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Ethical and safety implications of the growing use of civilian drones

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1. Biographical Note

Dr Stephen Wright is an Associate Professor in Aerospace Engineering at the University of West of England (UWE), UK, with a specialism in Avionics and Aircraft Systems. Prior to joining UWE, he spent 25 years as a software, electronics and systems engineer in the electronics and aerospace industry (Rolls-Royce, ST Microelectronics, and Airbus). His research now focuses on development of avionics and support systems for small (i.e. sub-7kg) Unmanned Air Vehicles (sUAV).

2. Abstract

This document responds to a request for evidence made by the House of Commons Science and Technology Committee on March 7th, 2019, seeking to inform an inquiry into the "ethical and safety implications of the growing use of civilian drones, of all sizes, across the UK".

Based on literature review and practical experience of the author in the field of novel sUAV development, the document seeks to provide background commentary on the current state of technology and practice in the field of sUAVs and relate this to the inquiry objectives.

3. Summary

- sUAVs may be regarded as presenting a spectrum of threats: ranging from high-volume/low-exposure through to and low-volume/high-exposure
- The common perception of sUAV threats is accidental and reckless incidents using commercial airframes.
- Proposed legislation anticipates these perceived capabilities, but overlooks those already available to skilled developers
- A salient risk is malicious deployment of improvised weaponised sUAVs, which will not be countered by legislation and requires active policing and countermeasures
- Proposed registration legislation will help to greatly reduce accidental threats and partially reduce reckless threats.
- Attention should be paid to the possible unintended consequences of legislation, particularly technology adaptation to circumvent it, and constraints placed on sanctioned UAV research and policing

4. Summary of Subject Matter Expertise

Dr Wright has established a group of staff based at UWE's Frenchay Bristol campus, developing a range of enabling technologies and practical applications for sUAVs. The group develops equipment of suitable maturity for enabling further technology investigation and demonstration. As part of the UWE, the group provides a variety of relevant expertise and resources for aerospace design, development, manufacture, and test flight.

The group has completed, or has in progress, sUAV development projects for a variety of commercial and research customers:

- MBDA UK Ltd
- UK Ministry of Defence (MoD)
- Atlantic Area European Regional Development Fund (INTERREG)
- UK Defence Science and Technology Laboratory (Dstl)
- IrvinGQ
- Leonardo Helicopter Division (LHD)
- Samad Aerospace
- MTJB Ltd
- UWE Department of Engineering, Design and Mathematics

A variety of sUAVs have been developed and flight-tested:

- "Agile": demonstration of high-acceleration multi-rotor flight (MBDA)
- "Jackdaw": investigation of long-endurance autonomous fixed-wing flight (MBDA)
- "SpeedRacer": demonstration of fixed-wing autonomous target interception (MBDA)
- "Spectre": sub-scale demonstrator of future multi-rotor/fixed-wing tilt-rotor (MBDA)
- "Stonefish": multi-rotor self-recovering surveillance station (MoD)
- "Thunderbird": rapidly reconfigurable multi-rotor vehicle (MTJB)
- "Wonderbot": programmable multi-rotor for undergraduate teaching (UWE)
- "Albatross": demonstration of product design multi-rotor (UWE)
- "Offshore UAV": aerial inspection of off-shore wind turbines (INTERREG)
- "TRED": demonstration of tactical multi-rotor usage (Dstl)

The group has also completed, or has in progress, multiple sUAV analysis projects:

- Avionics architecture for airborne artificial intelligence (MBDA)
- Ducted fan efficiency analysis (LHD)
- Safety Argument Structures for Autonomous Systems (Dstl)
- Open Architectures for future UAVs (Dstl)
- Flight controls for future VTOL aircraft (Samad)

5. Commercial environment

The sUAV industry is currently following the familiar economic trajectory of a nascent technology being initially exploited by small enterprises, followed by the consolidation and backing from larger corporations needed to advance. Despite the fragmented nature of the industry, many sUAV technologies are governed by a variety of emerging standards established collectively by the development community. Thus, to some extent sUAV technology may be regarded as following the same *unorganised* (or *self-organised*) model of previous knowledge-based technologies.

The partially matured nature of the industry is illustrated by the categories of product available in the sUAV market: two overlapping classes are defined here: *Custom* and *Commercial-Off-The-Shelf* (*COTS*).

Custom sUAVs are constructed by technically skilled amateurs and niche commercial manufacturers, using a variety of available components and sub-systems. Conversely, *COTS* ("shrink-wrapped") sUAVs are produced by larger commercial enterprises, employing mass-production of airframes and using proprietary systems and software. An intersection of the *Custom* and *COTS* markets exists in the "*Ready To Fly*" (RTF) niche in which small commercial suppliers provide pre-assembled *Custom* equipment.

The *Custom* approach offers greater flexibility and performance for a given price point. Conversely, the expertise and economies of scale offered by *COTS*-developed equipment offer greater sophistication, reliability, and ease of operation for unskilled operators The proliferation of sUAVs has been almost entirely driven by this *COTS* segment [4].

The early industrial consolidation and the resulting technical sophistication of *COTS* UAVs is well illustrated by the products of the DJI company of Shenzhen, China (shown in Figure 1 & Figure 2).

Figure 1: DJI Phantom Quadcopter

Figure 2: DJI Mavic Quadcopter

The success of DJI's products (particularly the Phantom and Mavic sUAVs illustrated) has established the company as the world's leading sUAV vendor and enabled the rapid expansion of the DJI company from approximately 90 employees at its creation in 2006, to approximately 4000 when the Mavic was introduced in 2016 [3]. The proliferation of DJI products has served to define public perception of the capabilities (and limitations) of sUAVs in general.

6. Technological Environment

Classes of technology that have arisen to enable sUAV proliferation are classified here by the functions that they contribute to the vehicle's operation: *Propulsion, Stabilisation and Control, Command and Navigation,* and *Communications*. *Propulsion* refers to the generation of thrust capable of being modulated with sufficient agility to allow controlled flight. *Stabilisation and Control* refers to sensing and control of vehicle stability: this category does not include accurate control of position, implying a need for a higher level of automatic or manual piloting to maintain and alter position. *Command and Navigation* (explicitly distinct from *Stabilisation and Control*) relates to all functions necessary to move between selected positions and hold station to accomplish a mission. Automation of this category relegates a human controller to a supervisory or management role and enables fully autonomous flight if desired. *Communications* relates to provision of sufficient air-to-ground communication to allow such piloting or mission-management.

For each of these categories, the current state of the art has been enabled by the convergence of several separate low-cost technologies developed for other consumer applications, particularly the smart-phone industry [5].

In the *Propulsion* domain, batteries using gel-polymer electrolytes ("Lithium Polymer") offer high energy-densities and high power-delivery compared to conventional alkali batteries. These improvements in energy and power density are made accessible by electronically commutated motors via microprocessor-controlled switching equipment. The availability of LiPo technology has enabled the development of electrically powered thrust-borne vehicles with practical flight endurance: conversely, applications and capabilities of sUAVs are now largely constrained by the limits of this same technology.

In the *Stabilisation and Control* domain, automatic stabilisation avionics have been made possible by low-cost gyroscope and accelerometers, small format-factor microprocessors, and open-source stabilisation software [1]. Development has been accelerated by the availability of open-source software development tools.

In the *Command and Navigation* domain, vehicle-mounted First-Person View (FPV) cameras, Global Position System (GPS) receivers, and open-source implementations of autonomous GPS navigation algorithms have provided high-level mission-management capabilities. Low-cost and low-weight sensing equipment and cameras have allowed mission tasks to be expanded.

In the *Communications* domain, relatively short range (i.e. sub three kilometre) digital communication links with ground equipment include low-bandwidth command and instrumentation equipment operating in the unlicensed *Low Power Device* and *Industrial, Scientific, and Medical* spectra. The domain has been further enhanced by the availability of flat-screen monitors and goggle-mounted display equipment, enabling portable screens and Head-up Displays (HUD) to be integrated into command equipment appropriate for in-field use.

The consumer-market origins of these technologies imply several strengths and weaknesses in relation to conventional manned aircraft, which frequently run counter to intuitive expectations. For example, due to advances in the *Propulsion* domain, accelerations of up to 10g and maximum airspeeds beyond 100 mph are achievable by vehicles costing less than £500. Conversely, position control via inertial-based methods is highly problematic, necessitating a variety of complex compensation technologies to accurately maintain station.

Significantly, the use of consumer grade hardware and software and simple architectures yield low reliability in both *availability* (assurance of commanded operation) and *integrity* (prevention of uncommanded operation), and vehicle-loss failure rates of the order of 100 hours is typical.

7. Threat analysis

7.1. Classes of threat

Three overlapping classes of threat implied by current sUAV technology are defined here, judged by the intentions of the human operator: *Accidental, Reckless,* and *Malicious*. These classes have been popularly described as "*The Clueless, The Careless, and The Criminal*".

Accidental threat covers those due to reasonable operator error or (more frequently) technical failure. *Reckless* covers threats due to illegal controlled flight, and accidental excursions due to insufficient operator training or experience. *Malicious* covers threats due to deliberate action by the operator, often implying some level of mission-specific modification to the vehicle itself.

7.2. The spectrum of threats

As discussed in Section 7.1, the boundaries of these classes of threat are not distinct, and each cover a range of activities and levels of sophistication. Example scenarios based on the author's experience and in escalating level of severity are cited here:

7.2.1. Controlled privacy intrusion (Malicious)
Targeted observation of members of the public. Motivations may include journalism, espionage, or abusive observation.

7.2.2. Propulsion-loss in public space (Accidental)
Loss of thrust causing impact in a populated space. Typical causes may be switching device failure, computer hardware failures, battery depletion, and mechanical failure of wiring and connectors.

7.2.3. Fly-away in public space (Accidental)
Controlled but unnavigated "fly-away", causing a vehicle to impact in a remote public space. Typical causes may be software failure or loss of communications.

7.2.4. Contraband smuggling (Malicious)
Deliberate delivery of contraband by an operator. Typical applications may be smuggling into prisons.

7.2.5. Deliberate proximity flying (Reckless)
A UAV being deliberately navigated close to a sensitive area, triggering an emergency response. Typical events may include unskilled observation missions near motorways and airports.

7.2.6. Improvised weaponisation (Malicious)
Deployment of improvised weapons developed from COTS or Custom airframes by skilled ameteurs (as discussed in Section 5). Examples of this have been observed in recent years during conflicts in the Middle East (Figure 3).

Figure 3: Improvised Weaponisation of Consumer UAV

7.2.7. Military-sponsored weaponisation (Malicious)
Deployment of nationally-funded but comparatively low-cost weapons developed from Custom airframes by experts (Section 5). Examples of this are currently under development by a variety of nations.

7.3. Threat Severity/Probability Trade-off

In common with common Risk Assessment methodology, the severity of a threat's outcome may be plotted against its probability of occurrence. Figure 4 shows such a qualitive plot for the example scenarios cited in Sections 7.2.1 - 7.2.7.

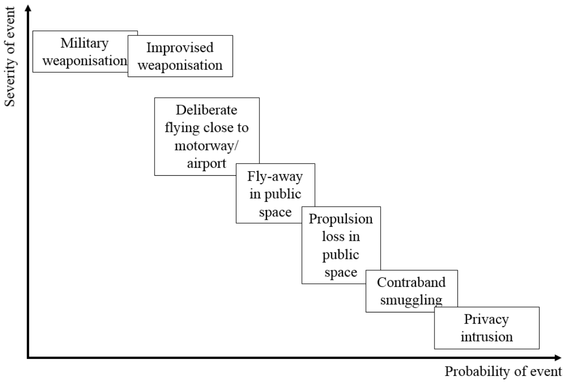

Figure 4: Event Severity/Probability

As implied by their position on the horizontal axis, actual incidents are dominated by accidental (occurring in public spaces on an almost daily basis but rarely reported), then reckless (with a few cases annually, and typically reported), and then malicious events (with no violent incidents currently reported in the UK).

8. Commentary on inquiry objectives

In this section, the previous observations and analysis are related to the Committee's stated issues of interest:

8.1. Citizen safety

"The ethical implications of civilian drones on citizen privacy and safety in the UK"

As shown in Figure 4 of Section 7.3, UAVs present a wide spectrum of potential scenarios, which trade off low-severity and high-probability against high-severity and low-probability. This is the dilemma of any defensive strategist facing a range of dissimilar threats: selection of the domains to address. Currently proposed legislation appears to focus on the high-severity/low-probability domain, whether as a reaction to reported incidents or due to these being issues most amenable to legislative solutions. This class of threat is currently overemphasized.

As also implied by Figure 4, a salient threat is improvised weaponisation (Section 7.2.6), combining a relatively high probability (due to ease of development and deployment), and high severity of outcome (i.e. feasibility of multiple deaths of uninvolved members of the public in a public space, resulting in a disproportionate response).

8.2. Built-in safety features

"The effectiveness of built-in drone safety features, such as tracking and monitoring capabilities, in mitigating the risks of civilian drones"

Currently available built-in safety features are generally limited to *geo-fencing*, in which the vehicle monitors its own geographical location via on-board GPS capability and actively limits its flight path against an on-board database of prohibited locations. Although effective when successfully deployed, the concept is reliant on technical expertise of the developer and cooperation of the operator. In practice the capability is limited to COTS and more advanced Custom UAVs (Section 5). The commonality inherent in COTS equipment has also resulted in geo-fencing override ("jailbreaking") tools becoming widely available to skilled amateurs.

Although not currently contributing directly to risk mitigation, internal logging of flight-path recording, currently implemented on most COTS and Custom UAVs, has the future potential to enforce good practice by provision of evidence of adherence to correct procedures.

8.3. Countermeasures

"The effectiveness of anti-drone technology in mitigating the risks of civilian drones"

Currently available countermeasures are largely based on ground-based jamming of ground/air communications, disruption of electronics by Electro-Magnetic Pulse, and cyber-level interception of command signals. These approaches are currently feasible due to the technology limitations (Section 6) and the general use of COTS equipment (Section 5). However, these methods may already be evaded by capabilities available to skilled developers: for example, fully autonomous flight with no requirement for ground/air links, hardening of electronics against EMP attack, high-speed flight (i.e. 80-100mph, 5-8g), and swarm deployment of vehicles.

It is probable that future countermeasures will rely on a combination of effectors, both ground-based and airborne. For example, the feasibility of low-cost, low-kinetic, non-impact vehicles, derived from drone technology and able to deploy these effectors safely in civilian environments, are being explored (Section 4).

8.4. Economic opportunities

"The economic opportunities arising from the growth of drone technology"

As discussed in Section 5, the global UAV industry is experiencing geometric growth, driven largely by small-scale entrepreneurs. UK businesses are succeeding in the market, leveraging existing aerospace and consumer electronics expertise, and led by small enterprises (commercial and academic). Conversely, both in the UK and abroad, large aerospace incumbents are struggling to adapt and integrate rapidly evolving technologies into their traditionally cautious business and development cycles.

8.5. Regulatory frameworks

"The success, or otherwise, of regulatory frameworks for civilian drones and what should be covered in the forthcoming Drones Bill"

Evidence has been requested to inform "A Bill to require drones to be marked and registered and to broadcast certain information electronically; to place restrictions on drone flight near aerodromes; and for connected purposes." In practice, these are distinct requirements, and should be addressed separately.

"Broadcast certain information electronically": as with the currently available safety measures discussed in Section 8.2, this requirement will require cooperation of both vendors and operators. It is likely to be resisted due to weight, cost, and reliability issues, and the requirement for technological development and investment.

"Place restrictions on drone flight near aerodromes;": these requirements can be met by the simple extension of simple extension of current legislation [1].

Generally, the proposals are driven by the current state of UAV technology and the limits of its capabilities, and require the cooperation of the regulated parties and, even with full collaboration, may be difficult to implement.

Currently proposed regulation will greatly reduce accidental and deter some reckless behaviour (Section 7). Conversely, it is likely to exacerbate the risk of successful malicious attacks, due to the constraints on sanctioned UAV research and deployment of countermeasures.

8.6. Planned registration

"The plans for registration of civilian drones in the UK"

Limited legislation (e.g. registration) is generally welcomed by the skilled community, motivated by a desire to avoid draconian legislation in reaction of a catastrophic accidental/reckless event.

Adaptation in reaction to legislation should be anticipated. For example, it is feasible to greatly extent the capability of sub-250g UAVs, and this process has already begun in anticipation of planned registration requirements (Figure 5).

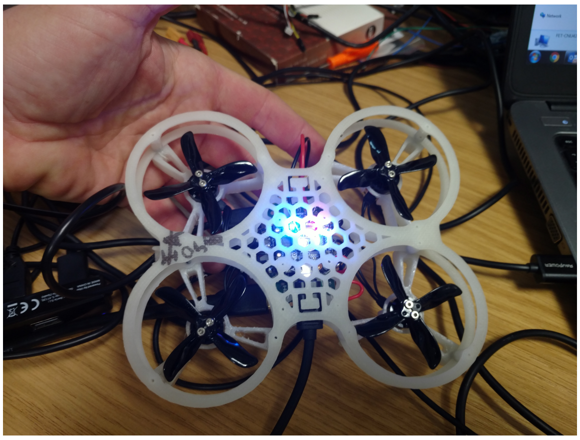

Figure 5: Custom 136g UAV

8.7. Safety education and research

“The current state of drone safety education and research in the UK”

The UK has supported a self-policing sUAV community for many decades, limited to skilled amateurs by technology capability. However, the ease of accessibility and operation of UAVs in the last ten years has given rise to many accidental threats (Section 7.1). Media coverage in the last two years has done much to raise awareness of an ethical responsibility amongst unskilled operators.

Commercial operation of UAVs is also efficiently regulated by “Permission for commercial operation” (PFCO) certification, and its attendant insurance requirements. This has in turn resulted in the emergence of an efficient and informed UAV insurance industry.

In the Research and Development domain, clarity is now emerging over classification boundaries between recreation, research, and commercial operations, and the appropriate controls that apply.

In the malicious domain, the threat is democratised by skilled amateurs developing Custom sUAVs, and with access to modest funding, as illustrated by the activities described in Section 3.

References

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