** PU.

17. Bespoke Platform design The risk in design of modification of civilian platforms is appreciated by military personnel, '*Military-grade platforms should be such that civilian grade platforms could not be altered easily to mimic their design*' **RN**, and '*The platforms must be licensed and legally approved to avoid any unethical usage such as terrorism,'* **Colonel, Kuwait.** I am sure a dutiful citizen will follow the required licensing and approval actions, but will a terrorist?

Asymmetric actors might use modified-UAVs as drones to target individuals or groups so they are injured or killed, damage or destroy property, or conduct activities to disrupt the target state, impacting economic or damaging psychological / morale damage to a wider civilian population. However, *'Dual-use cannot be legislated against- at least not in states like China. Plus, how do you prevent a line of code from a civilian coder being used in a military item?'* **Prof. L,** Portsmouth U. This inability to prevent post-sale physical or digital adaptation leaves only pre-sale legislative action. *'Unfortunately, the militarisation of civilian engineered products is inevitable. Control by legal enforced frameworks need to be put in place. This will enable military development to happen but allow for easier detection of criminal product development outside of this framework.* '**SW, Plymouth U.** how this allows for easier *detection* in practice is unclear.

Embed non-human responsibility.

A small number responded to this question, 12 responses with 11 'yes' and 1 'no'. '*The ethical grey area connot be fully considered by AI responsibility for taking life and shoud not be 'outsourced*', **ANON.** Today, very fast algorithms already assist or replace human decision processes entirely, but computation errors, like human ones, can occur with unforseen and widespread consequences. In October 2016 the UK pound lost 6% of its value, with blame partly due to algorithm trading. If two future militaries 'face off', having conventional or nuclear capability, reliant on 'hair-trigger' algorithms, which respond dynamically to each other like twitchy gun-slingers, the potential for disaster may literally result in widespread fallout **[145].** Of concern are unmanned platforms operating in the 'grey zone' at a sub-hostilities threshold, perhaps forward projected in areas of 'sea-denial', and by intention to 'de-escalate' conflict. The more realistic concern in the short term is perhaps the human response to rapid processing autonomous drones, and this issue has been raised as recently as January 2021 by General John Murray, head of Army Futures Command '*When you are defending against a drone swarm, a human may be required to make that first decision, but I am just not sure any human can keep u*p' **[146].** Also *'Design features would have to make the system compliant with safety and law of armed conflict legislation, including Artice 36 weapon reviews which are about the ability of the system to be employed successfully within the law of armed conflict. This is a consideration where ethics overrides cost as a driver.'* ***Lt Col***.

18. Negative impact of military use on civilian uptake is clear with several responses: '*The media's appetite for sensualising news stories such as the recent airport shutdowns due to drone flight and stories of how home deliveries will be made via drones etc. there are three distinct phases of pubic acceptance to new technology, Criticise, mock, and acceptance. Civilian Drones/UAVs are still in their critique* phase.' **SW, Plymouth Uni.** and '*In this stage civilian uptake is impacted by major news events',* **ANON.** I will come back to this point in my summary as it has serious consequences.

19. **Responsible human decision control process**. There is a general level of understanding as to the role of AI in augmenting the naval situational awareness, in an environment strongly dependent on trained human decision making. '*My understanding it is a decision-making process that has two distinct categories; intuitive and analytical decisions.* (It is) *Used by people typically commanding and leading an emergency for example.*' **SW,** Plymouth U. However, from the responses, only 12 out of 140 (from c. 600 approaches), is hardly overwhelming but a more carefully worded and targeted question might have achieved a greater volume of response.

Of these 12 responses, ten were 'yes', and two 'no'. *'Meaningful human control was proposed as a means to get past the impass on what 'autonomy' meant in efforts to ban Lethal Autonomous Weapons Systems. But that too has not resulted in progress in creating any legislation because it hits the same boundary definition problem, and the boundaries and definition are vital for functional laws. Stating that 'meaningful human control' is essential is easy to agree with. Working out what constitutes '**not quite meaningful enough**' is however the vital determinant for establishing a boundary in law*,' **Lt Col**. But these questions are *so* dependent on context and simultaneously agnostic of technology that attempts to create a law currently continue to fail. Either it is very difficult to create a workable law, or it may be impossible. This is certainly an area not going to be resolved in the short-term.

20. **Do you embed?** Few individuals would, or could, respond to this category but, '*All the responsibility should be on human decision makers not UAV.*' **Saudi Naval Captain.** Furthermore, concerns of non-human AI controlled UAV in 'busy' inhabited urban areas, yielded one response, '*Given the predicted usage is in urban areas, it would not be appropriate to do this.*' **SW,** PU.

22. Machine-based learning Less data was provided here but: '*Smart technology' could be used to help the survivability of the drone given the hostile environment it will be operating in,'* **Ex-RN.**

23. Exclude Payloads this sits with the omission of mounting points, '*Military sensor technology could be used for search and rescue missions if the cost of the technology decreased. Design at this stage could be considered for certain civilian drones with specialist uses.'* **Simon,** Plymouth U. There are concerns at limiting civilian access to life-saving technology developed by the military. *'If you are saving lives by surveilling Mediteranean boat crossings, the best technology will save the most lives*,' **Prof. L,** Portsmouth U. So to exclude civilians using 'the best' technology whether it might be used in a possible 'clandestine' manner, would be morally wrong if those in peril at sea were to lose their lives unneccesarily. I think this is a valid point as the first Royal Naval Philips fire-fighting maritime camera, has since profitted civilian mariners generally through military to civilian transfer technology.

24 Kill decision A significant question from my perspective, but with limited military response and also few civilian responses (perhaps more surprisingly), with a general unwillingness to engage or be attributed, typically: '*This matter must be carefully considered before it is allowed to become a fact of warfare. We must balance the AI technological edge with the ethical implications."* **ANON,** and '*I believe this (decision) should be taken by human only*.' **Saudi Naval Captain.**

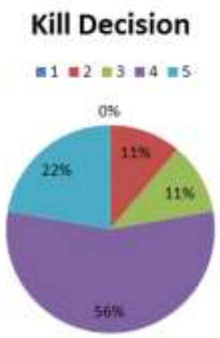

Figure 43: The importance of Kill Decision in UAV Platform Design.

This is the last Pie chart presented in my report, and one of the most important criteria I would have wanted more ammunition for. However there were only 9 responses in this category. When considered, though 78% lie in categories 4 - 5, rising to 89% in categories 3 – 5, which is a relatively strong indicator of high regard, from an ethical viewpoint, albeit a small data set. A comprehensive study on drone ethics, **[147]** by Mary Manjikian, at the US Army War College's Strategic Studies Institute presents the case for the ethical arguments against drones, based upon technological specifications e.g. do these weapons make them more or less discriminating than manned systems? She identifies arguments such as: (would an honourable nation use this kind of weapon?), the relationship with adversary arguments (is using this weapon an appropriate way to treat enemies?), the effects on the international community and legitimacy (are we changing the laws of war?), and the relationship to specific doctrines, strategies, and tactics (e.g. just war situational ethics how does the use of these weapons affect our ability to fight a just war?)**.** Manjikian is right to raise these points in the context of work by Aleksander Fatic '*The Ethics of Drone Warfare*' as his paper investigates the compatibility of modern technologies of warfare, specifically use of offensive drones, with traditional military ethics and suggests the new technologies radically change the value system of the military in ways which make large parts of traditional military ethics inapplicable, developing a conceptual strategy to explore the compatibility of drone warfare with traditional military ethics, showing mixed results at best **[148].** Concerning the multi-dimensional '*moral maze*' of drone attacks, it is unsurprising that as far as ethics and regulation go rogue states and non-state actors are unconstrained by the Laws of Armed Conflict, which enables them to gain advantage using tactics that **cannot** be reciprocated by law-abiding nations.

Drone use is already *prima facie* morally controversial because it fails to satisfy key conditions for justified use of military force, does the military need courage? -the drone operator doesn't need it, does it require sacrifice? It is costless in terms of risks to ones own soldiers. Justice appears to have no role in drone war operations, except in targeted killings of '***the wanted dead or alive***' category, and what is the role of traditional military virtues such as respect of the enemy when an operator 3000 km away doing a '9 to 5 job' completely disconnected from the consequences of their actions? It is in this capacity Michael Boyle advocates American drone-based targeted killing represents a fundamentally new challenge to traditional legal and ethical standards of armed conflict. He argues the novelty of drones flows less from the technology itself than from the US Obama administration's articulation of a *presumptive* right of anticipatory self-defence, which allowed it to strike anywhere in the world where Al Qaeda and its allies were present. This is a perhaps a distortion of traditional ethical principles, but from a Sun Tzu warfighting perspective is deemed perhaps both just (minimising the overall cost/damage of delaying actual warfare), and necessary. This '*right*' was continued by the US Trump administration, notably the Jan. 2020 killing of Iranian General Solemaini in Iraq, unlikely to change in the light of future administratons as it is perceived as simply *too effective* not to use. However, pre-emptive justification is a worrying trend, reminiscent of the precog '*thought crime'* parallels in ***Minority Report*** **[149]** where we intervene, in our case with lethal force *before* any crime has taken place**.** It isn't surprising in this context according to *Human Rights Watch* that '*A pre-emptive prohibition on the development and use of these weapons is needed*' **[150]**. However, the reality is these platforms **WILL** be used, and questions arise as to *how* drone aircraft may function in the future and *what* ethical issues *may* arise for future development, with the inevitable deployment of autonomous drones **[151]**. The killing of General Soleimani in January 2020 was just another step in the ongoing gladiatorial national use at sub war threshold, more akin to a mediaeval champions' encounter; which is preferable to full conflict. A brief review of public historic US - Iran 'drone wars' began with the US shooting down an Iranian drone in March 2009 over Iraq. In December 2011 Iran in turn shot down a US RQ-170 on a spy mission from Afghanistan. Whilst in May 2017 US fighters show down 2 Shahel-129s in Syria. In December 2017 the US accused Iran of supplying drones to Houthi rebels in Syria with Iran claiming to have taken down a US Global Hawk in the Gulf of Oman, and in July 2019 the US downed in turn an Iranian drone over the Persian Gulf.

The death of General Soleimani takes the US – Iranian drone war activity to a new level, and it may prove counter-productive to future peace efforts. After all Soleimani was not an Iraqi insurgent, nor terrorist, but a General of a foreign national force. Legally what crime had been committed at the point of execution? What of civilian collateral deaths and damage? Incorrect target designation of civilians unfortunately does occur, with one mistaken Predator audio transcript having taken out a convoy of civilian Afghan women and children after several hours of debate starting with a Predator Pilot reviewing a scene, stating '*Is that a ... rifle?*', and the Sensor Operator coming back with '*Can't really tell right now, but it does look like an object*.' Operators will be less inclined to deliver ordnance if they believe their actions may not stand up under legal scrutiny; although the knowledge their actions *were* being recorded did not prevent this incident.

To counter lack of ethical accountability, recording all imagery, data, signals should be mandated for post operation justification, and as evidence if required in international court of law, and for military platform decision making, given recording flight operations is common place for training and mission evaluation purposes. This is consistent with the All Party Parliamentary Group on Drones and the Birmingham Policy Commission, who have both called on the Ministry of Defence to be more transparent in its actions.

24 Autonomy: According to Krishnan **[152]** there are 4 types of autonomy related to drones: (i) *Teleoperation* which involves continual remote control. (ii) *Pre-programmed autonomy* involving a range of pre programmed computer director activities. (iii) *Supervised autonomy* when problems with drones occurs drone operators make corrections, and (iv) *Complete autonomy* In this case a robotic drone system can identify and handle probems that arise without human intervention.

Collision avoidance is one of the enabling technologies that define autonomous drones at a pre-programmed level. Artificial Intelligence also plays a key role in smart weapons engineering of autonomous systems in military operations. Although intended not as a report discussing LAWS to great extent, it is worth considering the rapid developments in this area. Military LAWS drone applications *are* different; they may be programmed to undertake certain decisions automatically, so what of circumstances where kill capability *should* or *should not* be denied? Although ethical drone end-user examples exist where autonomy may be important, e.g. humanitarian applications rather than sustainability platform designed platforms *per se*, UAVs may be designed to exclude potential weapon mounting points, yet still equipped for multiple modular sensor payloads, such as the UN FALCO UAV. In response to Parliamentary debate in 2013 Foreign Office Minister Alistair Burt outlined the Government's position in the debate led by Nia Griffith: '*As a matter of policy, Her Majesty's Government are clear that the operation of our weapons will always be under human control as an absolute guarantee of human oversight and authority and of accountability for weapons usage*.'

Nonetheless, technological developments continue in this field. There are certainly ethical and social values connected to increasing weaponisation of autonomous technologies. Although LAWS *might* function indiscriminately in the field, it is conceivable that their use could reduce or even eliminate harm. One UN report **[153]** discusses the main ethical considerations, and the drivers increasing autonomy in asymmetric conflict, and how weaponisation of autonomous technologies may impact, and threaten fundamental and widely accepted ethical principles, enshrined within the UN Charter and the Universal Declaration of Human Rights. Other recent urgent reports are trying to establish rules and protocols under international law regarding human rights and use of drones and robots **[154]**. Allied with LAWS is the increasing use of AI to promote autonomy. This synergy extends the reach and persistence of ISR and weapon systems, to provide information advantages for multi-faceted domain understanding and assessment, decision-making, and thus determining battle tempo. AI provides the ability to scale physical materiel, and battlefield points of '*presence*' increasingly independent of the *real* numbers and locations of human combatants. Synergies between networked platforms may create networked *mass*, large numbers of interconnected soldiers, and materiel, contributing to resilient intelligence, surveillance and reconnaissance networks.

Criticisms of totally autonomous war-fighting systems assert that AI controlled autonomous systems are simply 'ethical cover' for an otherwise mechanised killing act. There is some justification for this position, since one of the combatant's orders is to kill those who refuse to surrender, and if the purpose of a soldier is to follow orders to the letter, and machines do this *more* efficiently than humans, without suffering from fatigue, stress, PTSD etc., then what is the point of risking our own forces? However, they are unlikely to be given an entirely 'free hand' even if this is possible. Use of human-automation 'collaborative teaming' as already introduced is more likely, but will require human 'trust' in the AI system defined as the '*attitude that an agent will help achieve an individual's goals in a situation characterised by uncertainty and vulnerability*' **[155].** As yet no one has considered the possible suffering ethical dimension for non-human AI combatants, even if 'suffering' is decision-conflicted states resulting from a machine learning from so many scenarios that it may blur assessment between 'friend and foe'? According to General Sir Richard Dannatt **[156]**, **'***Technology has also produced mixed benefits in the field of military operations, and posed additional dilemmas, many of them moral: remotely piloted vehicles, some of them carrying missiles, non-lethal weapons, surveillance and search equipment, as well as networked capability, all pose questions about their use on the battlefield',* and furthermore, '(it) *Depends on the capability. There are some things that shouldn't be released (such as lethal weapons) to civilians without significant regulation behind it us'* **Ex-naval intelligence.**

23. **Countermeasures** a) Where design mitigation is not sufficient countermeasures will be required. Although we will not specifically discuss countermeasures in any great detail in this report these obviously depend upon the threat posed by both military drones and civilian modified UAVs, "*Civilian UAVs are used by nefarious actors in asymmetric warfare, hence they should be designed to be as difficult to convert as possible for such nefarious uses.*" Australian **DroneShield**.

b) **Greatest threat posed by UAV systems:** '*Asymmetric warfare- using drones to kill or enable other killing technologies (for example directing fires or creating distractions for car bomb attacks etc.)'*

c) **Danger of potential UAV attacks on military targets:** "*It is still a relatively new area, and people tend to be reactive –hence there is a lot of awareness of drone danger where drone attacks have taken place e.g. Middle East, but not for example domestically in UK or US.* **Drone Company ANON** The remoteness of modern war conducted thousands of miles away has little impact today on the lives of a typical UK citizen, except in terms of rare reprisal 'terrorist' attacks, that by their unexpected and violent nature, strongly affronts our senses as immoral and unprovoked attacks upon a peaceful and law-abiding country.

d) **On civilian places:** '*There is still an emerging threat that people are learning about the Gatwick drone shutdown incident has helped to promote'*, **Australian source**.

e) '*This is generally less concern, especially given general public can't use drone countermeasures,'* Australia**, Droneshield**.

25a. **Earth Observation** and humanitarian applications requires urgent response: '*Rapid and flexible deployment, for detailed damage mapping and Search and Rescue Applications.'* ***ANON.*** Certainly drones and UAVs have been used to effect numerous rescue at sea. Whilst testing a drone to detect sharks off a beach in New South Wales in 2018, Australian lifeguards spotted two men struggling to swim in violent surf. The drone was then dispatched to drop an inflatable pod, which the men used to reach shore safely **[157].** The RNLI has recently conducted its own tests in the UK.

28. **History** Although drone platforms have already been discussed historically the corporate applications proliferation has been remarkably fast: '*DroneShield is one of the global pioneers in this space, starting with acoustics-based drone detection about 5 years ago, gradually moving to a wide suite of products in response to end customer requirements*.' ***DroneShield****.* And a not uncommon story from another recent start-up company: '*Our company began repurposing our RF sensors for drone detection a few years ago. We found our detection solution to be very effective and have successfully integrated with larger systems such as L3's Drone Guardian,'* **US Ex - military.**

Similarly university researchers have quickly leapt on the UAV bandwagon, '*We started using UAVs in 2015 and since that we have increased their use and their capabilities. At the moment we are getting 5 new equipment equipped with hyperspectral sensors, LiDAR and new high resolution thermal cameras along with a new fix-wing UAV for extending the special scale of our coastal research mainly,'* and '*We have 7 UAV (<8kg mtow) for research equipped with RGB. Multispectral and thermal sensors. We use them mainly in the fields of environmental monitoring, marine research and archaeology survey*. **Uni Cadiz.**

Temporal Surveillance Frequency

There is no universal specific frequency requirement but frequency requirements are universal. The responses from Qatari maritime professionals for all daily supply of surveillance data is interesting, with most responses fell in the category: 2-6 times daily. Respondents frequently commented on this topic area: *"For maritime surveillance near real-time information is needed* (with) *up to 20 min delay.',* and *'Immediate detection of vessels in distress,' and if aided by covert UAV platforms, 'Correct identification and accurate tracking.'* Most end-users are aware of the differences in sensors information updates, being not as frequent practically for most systems as for AIS. One response from Qatar '*4-5m rib* (size)*, look for clear view of any vessel entering Qatar Coast illegally to be able to complete successful mission without putting any Coastguard personnel in danger.'*

b) Costs to build **'***The unit cost of the drone will need to be as low cost as possible due to the intension of using it in a 'UAV swarm'* ***SW, PU*** '(It costs) *About £20K to purchase all of the UAVs and sensors that we run; operating costs depend on the remoteness of the deployment.'* ***Prof T. Portsmouth,*** and '(It costs) *c. £8000 to build and operate'.* '*Initially we were limited to Phantoms; we recently upgraded to the Wingtra VTOL with multispectral (VIR) scanner*.' ***Prof T. Portsmouth,*** and *'It demonstrates that RAS implementation is not simply a process of platform acquisition: it is a digital transformation which needs to be tackled as such.'* This costs range is unfortunately affordable to a terrorist organisation.

c) Finance Military and civilian customers both expect a great deal of capability at ever decreasing costs, whether this is an unreasonable expectation or not. '*lower than the cost of the existing system providing (it gives) the same or better functionalities Highly reliable with availability not less than 99.9%*'. The pressure and demand to provide *more* functionality, with *greater* reliability than current means upstream must strive ever harder to improve provision at lower passed on end-user costs, which include costs to build, ongoing running costs, and consumables.

6 SUMMARY

6.1 Policy Recommendations

There are policy strategies proposed from existing literature, and from our report, which should inform effective response to modified small COTS UAV systems. One report [158] recommended UK Government should develop a communication strategy to help understand the strengths, weaknesses, opportunities and threats of swarming drones. The UK should update existing policy, including its position on LAWS.

- Their report, and a report by Friese **[159]** confirms my position that it is important to draw together user communities to engage with a consultation process to identify potential threats posed by small UAVs, and must include: upstream manufacturers, downstream operators, CAA, Security Agencies, and Civil Liberties groups. The lack of conversation between manufacturers, users and countermeasures suppliers must be addressed. The report recommended safeguards to cover a spectrum of escalation response proportionate to the threat state. We are also increasingly looking at the 'swarm threat' from coordinated multiple drones. There is a rapid development in collaborative UAV swarming control mechanisms, to the position that network swarm formation will prioritise the swarm leader by virtue of its best communications / energy and resources capabilities, and consequently the system is robust against leader loss **[160].**

Development of UAVs, and allied technologies of artificial intelligence and autonomous systems, reliant heavily on data processing and image fusing multiple sources from 'big data', is in its infancy and changing rapidly. As such small hobbyist and commercial drones which rely on potential dual-use technologies, do **not** provide a simple route to creating a nuclear technology 'trigger list' in accordance with the Zangger Committee, yet,

- UK Government should encourage multilateral discussions and consult the Arms Trade Treaty, the Wassenaar Arrangement, the Missile Technology Control Regime etc. to explore parallel solutions, as there is no need to start from scratch and 'reinvent the wheel'. UK should upgrade control lists and improve risk assessments of existing export arms control regimes, in regard to the risk of destabilising current small wars' '*status quo*'. UK Government should consider what types of UAVs and related technologies may be misused or subverted to unwanted hostile-actor use. However, as with cyber warfare advantage, it is unlikely high-tech nations which perceive they have a strategic and tactical advantage over their global competitors, with different ideological drivers, and limited overseas 'interference / influence' will readily choose to surrender their advantage to international law, but rather seek to exploit that advantage further **[161]**. At the international level, regulation of potentially problematic future UAV systems might be modelled on the nuclear non-proliferation treaty as it allows civilian cooperation on development of autonomous technology, yet retaining clear control within the military sector, whilst complying with international humanitarian law.

- Practically it will be important to encourage UK UAV and military drone manufacturers to talk to each other, to 'raise the bar' on export of military grade platforms, and some of the larger civilian platforms which might be modified for ordnance delivery, as indicated by our 3D scattergram graphs of endurance, range and mass (**figures 21A and 21B** respectively). This may result in a database of 'dual-use' UAVs that might be misused for military exploitation. There is no doubt that there are platforms able to deliver payloads including explosives (several kg) exceeding ranges far beyond a few kilometres, and can capture high-definition real-time ISR images with persistence of several hours in this category. However, in these comprehensive and inclusive discussions on use and proliferation of dual-use and military drones, although it is *partly* a matter for the UK Government, and others to 'raise the bar', manufacturers must be invited to address the question of how high to set the bar, for if it is set too high it may make the UK UAV industry uncompetitive.
- We should establish a regulatory framework for mandated UAV platform design and systems above an agreed: size, mass, endurance etc., with the addition of GPS and AIS capability. Such a framework should liaise closely with future military technologies to minimise needless collateral damage.

Possible Scenario: Consider a proposed new build civilian engineering UAV platform for long duration heavy electric powerline operation work, with BLOS capability. Let us say the initially proposed parameters are: Endurance 500 minutes for persistent flight, Mass 1000kg, and a usual working Range due to the difficult terrain of between 10 - 20km, but with BLOS, might attain an un-laden flight limit of up to 150km, which is the value we will take here. This platform is added in **figure 44** with the proposed UAV platform indicated as **black** alongside the other previously displayed categories.

If this platform exceeds certain laid down criteria as 'reasonable' for the particular long endurance heavy lift task it will be 'flagged up'. Design criteria experts may reasonably examine the requirement, if the payload needed to be carried is 20kg max, then a general rule of Payload Mass = 0.2 GTOW in this case requires an overall GTOW of c. *100 kg*. This would become the revised platform mass maximum, whilst providing 20kg of lift, and even a 'spare capacity' in the modelling of a further 0.2 Payload Mass = 4kg, which would be acceptable for such a tasking.

Similar reductions of range, by battery limitation, supported by those already imposed on payload mass, could drop this factor from 150km to 100km, but still more than enough to do the required load task. Similarly Endurance could be reduced from 500 to 300 minutes aloft, by no means preventing the required tasked engineering. The consequent new set of parameters is displayed with the '**cyan**' filled circle, and now falls within the regarded 'safe' design envelope criteria, albeit at the upper range. This is one way in which ethical design engineering of UAVs might be quantified and delivered.

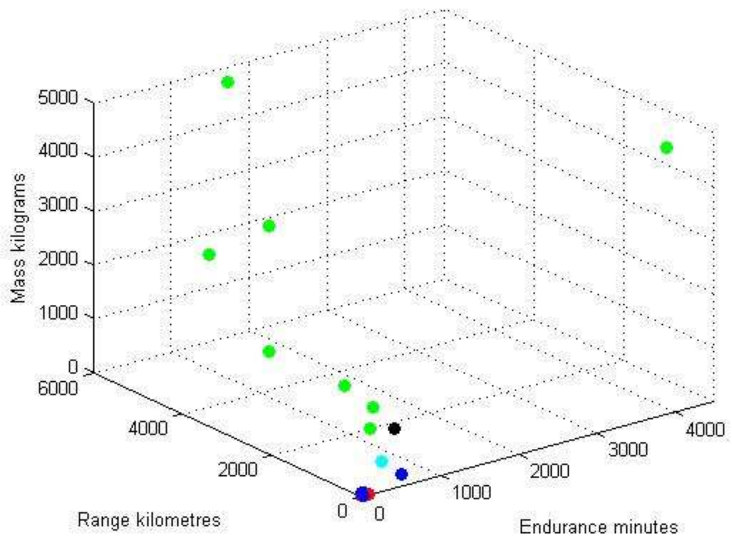

Figure 44: Small and Medium Civilian (Red), Small and Medium Military Drones (Blue), Large military drones (Green), Proposed Civilian Drone (Black), Design Limited Drone (Cyan).

- UK Government should establish a Parliamentary Committee with oversight of civilian UAV manufacture and its countermeasures, drawing upon existing UK actors such as: manufacturers, countermeasures companies, representatives from the UK military, civilian research, and centres such as the ***Changing Character of Warfare Centre, Pembroke College, Oxford***, the ***Dartmouth Centre for SeaPower and Strategy***, and government, critical UK infrastructure representatives, etc. to identify potential future drones threats, and how to counter such threats ***before*** they happen. Increasing numbers of private countermeasures firms active in maritime and land domain, many from UK and US armed forces, should be co-opted.
- UK Government should develop a communication strategy to inform the public about the dangers, capabilities, opportunities, and complexities of UAV systems.
- UK Government should establish, as a matter of urgency, a 'think tank' such *as* ***CCW, Pembroke College*** to address growing public apprehension, as well as that held amongst UK government and non-governmental organisations, about potential for operation of remotely controlled and fully autonomous lethal drones. A broader public discussion on the opportunities and limitations for

civilian UAV technology must be undertaken as a means of providing an educating and informing tool for both Houses of Parliament, along the lines of the Foundation of Science and Technology meetings hosted at the Royal Society. In this discussion the UK should develop a comprehensive overview of current challenges and future risks associated with emerging UAV technologies applicable to the digitally augmented conflict environment.

Overall UK should upgrade control lists and improve risk assessments of existing export arms control regimes, in regard to the risk of destabilising current small wars' '*status quo'*. UK Government should consider what types of UAVs and related technologies may be misused or subverted to unwanted hostile-actor use.

Platform Self-Defence Regulatory and Policy Recommendations

In the case of civilian aircraft and ships some aspects of self-defence should be explored, if simply to purchase a merchant ship, or civilian aircraft more time to respond to a threat. Pilots and ships' captains should keep proper visual and radar watch, and be prepared to alert authorities, and prepare counter-measures, but its primary role near an airfield is safe flight/take-off and landing/ and crew overload is a real risk.

- Automated civilian countermeasures like military infrared countermeasures, e.g. DIRCM are a commercial civilian growth opportunity. A range of specialist sensors, passive protection and active protection measures should be established for over land and sea operation. Non-lethal defence measures such as water jets, gas-guns, nets and laser dazzlers offer possibilities that already exist, to some extent, in countermeasures for anti-piracy protection.

In terms of maritime security, multiple threats in dangerous lawless areas are likely, e.g. UAV swarms *with* piracy, as such should there be public alert measures 'apps' and warning systems? It will be possible in the near future, especially in an insecure environment such as Yemen, where hostile actor drones have been deployed, to conduct a full Cyber assault on port/maritime infrastructure and their services, including port-controlled UAV and autonomous platforms.

- Consequently, I recommend, in light of previous points, that security addition to SOLAS for ship and port security code and practice is required, with moves to develop ship-based AIS technology for UAV platforms, with UAV alert information sharing partnerships. The roadmap for this parallel implementation exists. It is important to develop organisational UAV threat awareness and competence. However this may present resourcing issues, namely who will pay, especially for security, and training, and how do we legislate for UAV development overseas? How do we ensure commitments from the UAV industry, when many larger commercial COTS drones are built abroad, and sold via EBay, Alibaba etc., unhindered by humanitarian concerns?
- UK Government policy on UAV systems should be updated to address current and anticipated emerging issues, e.g. the distinction between fully automated and autonomous systems, and whether rapid-response automated defence systems will exclude future human decisions-making.
- UK Government should carry out a sweeping and wide-ranging consultation to identify **regulatory** gaps for potential small civilian modified COTS UAVs to include manufacturers, operators, civilian aviation authorities, national security agencies etc. over land and sea. Regulation of small UAVs should differentiation between use by individuals (hobbyists) and by industry with regulation of industry drones being potentially easier than private bespoke electronics hobbyist drones. The **US and Eire** have introduced registration of small UAVs, with some success. Policymakers should engage in information-sharing with other countries regarding small COTS UAV regulation.
- There is a lack of clarity regarding current management of small UAVs, for instance there are no simple adequate universal established safeguards to counter hostile drones. Potential solutions may include measures such as licence registration, geolocation protocols (to detect approaching drones) physical protection of vulnerable sites (e.g. with nets) intrusive countermeasures (such as jamming GPS or hijacking control systems, and aggressive countermeasures (shooting the drones down or deploying UAV swarms to attack hostile UAVs, but all have their drawbacks. Drone manufacturers, users, and countermeasures companies are NOT talking to each other in a joined-up manner, as evidenced by one respondent comment to talking with UAV manufacturers, that will be kept

nameless: '*We are a counterdrone company, …As such, we don't really look into the drone-related areas you mention (anti-drone is surprisingly unrelated to drones, perhaps the closest analogy would be bullet makers usually don't study medicine!)*'
ANON

Media has also influenced public perception about use of military drones, confusing perhaps the impact of UAVs on conflict and peace processes, and often misrepresented or exaggerated by the press; this creates fear and uncertainty about ethics and military efficiency. There is a general lack of clarity on *how* international law and regulatory frameworks will apply to future military use of UAVs. Legal definitions are blurred by UAVs operating in the so-called 'grey zone' of war, and terms such as unlawful combatants, and pre-active targeted lethal action are not as clear as they could be.

- Identification of threats, potential scenarios risk probabilities, the perception of risk, and likely resulting damage, is essential before a significant public event actually occurs. This initiative must not be driven by ill-informed politicians chasing emotional public clamour, activist influence groups, nor as part of a poorly thought out knee-jerk response to the media after a terrorist incident, nor as a strategy to gain re-election advantage points. Hence, the value of addressing these issues urgently, before the 'horse has bolted'.

Future civilian UAV technology will present new challenges, for instance the degree of human intervention. For compliance with Article 36 of the Geneva conventions there must be a clear divide between whether a human or machine is making the decision. Human decision-making may present vulnerabilities in future defensive systems. With increasing speed and unpredictability of inbound threats, we might have to accept autonomous or highly automated response countermeasures systems (**esrc.ukri.org**).

High risks drones can operate beyond visual line of sight in non-segregated airspace, with overflight of congested urban areas with high population density represent a significant risk. Further weaponisation, or failure to properly counter with kinetic energy countermeasures, may result in a platform hitting the ground, and is a major problem to solve. The UK must develop new defensive systems as the threat from small UAVs grows. Consequently more '*frangible*' platforms might reduce impact damage upon collision with aircraft, other platforms, or countermeasures response, which leads to several design-related issues.

Design Recommendations

- *Enhanced visibility* of small COTS UAV platform construction could be mandated with UV fluorescent paint, due to visible natural UV levels or stimulated UV laser scatter, with an option of integrated laser optical retroreflectors on larger COTS UAVs, or radar reflective paint.
- The fitting of small radar reflective elements, dihedral or trihedral corner reflectors could be fitted beneath the outer GPR skin of larger platform frames; this will enhance radar reflections making otherwise 'invisible' platforms highly visible. As stated earlier: *'Putting elements into the design that increase radar reflectivity ... may be much more difficult for a criminal or terrorist to remove.'* **Lt Col, British Army.**
- *Minimal design*- Civilian Platforms should be designed with limited capacity for fitting other payloads than that they are *functionally* designed to provide. All platforms should have fittings and mounts with the least capacity for passive hostile ordnance. All platforms should have a minimal extra payload capacity within the commercial platform range for extra payload addition.
- *Legislation* Platforms should be mandated and checked to include AIS. AIS systems should be integral to civilian UAV platform design, and they should not be switched off so AIS provides the necessary persistence monitoring to catch illegal or inappropriate activities in the act. UAV Design may be restricted by CAA UAV legislation as this is a civil matter currently, and if done with careful design should remain so.
- *New functional materials* Design should incorporate smart embedded sensors and functional materials which improve platform survival probability.

As autonomy and multi-vehicle swarm control becomes more mature UK Armed Forces must anticipate use of inexpensive, expendable drones and modified UAVs against UK ships, shore-based infrastructure, and likely military and civilian targets at home and abroad in the near future.

- In terms of maritime security, multiple threats in dangerous areas are likely, e.g. UAV swarm with piracy, and as such public **alert measure** '**apps**' and warning systems may be required. Our own Loitering UAV operations may conduct safe surveillance at long stand-off ranges without those observed knowing they are under observation, and perhaps prevent maritime piracy attacks, as discussed in the conclusion section, before they happened.

Addressing the often raised question of whether drones *really* confer air superiority, the clear evidence is drones did provide short-term immediate Azeri gains for the small war in Armenia in certain terrain conditions, but this is unlikely to be repeated as countermeasures rapidly become more effective, playing 'catch up' with the threat; nor in likely future conventional war-fighting scenarios. However, it does increase the 'grammar' of military options available, and in urban settings this will likely be applied more commonly, allowing hostile non-state actors to act without impunity, and very likely with foreign-made bought systems, rather than indigenous COTS modified drones.

CONCLUSIONS

Small drone risks _and_ benefits should not be understated. On one hand there is a wide range of realised as well as potential humanitarian uses- search and rescue, disaster management, delivering packages, legitimate public surveillance etc., as well as from a terrorist perspective- a wide scale of 'beneficial' outputs, from creating feeling of civilian fear and panic when in the air; to 'threatening' to bring down an airliner, and to other hostile activities such as IED, grenade and bomb delivery, etc.

Do drones present an existential risk? Certainly, but most may be blocked relatively easily from flying into prohibited airspace with 'geo-fencing', a GPS-based system which stops drones from flying where they shouldn't. Leading UAV manufacturers can incorporate this feature as standard. What of modified UAVs packed with explosives or chemical weapons? This is possible, as discussed, but if you really want to create mass terror event, it is easier, cheaper, and perhaps achievable on greater scale, to simply blow up a car, bus, or shopping centre, using multiple remotely detonated bombs, and not even be in the country of attack at the time.

Drones, although used by coalition forces to provide a *partial* solution to Middle East insurgencies, are also a 'double-edged' sword. They do not by themselves achieve political outcomes except possible 'leverage' to a combatant force experiencing an unacceptable level of materiel loss, or disruption of command structure. The fatal drone attack death on Iranian General Soleimani did **not** achieve this. As insurgents use drones more, they may enhance their own credibility and legitimacy with their indigenous target population, and are being used as an effective political tool.

According to Poplin **[162]** '*It seems clear that militant groups are eager to celebrate legitimacy in a propaganda war that has taken on* _increased_ *importance*.' However, insurgent actors will not be likely to achieve a sustained competitive advantage in drones or modified-UAVs but will rely on them more. Terrorist drone use may also vilify the platform technology to the extent that the legitimacy of our own drone use may be questioned, which would impact stabilisation and overall operations, as did the press fall out from operational use of F117A stealth fighter aircraft, after the *Amiriyah* shelter bombing did in Iraq (13 February 1991).

Current small commercial UAVs, may be modified and armed, with relative ease, and as demonstrated in our multidimensional analysis, in terms of endurance, range and platform mass, have sufficient overlap with military drones to warrant ongoing concern. Even relative cheap hobbyist drones, may be purchased by individuals or groups with a comparatively low level of sophistication compared with higher-end military systems, but requires **no** significant infrastructure to operate them. A key aspect for these systems is they may be used freely in uncontested civilian airspace to disrupt transport, create fear, as well as carrying ordnance and other payloads.

The potential for neutralising an attacking hostile actor's small drone 'air force' on the ground, prior to launch, is minimal. It is difficult to detect them as they are covert, many hand-launched, and provide little exposure to air or space surveillance. They are also easily inserted within an urban environment. It may become increasingly difficult to attribute the source of UAV attacks, especially if civilian UAVs are 'hijacked'. Swarming is a real possibility for mass-precision attacks which could overwhelm defences due to sheer numbers. As autonomy and multi-vehicle swarm control becomes more mature UK Armed Forces must anticipate use of inexpensive, expendable drones and modified UAVs against UK ships, shore-based infrastructure, and likely military and civilian targets at home and abroad in future conflict. Defence against small modified COTS drones should be a high priority. At sea we must anticipate greater use of mother ship platforms, threats which are much less weather dependent in terms of operations, with greater range, endurance and payload carrying capacity, augmenting current small boat swarm piracy attacks. In terms of maritime security, multiple threats in dangerous areas are likely, e.g. UAV swarm with piracy, and as such public alert measure 'apps' and warning systems should be developed.

Maritime Terrorism

Drones and modified COTS UAVs may be used by terrorists in the maritime domain for offensive action, by attacking shore side, e.g. iconic targets, plants (power, industrial, desalination), offshore platforms and infrastructure, port facilities, e.g. 'hub ports' such as Shanghai or Rotterdam, global choke points such as the Strait of Hormuz, Bab el-Mandeb, Suez or Panama Canals, coastal cities, maritime vessels (warships, passenger or cargo vessels) for their propaganda or strategic purposes.

- Presently, most maritime terrorist activities are logistically dependent, and require movement of: insurgents/operatives, arms/equipment, money/documents, drugs etc. to generate funds, and this is a potential intelligence/ exploitable potential weakness to their own supply chain.

Possible future attack scenarios

These include a range of options, e.g. Suicide bombs at sea, with small fast moving UAV swarms by remotely piloted platforms, and would most likely take the form of 'Hit and run' attacks on land and in urban settings, using small UAV platforms firing assault rifles, RPGs, or in the future launching anti-ship missiles? Remote or autonomous control permits stand-off attacks with drones to drop bombs, or mines, cheap and very effective. These can easily place explosive devices in ports, merchant ships and warships, and in otherwise well-guarded buildings, etc. At the same time it would be possible to conduct a full Cyber assault on port/maritime services and infrastructure, including any port-controlled UAV and autonomous platforms.

Whilst maritime terrorism is not a new phenomenon, there has been growing realisation since the 911 attacks of the dangers over land and sea; that existing domestic and international legal measures are inadequate, especially against lone-wolf attacks, or groups who will not keep to the 'letter of the law'. Over the last decade there have been a growing number of increasingly deadly attacks. As such the 'bomb in the box' concept of using a small container to smuggle/detonate CBRN in a high priority location (critical infrastructure), or a one-off attempt in a public space, although generally low probability, may have great symbolic value. Using UAVs to release biological/chemical agents without warning or fanfare is a greater concern, and would only be detected when cases of an unknown origin started to show up in hospitals, with obvious delayed effective medical response.

Rise of Global and Regional UAV Competitiveness

Maritime Power is at the heart of the global system and we cannot ignore geopolitical and geo-economic realities which are more relevant today than ever in terms of volume. The role of UAVs and autonomous systems in this already complex tapestry, provides a new thread to the story. It is no longer benign in security terms, and trade routes are increasingly competitive and complex. Increasing number of nations have navies capable of platform modification which includes drones and other high-tech assets: Directed Energy Weapons, Electromagnetic Pulse weapon systems, or carry out sophisticated forms of electronic attack, cyber warfare etc. beyond traditional methods. The transfer of redundant ships/weapons from established naval powers, via exports and 'new build', combined with growing indigenous naval UAV platform and autonomous industry developments will proliferate widespread availability of high tech autonomous UAV platforms and weapons, sensors, and missile systems.

For the UK, and in the light of CV-19, it has arguably never been so challenging for a maritime nation to differentiate between emerging potential threats, and with the level of resources currently allocated to the RN, and the wider UK Armed Forces to countering all these potential threats, including that of hostile actor UAV operation, whilst dealing with current global existential crises, is difficult to say the least.

The effects produced by most modified UAV delivered payloads, or captured military drones, notwithstanding comments raised in this report downplaying CBNR attack, serves to augment terrorist damage objectives, as basic and more reliable methods can deliver more potent payloads to a target.

Overall, the wide range of responses should be considered representative of the UAV platform sensors market. The literature review highlighted that the market has grown dramatically in recent years and is expected to grow in coming decades. This report provides quantified findings from the Military and Civilian UAV/drone community, examined with responses provided across many areas: persistence, Night-Day, AIS capabilities, etc. Likert responses accompanied by comments provided valued insights into the thinking of different users, more helpful with quantitative material questions. The more abstract perceived criteria, the *less* coherent multiple-related Likert responses and comments were. However, the quantitative use of multiple platform related criteria: Endurance, Mass, and Range is shown as a credible means towards limiting exploitation.

- As such quantitative evaluation with 3 dimensional analysis of: Endurance, Range and Mass, could limit platform exploitation. Improvements in robustness using smart composites: glass fibre, optical fibre with embedded sensors, or carbon nanotubes, is of more interest than 'green' materials in themselves.

The mismatch between manufacturers, users, and countermeasures company communities is important, and shows there is work to be done in gauging and bridging demand for specific customer services. Matching 'end to end' is a process, through getting to know each other and their expectations. Neither party should refrain from asking pertinent and difficult questions. Lack of conversation between manufacturers and users is surprising, but this this is evidenced in conversation with the countermeasures community. 'The reality is even with trying to minimise exploitation it cannot be stopped. How do you stop it? This is an issue faced by military forces today.' *I'm not sure how this is even possible. You could never fit a weapon locating radar into a nano-UAV, but a basic electro-optical camera has military utility on a UAV. Is there some technical boundary that makes sensors exclusively military that I'm not aware of,'* **Lt Col,** British Army. And the answer to that of course is no.

There is opportunity for future study, namely comparing possible correlations between different user groups in terms of Likert responses, (e.g. upstream and downstream) to look at those categories which are extremely well-matched, and those that are less so. We shall also conduct further deductive research in categories such as endurance, range, GTOW, and mass payload to explore empirical relationships that may exist across different scale sizes of UAVs using dimensional analysis.

It is the emerging UAV technologies which present novel risks, and may even undermine peace and stability in the long run. We should be under no illusions, even if all the reasonable safeguards are put into place, and with export restrictions so effective that 'scales are tipped' in favour of what *should* only be limited home-made modification; as seen with the Armenia conflict, there is usually a nation or two prepared to unilaterally supply arms to one side of a conflict, thus destabilising the '*status quo'*.

Small COTS UAV platforms, embracing new emerging and sophisticated technological capabilities can overcome many of the human limitations encountered in conflicts. Strategy and tactics are largely defined and updated by the technology used, and UAV are no exception to this rule. UAVs have entered the battlefield at pace, and change is accelerating, profoundly altering the way in which contemporary war is organised and conducted. We ‘hover’ today at the threshold of the enormous potential UAVs and drones, combined synergistically, may offer with provision of strategic and tactical options for application of air power to all actors. There are no simple safeguards to deal with small COTS modified drones operated with hostile intent, in this ‘*grey zone*’ of multiple technologies, agnostic to application intent; and which provide *potential* solutions within civil and legislative frameworks which we have surveyed. As well as setting boundaries to physically designed countermeasures, all of these approaches have limitations and/or risks of collateral damage, at levels which may prove unacceptable, yet assessment of these risks *must* be undertaken immediately, and countermeasures developed with the highest priority.

‘There must be a beginning of any great matter, but the continuing unto the end until it be thoroughly finished yields the true glory.’

Sir Francis Drake.

7. PROJECT-RELATED PUBLICATIONS

7.1 Publications Arising Directly, and Indirectly, From This Project

[1] Lavers, CR, Johnson, R, 'Experimental modelling with theoretical validation of liquid crystal display elements for UAV optimal (optical) stealth', in the SPIE Digital Library as part of the 11525 conference proceedings: http://dx.doi.org/10.1117/12.2585165

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9. APPENDICES

9.1 Questionnaire

Unmanned Aerial Vehicle Design Study Stakeholder Consultation

Short-term Fellowship Changing Character of War Centre, Pembroke College, Oxford 2020

Introduction

Overview of Research

I am currently undertaking a short-term fellowship at the Changing Character of War Centre, Pembroke College, Oxford. As part of my research programme I am looking at design of UAV platforms, and how to prevent design aspects which may lead to improper application of drone technology. As such I am particularly interested in any ethical and sustainability implications, and areas of civilian-military overlap.

In order to underpin the dissertation, and potential introduction of security design safeguards, I am consulting with a wide range of stakeholders, potential customers, and interested entities. In this context, I would really value the opportunity to engage you in this research and to hear your views. I am particularly keen to establish your thoughts around:

- Civilian and military surveillance requirements, particularly maritime,
- Current activities in the domain of surveillance and security,
- New materials, and sustainability, sensors and energy sources,
- Your technical requirement for UAV-derived surveillance,
- Current and future cost expenditure for surveillance & security,
- Previous experience of purchasing UAVs and/or UAV services for surveillance,
- The drivers that would trigger you to manufacture/purchase UAVs and/or UAV services for surveillance/security,
- Your experience of purchasing/providing UAV platform data, and the associated applications.

Depending on your answers, the survey will take approximately 45 minutes to complete. Whilst I feel there is the potential for mutual value in knowing the views of individual stakeholders or interested entities, I would be happy to anonymise your response should this be preferred.

Please feel free to forward this survey to others who may be willing to provide frank, informed comment on this research based proposal, or if you feel you are not the most appropriate person to answer it on behalf of your organisation.

Should you have any specific questions about this survey, or the research more generally, please don't hesitate to contact *Dr Chris Lavers, Subject Matter Expert Radar and Telecommunications, Dartmouth Centre for SeaPower and Strategy, Britannia Royal Naval College, Devon, TQ6 OHJ*, christopher.lavers@pmb.ox.ac.uk or chris.lavers@brnc.ac.uk christopher.lavers@plymouth.ac.uk

About You and Your Organisation

1. To begin with, I would like to find out a little more about you. Please could you let me know the following details:

Name and nationality	
Employment: civilian or military	

If civilian organisation:

Name of civilian organisation	
Role and function served	

If military organisation:

Army, Navy, Air Force	
Rank and function served (e.g. intelligence)	

Applications

2. What UAV applications does your company/organisation use/provide?

Lidar & Point Cloud measurements	
Radar imaging	
Night Vision Capability	
Thermal Imaging	
Photogrammetry Surveying & Mapping	
Agriculture/Land Management, e.g. precision farming	
Environmental monitoring	
Construction	
Urban	
Surveillance (COVID-19) or otherwise, e.g. medical supplies.	
Oceanography	
Other (state) e.g. medical support	

3. As a user or provider of the listed UAV applications which interest you and what are your required frequencies (e.g. daily, hourly etc.)?

	YES	Associated frequency of data updating required.
Vessel detection		
Illegal fishing		
Piracy		
Port security		
Search and rescue		
Border control		
Illegal immigration		
Cueing airborne assets or vessels		
Surveillance (land, sea, lake, or river)		
Other (please specify below)		

Would you like to comment further?

4. Which of the following data types do you require/provide?

High resolution SAR	
Domain awareness	
Electro-optical	
None of the above	

Would you like to comment further?

5. On a scale from 1 to 5, how important is it for UAV platform design to incorporate the following where 1 is "not important" and 5 is "very important":

Not at all important → Very important

	1	**2**	**3**	**4**	**5**
Navigation-related sensors					
Conduct Multi-mode operations					
Develop your own remote sensing equipment					

UAV use for Maritime and Littoral operations					

Would you like to comment further?

Sensors 6. On a scale from 1 to 5, how important are the following sensors to your applications.

Not at all important → Very important

	1	2	3	4	5
Chemical sensors					
Radiological sensors					
Drug detection sensors					
Meteorological sensors					
Biological sensors					
Toxic chemicals, e.g. fire fumes.					

Would you like to comment further?

Energy sources 7. On a scale from 1 to 5, how important are the following energy sources to your applications.

Not at all important → Very important

	1	2	3	4	5
Aviation fuel					
Battery cells					
Fuel cells					
Solar panels					

Would you like to comment further?

Payloads 8. On a scale from 1 to 5, how important are the following payloads to your applications.

Not at all important → Very important

	1	2	3	4	5
Mail					
Medical supplies					
Food					
Fire extinguishers					

Would you like to comment further?

Materials 9. On a scale from 1 to 5, how important are the following environmental sustainability design issues: where 1 is "not important" and 5 is "very important".

Not at all important ⟶ Very important

	1	**2**	**3**	**4**	**5**
Use of "green" materials e.g. GreenTec Pro Polyester Biopolymer, DURABIO, etc.					
Natural woven fibres					
Recycled plastics					
Minimal carbon footprint					

Would you like to comment further?

10. On a scale from 1 to 5, how important is it to include the following UAV design materials: where 1 is "not important" and 5 is "very important".

Not at all important ⟶ Very important

	1	**2**	**3**	**4**	**5**
Reduced mass materials					
Superlight aerogels					
Carbon Fibre					
Heat Resistant Ceramics					
GRP					
Polymers					
Other materials (state what)					

Would you like to comment further?

Design Characteristics 11. On scale from 1 to 5, how important is it for UAV platform design characteristics where 1 "not important" and 5 "very important" for the following:

Not at all important → Very important

	1	**2**	**3**	**4**	**5**
Endurance (time aloft)					
Altitude (in km)					
Range (in km)					
Simplicity					
Payload mass					
Maintain your own platforms					
Redundancy					
Night and Day (24/7) ability					
All weather capability					
Persistency and loitering					
Graceful Degradation					
Water Resistant (Hydrophobic)					
De-icing ability					

Would you like to comment further?

12. On a scale from 1 to 5, how important is "Self-healing" for Control surfaces and Coatings (In-built into Coating layer) for your UAV design: where 1 is "not important" and 5 is "very important".

→ Very important

1	**2**	**3**	**4**	**5**

Would you like to comment further?

Requirements 13. (a) How important is Multifunctional (multi-application) capability to you?

Would you like to comment further?

13. (b) On a scale from 1 to 5, how important are the following design benefits, and drivers: where 1 is "not important" and 5 is "very important".

Not at all important → Very important

	1	2	3	4	5
Reducing power consumption					
Increasing data-handling and processing					
Human Operated Systems					
Human Delegated Systems					
Human Supervised Systems					
Fully Autonomous Action					
On-board diagnostics, adaptive re-routing of signals.					
Increasing algorithm analysis					
Image acquisition stitching mosaic feature extraction					
Multi-spectral capability					
Having Multiple sensor data fusion					

Would you like to comment further?

13. (c) On a scale from 1 to 5, how important are the following design benefits, and drivers: where 1 is "not important" and 5 is "very important".

Not at all important → Very important

	1	2	3	4	5
Provision of Real-time operational scenarios					
Software/hardware tamper modification protection measures					
EMP or jamming proof (specify)					
Omitting mounting points which could support potential heavy military/criminal payloads.					
Collision avoidance software					
Fitting a platform with GPS and AIS.					
Should AIS be mandatory for all UAV platforms?					
Should further CAA UAV legislation be introduced?					

Would you like to comment further?

Design 14. On a scale from 1 to 5, how important is "ethical" UAV design: where 1 is "not important" and 5 is "very important".

Not at all important → Very important

	1	2	3	4	5

Would you like to comment further?

15. On a scale from 1 to 5, How important is it for platforms to have the following attributes, where 1 is "not important" and 5 is "very important".

Not at all important → Very important

	1	2	3	4	5
Low-cost design					
3D Print Fabrication					
Able to Deploy in high risk areas					
Human decision if AI decision making is compromised					
'Return to Origin' if fault detected & Auto-Pilot					

Would you like to comment further?

16. On a scale from 1 to 5, is there an ethical responsibility for engineers to design civilian UAVs *differently* to military drones, to ensure human welfare, safety, and privacy: where 1 is "not important" and 5 is "very important"?

Not at all important → Very important

	1	2	3	4	5

Would you like to comment further?

17. Should there be a legally enforced framework to prevent modification of civil platforms which may create 'bespoke' military-grade platforms?

YES	NO

Would you like to comment further?

Perception. 18. Do you think drone attacks or military use negatively impact civilian UAV uptake, or increase public mistrust?

YES	NO

Would you like to comment further?

19. What do you understand by a “responsible” human decision control process, and do you consider this important?

YES	NO

Would you like to comment further?

20. Do you embed responsible non-human ethical decision making (near real-time) into your UAV platforms?

YES	NO

Would you like to comment further?

21. As an end-user/manufacturer are your “ethical” drone design technology benefits, and drivers purely financial ones?

YES	NO

Would you like to comment further?

Concepts. 22. On a scale from 1 to 5, how important are the following military design factors: where 1 is “not important” and 5 is “very important”.

Not at all important ⟶ Very important

	1	**2**	**3**	**4**	**5**
Machine-based learning					
Hybrid warfare UAV drones					
“Smart” technology					

Would you like to comment further?

23. Threats and Countermeasures On a scale from 1 to 5, how important is it that civilian UAVs are designed to exclude potential military sensor payloads, where 1 is “not important” and 5 is “very important”.

Not at all important ⟶ Very important

	1	**2**	**3**	**4**	**5**

Would you like to comment further?

24. On a scale from 1 to 5, how important is it that military data acquisition systems, might undertake kill decisions automatically: where 1 is "not important" and 5 is "very important".

Not at all important ⟶ Very important

	1	2	3	4	5

Would you like to comment further?

25. Your Organisation On a scale from 1 to 5, What are your organisation's core competencies in the field of UAV development, where 1 is "not important" and 5 is "very important":

Not at all important ⟶ Very important

	1	2	3	4	5
Whole system design					
Specific payloads					
Power systems					
On-board computing and data handling					

Sub-systems

Commercially off the shelf					
Your Own Development					
Partner development					

26. How many people does your organisation employ, and what is your company turnover p.a.?

27. Please provide details about the UAVs your organisation uses/manufactures (range, endurance, cost, platform mass, dimensions, payload mass etc.). Email pdf details if possible.

28. (a) What mission benefits do your UAV systems provide for you with earth observation?

(b) What are the costs to build, and operate your own UAV system?

(c) What is the history of the development of your UAV systems?

Thank you for taking part in this questionnaire, is there anything else you would like to state?

If you would be willing for me to either talk over the phone in more detail, or permit a visit (UK), then please contact me by email, or to send any product details in the post, post to:

Dr Chris Lavers, Head of Sensors, Britannia Royal Naval College, College Way, Dartmouth, Devon, TQ6 OHJ

Please return the completed electronic questionnaire to: christopher.lavers@plymouth.ac.uk or chris.lavers@brnc.ac.uk or christopher.lavers@pmb.ox.ac.uk THANK YOU for your time!

9.2 Security and Surveillance Market Share

Security

Airport and Marine Security The global airport and marine port security market is estimated to grow from US$53.84bn 2016 to US$110.52bn 2025[36]. Surveillance systems incorporating UAV systems show the highest growth within the market over this period, and shows great promise for UAV operation.

Maritime and Border Security Initial market analysis indicates between 2015 - 2025 the global maritime and border security market will increase by a CAGR range of 4.23% [37] to 7.7%, [38] from US$15.32-23.7bn. Dominating global regions are anticipated to be Asia Pacific, in particular China with an expected investment of US$39.2bn, followed by North America and Europe. There has also been an increasing trend in emerging countries such as Brazil, Russia, China, and India implementing maritime security solutions. This increase is reportedly due to growing instances of maritime threats as well as increasing laws and regulations[39]. Strategic Defence Intelligence (2015) reported that maritime surveillance and detection is expected to account for the largest share of the maritime and border security sector over the next decade, accounting for 38% of total investment. However, in terms of contribution it is reported the vessel security segment is the largest contributor for maritime security. North America is expected to be the largest market in terms of revenue contribution, whereas Asia Pacific is likely to experience increased market traction in coming years [40]. How this will be impacted by COVID-19 is currently unclear.

Maritime Reconnaissance and Surveillance: Maritime Patrol Aircraft The overall global market in this category is estimated at a value of US$50bn over the next decade.[41] The sector includes Maritime UAV and Patrol Aircrafts, and Airborne Anti-Submarine Warfare Sensors. This role may be filled partly by future satellite-based sensor systems as well as UAV systems.

Pseudo-Satellite and Satellite Industry Global total satellite industry revenues reached US$208B in 2015, representing a growth rate of 3% from 2014 and 20% from 2010. Within this area satellite services include consumer services, fixed satellite, mobile satellite and earth observation services. Revenues from earth observation grew by 10% in 2015 to US$1.8B.[42] Growth in earth observation services arises from satellite manufacturing, with 54% of satellites launched in 2015 for earth observation services, compared to 16% for commercial communications and 10% for civil/military communications. It is into this market that UAV system developments may cut deeply as platform developments mature significantly, providing local precise area solutions, and as larger systems also mature, more detailed wider-area studies. In reality UAV systems will augment existing satellite systems.

Security and surveillance radar market: The global security and surveillance radar market was estimated to reach US$8.61B by 2019, growth driven by increasingly diverse and rapid radar technology developments. Currently, the US and Europe represent the largest security and surveillance radar systems markets, however, recent economic slowdown in western markets have emerged, increased by the impact of COVID-19 [ref my article]. Analysis of global regions indicate emerging economies such as Brazil, India and South Africa are growing current market share, with South Korea, Japan, Canada and Taiwan providing added drive to market growth.[44]

9.3 Emergent Technologies

Advanced Electronic and optical materials: this includes carbon micro structure materials, semiconductor technology, new quantum materials which provide military advantages harnessing developments in electro-optic materials.

Advanced materials: these harness modelling, synthesis and processing to yield innovative capabilities through advanced materials and processing: yielding smart/functional materials, modelling, design to provide through life support for platform structural materials, yielding low observable materials across a range of spectral threats (pan-spectral stealth).

Autonomy: the military capability, with enhanced automation to reduce dependence on humans namely: robotics, platform automation, and intelligent munitions.

Communications: increased effectiveness and communications range will provide a pervasive network to enable voice, video, text and data with: Radio Frequency (RF), microwave, and MilliMetre (MM) wave systems, infra-red, optical / ultra violet, with adaptable signal structures, and novel modes of dynamic adaptive operation.

Data and information technologies: military information and IT system superiority is focused to yield total information superiority, data exploitation, machine intelligence, near-real time language interpretive technology, communications and adaptive gracefully degrading networks.

Emerging quantum technologies: will provide 'game' changing quantum technology to enable machines, components, information processing, sensors, and pervasively portable security.

Energy and power: will assure and augment future military ability to provide efficient and cost effective alternatives to fossil fuels. Clean 'low carbon' power sources with advanced power transmission and delivery, energy storage technology are key l to minimising platform detectability and carbon footprint.

Future computing: up-to-date computing power must provide for all military technology combatants and units seamlessly, to aid military information age superiority, and provide leverage with new paradigms, hardware, software, in bespoke 21st Century systems.

High power technologies: will provide advanced high power sources and control systems with semiconductor technology, electro-optical as well as other short electromagnetic wavelengths, novel high power technologies, and RF systems with sufficient bandwidth.

Human focussed technology: will reduce the burden on military personnel, augmenting human capabilities exploiting and expanding the physical, physiological, cultural and sociological dimensions.

Medical advances: will look strongly to biological science to provide 21st Century military medicine for health and well-being using nanomedicine, and synthetic biological engineering (e.g. artificial blood).

Micro and nanotechnologies: these will provide military advantage through application of lab-on-a-chip approaches, nanomachines and systems, and medical micro/nano sensors.

Micro-Electronics: these military systems will provide low power microsystems, processing architectures, material technology, and novel concepts for analogue and digital communications.

System integration: A Cross discipline integrated approach to systems engineering and architectures will explore novel concepts in complexity, chaos, emergent properties, and technology.

Appendix 9.4 Table of UAVs used in example Matlab plots

UAV Parameters

Civilian

Platform	Endurance/ minutes	Range/ km	Mass/ Kg
Parrot BeeBop	12	0.25	0.4
Blade 350 2 by 2	10	1	1
3 DRS IRIS Plus	16	1	0.9
DJI Phantom 2 Vision	25	0.6	1.2
Phantom Prof	28	1.9	1.2
Walker Scout x4	25	1.2	1.2
Yuneeq 500Typhoon	25	0.6	1.7
Skylib X4XLTiQR	15	25	1.1
Altium Zenith ATX8	45	1	15
MicroDrones MD4	88	5	3.1
DelFly	15	1	0.0037
Avitron V2.0	7.5	1.8	0.092
uavrsII china	120	20	40
ASTEC FALCON 8	20	1	2.3
Aeryon SkyRanger R60	50	5	3.3
Aibot X6 Version 2	20	1	3.4
Xmobots Apoena	480	60	35
LA100	5	0.5	0.85
LA200	30	3	0.85
LA300	45	30	0.85
LP960	25	5	1.25
LV580	25	5	0.95
LM450	45	5	0.95
Primoco UAV	600	1500	150
Applied Aeronautics	300	350	10
IF 750 Quadcopter	30	10	6.2
IF 1000 Hexaquadcopter	35	10	9.6
IF1200 Hexacopter	40	10	20
HM V230	360	100	38
HM350	1440	150	220
HW 310A	360	100	75

MILITARY			
AeroE Switchblade 600	60	40	23
NanoHummingbird	8	1	0.019
Raven lightweight	90	10	1.9
RQ-11lb RAVEN	60	6.2	2
Schiebel CamCopter	600	180	110
Germany sensocopter	0.9	3	60
Finland Mass MAV	60	20	3.5
US Arcturus UAV	720	14	36
CH1	360	740	40
CH802	150	30	1
CH803	300	30	18
DVF2000ER	420	50	225
THALES Watchkeeper	1020	150	450
Airbus Atlante	10	10	570
UK Phoenix	240	50	175
Ababil	90	50	83
IAI Harpy loitering	120	500	135
HW 210A	720	80	22
SKELDAR	360	100	235
Insitu RQ-21	960	93	61
	420	150	30
Desert Hawk III	90	15	4
LM Aquila MQM105	180	400	200
Burraq Pak	720	1000	1000
WZ-2000	180	2400	1700
MQ-9 Reaper	1680	5926	4760
Predator	840	1850	1020
Heron	4200	500	4650
WJ600	300	350	1000
A160 Hummingbird	1200	4170	2948
XP Male	1200	5500	1910


NO DRONE
ZONE