Nuclear Decommissioning Authority

Unmanned Aerial Vehicles (UAVs) in Nuclear Decommissioning – Current Use and Future Opportunities

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Preface

This technical report has been prepared by Wood under contract to the Nuclear Decommissioning Authority (NDA). The report has been reviewed by Wood and NDA prior to publication. The views expressed and conclusions drawn are those of the authors and do not necessarily represent those of NDA. The inclusion of specific technology within this report should not be interpreted as NDA endorsement.

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Executive Summary

A UAV is a remotely- or autonomously-controlled robotic aerial platform. There is broad interest across the NDA Group in assessing the viability of UAV technologies to support decommissioning work. Across many sites UAVs have already been deployed either to directly support ongoing programmes, as technology demonstrations, or tests of system viability.

The three main UAV types are ‘fixed wing’, ‘rotary’, and ‘hybrid’, with different capabilities in term of manoeuvrability and flight efficiency. UAVs are typically powered by on-board energy sources, such as batteries, chemical engines, or fuel cells, though tethered UAVs are also available. UAVs are typically deployed with a payload, such as a sensor, an effector, or even cargo. The technology to automate UAV flights with minimal or no human intervention is available, but is limited in its use in the UK by aerospace regulations.

Regulations for external UAV flights in the UK are enforced by the Civil Aviation Authority (CAA), which classifies the level of oversight required for the deployment of UAV systems based on their mass and their complexity, with lower mass, lower complexity systems requiring less oversight. UAVs to be flown for commercial gain (e.g. in industrial uses) must be covered by a permission for commercial operation (PfCO), which requires suitable safety, competency and insurance criteria to be met by the operating company. There are presently 4961 PfCO holders in the UK (as of February 2019). The CAA does not regulate UAVs used for internal deployments i.e. where there is no risk of interference with other external flights.

Information on 20 UAV deployments was gathered through interviews with NDA Group and AWE personnel. These deployments typically used off-the-shelf (OTS) UAV platforms with in-house pilots to assist with regular visual inspections, external (3rd party) UAV service providers to supply photography or other data to assist with ongoing projects, or were technology demonstrations of UAV systems in development for use on nuclear sites. The use of UAVs was generally found to be beneficial in terms of safety, cost, and time, compared to more traditional methods (e.g. working at height via scaffolding).

The commercial UAV market is expected to undergo a period of rapid growth, with multiple suppliers of a wide range of services and technologies available. In the nuclear sector specifically, while there is expected to be a more limited number of suppliers due to security vetting requirements, there is still expected to be sufficient choice for decommissioning organisations to conduct ‘Make/Buy’ decisions with few restraints from market availability.

Developments in UAV technologies for use in UK decommissioning are expected to come from a number of areas. In the short-term, wide-area radiation monitoring, radiation hardening of UAV technology, building information modelling, and UAVs for emergency response are expected to be key developmental themes. In the medium- and long-terms, radiation sensor development, increased flight autonomy and duration, the development of reduced downdraught platforms, extended flight (i.e. days) systems, swarming UAV systems, and heavy cargo and personnel systems are expected to be able to support decommissioning challenges.

Keywords

Unmanned Aerial Vehicle, UAV, Drone

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Table of Acronyms and Abbreviations

AoF	Allocation of Function
BRLoS	Beyond Radio Line of Sight
BVLoS	Beyond Visual Line of Sight
C&I	Control and Instrumentation
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
ConOps	Concept of Operations
CUAV	Counter Unmanned Aerial Vehicle
EASA	European Aviation Safety Agency
ECITB	Engineering Construction Industry Training Board
FPV	First Person View
GPS	Global Positioning System
HF	Human Factors
LiDAR	Light Detection and Ranging
LiPo	Lithium Polymer
LTA	Lighter Than Air
IP	Intellectual Property
MAA	Military Aviation Authority
MEWP	Mobile Elevating Work Platforms
NQE	Nationally Qualified Entity
Ofcom	Office of Communication
ONR	Office for Nuclear Regulation
OSC	Operating Safety Case
OTS	Off The Shelf
PfCO	Permission for Commercial Operations
ROV	Remotely Operated Vehicle
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPAV	Remotely Piloted Aerial Vehicle
SAP	Safety Assessment Principle
SD	Secure Digital
SLC	Site Licence Company
SUA	Small Unmanned Aircraft
(s)UAV	(small) Unmanned Aerial Vehicle
SyAP	Security Assessment Principle
TAG	Technical Assessment Guide
TRL	Technology Readiness Level
UAS	Unmanned Aircraft System, *or* Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
VTOL	Vertical Take-Off and Landing

1 Introduction

An unmanned aerial vehicle (UAV) is a remotely or autonomously controlled aerial platform, which does not hold the pilot on-board. In recent years there has been a great increase in the availability of consumer and commercial UAV systems, as well as their adoption into industrial sectors to support various tasks, such as inspections, and asset condition monitoring. Potential benefits of UAV deployment over the utilisation of personnel include decreased risks, costs and time.

There is broad interest across the NDA Group in assessing the viability of UAV technologies to support decommissioning work. Across many sites UAVs have already been deployed either to directly support ongoing work, as technology demonstrations, or tests of system or procedure viability. There is, therefore, an opportunity to collate and disseminate current deployment experience of UAV systems on decommissioning sites across the Group to aid the programmes of other sites, ensuring that learning and best-practices are shared.

In addition, it is expected that UAV and related technologies (sensors, batteries, etc.), will continue to develop swiftly, and that the capability of UAV systems to assist with decommissioning activities will increase with this development. In parallel with this technological development, the regulatory environment for UAV use in the UK is also expected to change, which will dictate the ways in which UAVs may be used to support UK decommissioning. As such, an assessment of potential developmental avenues for UAVs which may support UK decommissioning is warranted.

As part of the current study, information from various NDA Group organisations (Sellafield Ltd., Magnox Ltd., LLW Repository Ltd. and Dounreay Site Restoration Ltd.) and AWE was collected through a series of interviews focusing on UAV deployments by these organisations, including the reason for the deployments and their success, the information gathered, the type of UAV deployed, any safety and security considerations, etc.

Information from the project team, comprising subject matters experts in the commercial use of UAVs and of UAV technologies, was also gathered to provide information on the following areas:

- An overview of UAVs from a technical and regulatory perspective, with specific focus on the situation as relevant to the UK;
- Information on the UK UAV commercial market;
- Case studies of UAV deployments in a nuclear and non-nuclear commercial context, both in the UK and globally; and
- Areas of potential technological and regulatory developments in the short-, medium- and long-term.

This report thus comprises four main sections. Section 2 provides an overview of UAVs from a technical standpoint, as well as an overview of the current UK regulatory environment controlling the use of UAVs. Section 3 summarises relevant aspects of UAV deployment across NDA Group organisations and AWE, with further information for each individual case study presented in the Appendix. Section 4 presents the results of a market analysis of the UK UAV sector, with both Porter’s Five Forces and PESTLE assessments conducted. Section 5 discusses potential short-, medium- and long-term developments in the use of UAVs in UK decommissioning by combining case studies for current UAV uses in various sectors both nationally and internationally, as well as information on ongoing R&D projects for UAV systems.

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2 Overview of UAVs

2.1 Nomenclature

There are several terms in common usage which are used to describe UAV systems. In addition to 'UAV', other terms in general use include: 'Unmanned Aircraft System' or 'Unmanned Aerial System' (UAS), which tends to include the ground-based control systems as well as the aerial platform; 'drone', which tends to be used to describe the aerial platform in a less technical manner; 'Remotely Piloted Aircraft System (RPAS); and Remotely Piloted Aerial Vehicle (RPAV). To differentiate different sizes of UAV, size descriptors may be prepended the acronym, (e.g. sUAV – small Unmanned Aerial Vehicle).

For consistency, in this report the term 'UAV' will be used to describe the aerial platform and payload. When discussing the regulatory considerations for UAV use (Section 2.7), the term 'UAS' will also be used in order to align with the terminology adopted within the relevant regulatory documentation.

2.2 Architecture

A UAV is a remotely- or autonomously-controlled aerial platform. Unlike piloted-aircraft, the operator of the vehicle is not physically present onboard the vehicle, though an aerial platform controlled by autonomous on-board software would still count as a UAV. In addition, a level of spatial self-control is typical of UAVs; a weather balloon would not usually be considered to be a UAV, despite fulfilling the 'unmanned' and 'aerial' aspects of the designation.

At its core, a UAV will comprise components required to fulfil its role as a UAV: a method of flight, a method of remote control, a method to power the system, etc. To be of use in an industrial situation, however, the platform will need additional payload components, e.g. cameras or other sensors. There are many components that contribute to a UAV system and the choice will depend on the task the UAV is expected to perform. The different components can be classed as the 'UAV architecture'. To create or specify a UAV system, the user needs to understand the problem they wish to solve and then combine features into an architecture that offers the best solution.

2.3 UAV Platform

2.3.1 Flight

There are three main methods for UAV flight:

- **Fixed Wing**. Like traditional aeroplanes, these UAVs generate lift by forcing air movement over aerofoils built into their structure. Fixed-wing UAVs benefit from more efficient lift than rotary UAVs (see below), tending to achieve longer flight times for comparable power sources. A detriment to this method is that the UAV must be constantly moving to generate lift, and its manoeuvrability is constrained by this necessity. An example usage case for fixed-wing UAV would be geographical image mapping of large areas.
- **Rotary**. Like a helicopter, this method allows the UAV to fly and manoeuvre by generating lift directly from directional propellers. This allows the UAV to perform vertical take-off and landing (VTOL). Rotary UAVs also have good manoeuvrability and are able to maintain position by hovering in-place. Many different rotor configurations are possible (1 rotor to over 12), and typically

they are in 4, 6 or 8 rotor configurations (named quad- hex- or octo-copters, respectively). An example usage case for a rotary system would be to take a series of close-up images of an interior building structure.

- **Hybrid**. These are a combination of fixed wing and rotor systems, designed to combine benefits from both, e.g. systems that are capable of VTOL, but also longer flight durations. An example usage case may be use by emergency responders to deliver critical equipment from a confined area (e.g. a blocked motorway) to an accident site several miles away.

In addition to those mentioned above, there are a number of less common methods including airships/balloons, kites/parachutes, gliders and flapping wings (to mimic bird flight).

2.3.2 Power

Power for a UAV may come from a number of sources, typically incorporated into the UAV itself.

- **Electric/battery**. These tend to be light-weight lithium polymer (LiPo) batteries due to their good capacity to weight ratio. Storage capacity (and so flight time) is lower than other methods, though many UAV systems are designed that replacing and/or recharging the battery is a straightforward task.
- **Diesel/petrol engines**. These UAVs use internal combustion to power their flight, and tend to be used on larger UAVs due to the greater weight of their systems. They provide much longer flight times than batteries.
- **Fuel cells**. These power sources offer longer flight times than batteries but have less weight than a petrol engine. These are typically developmental technologies, and are a less common power system than batteries or internal combustion engines.

Less common fuel sources include solar, which may be used for high altitude UAVs, and tethered UAVs that take power from the ground through a connecting cable and can stay aloft for very long durations.

2.3.3 Flight Duration

The flight duration for a typical industrial-use rotary UAV is often short, typically under 30 minutes. As such, pre-planning of the flight and power requirements is recommended. To increase flight duration, improved batteries (or doubling up of batteries) and fuel cells are commonly used.

2.3.4 Control Systems

UAVs are typically controlled remotely by an operator, though semi- or fully-autonomous control systems may also be used. Direct control interfaces may be joysticks, or touchscreen consoles. To allow a more direct piloting experience a first person view (FPV) may be commonly used, whereby data from an on-board camera are streamed live to the operator. These live data may be viewed on a screen or with goggles. The ability to fly a UAV when it is out of sight (beyond visual line of sight, BVLoS) will often use this method to relay information about the position and orientation of the UAV back to the pilot, although regulations may mean it is not legal in certain jurisdictions, such as in the UK (see Section 2.7). An example of semi-autonomous control would be where a UAV can follow a pre-programmed route. Fully autonomous UAVs may use collision avoidance technologies, such as LiDAR (Light Detection and Ranging) mapping, to complete their route.

2.3.5 Payload

In addition to the core-systems required for flight and control of the UAV, a UAV is typically used with an onboard payload that provides its key capability. Payloads may broadly be classed as ‘sensors’, ‘effectors’, or ‘cargo’. Sensors and effectors are discussed in more detail in Sections 2.4 and 2.5, with cargo referring generally to any payload which is transported by the UAV from one location to another.

The weight that a typical industrial-use UAV can lift is often very low – under 5 kg is common even for large UAVs – and this limits the payload-types that can be used. There are several “heavy-lift” UAVs that can carry a few tens of kilograms. To carry more weight, a larger UAV with a petrol engine is normally used.

2.3.6 Data Output

Data output from a UAV will come from two main sources: the core control systems and the payload (if applicable).

Data from the core control systems are typically remotely communicated with low latency, and is used to relay the condition of the UAV for flight purposes. This comprises both data for human interpretation (e.g. altitude, position, speed, etc.) as well as system level data (confirmation that a control command has been received, confirmation that a UAV is still within range of the control signal, etc.). The high speed of this data transfer is important, as it is often required by the pilot to make second-to-second decisions on their control of the UAV. Data are typically transmitted over radio frequencies, and different data transfer protocols may be used (WiFi, 5G, etc.)

Data output by a payload may be greater than is able to be directly communicated remotely, particularly if the data are from a high-resolution camera. In these cases full-quality data from the payload is typically stored locally on the UAV, e.g. on an on-board hard-drive or SD card. Compressed data may be transmitted wirelessly to the operator to verify that the correct data have been acquired (e.g. the correct location on a pipe has been photographed). The high-quality data may then be collected from the UAV once the flight is complete.

Tethered UAVs may use their cable for data transfer, typically allowing greater data bandwidths (i.e. faster data transfer) than wireless transfer.

2.3.7 UAV Design Considerations

One of the key challenges with UAV design is to balance the requirements to carry a specific payload and the requirements for a suitable flight duration. Increasing battery size or using fuel cells can increase the weight of the UAV system, which then reduces the available carrying capacity for the payload.

Another key challenge is the trade-off between flight duration and manoeuvrability. Fixed wing and hybrid designs have much longer flight durations due to their use of more efficient aerofoils to generate lift, at the expense of the manoeuvrability of a rotor UAV.

2.4 Sensors

Many UAVs are used for visual inspection and will include a high resolution camera or the ability to mount one as a payload. The cameras may be designed to record digital image or video data, and many modern cameras have extremely high definition, useful for detailed inspections.

Multispectral imagers allow the UAV to collect images from non-visible wavelengths - typically infrared and ultraviolet. These are used widely in agriculture and search and rescue operations, as well as for concrete inspections, soil contamination monitoring and mapping of thermal fluxes (e.g. through a building's roof).

Ionising-radiation detectors can be mounted on a UAV and typically detect γ-radiation, though detectors for β-radiation, X-rays and neutrons are also available[1]. The accuracy is dependent on the flight speed of the UAV (a lower flight speed leads to better resolution), distance from the source (closer proximity increases resolution) and stability of flight (the more stable the flight, the better the result). Hence the choice of detector, software and UAV type is highly dependent of the radiation that is to be measured.

LiDAR measures distance between the sensor and a surface and is often used in conjunction with GPS (global positioning system) data for mapping both natural and manmade environments. For GPS-denied environments (such as indoors or under bridges) LiDAR may be used in conjunction with other technologies such as antennas, pre-mapped environmental data (areas scanned in 3D prior to deployment) and vision-aided systems. LiDAR may also be used for collision avoidance where it is used to keep the UAV a certain distance away from an object.

2.4.1 Sensor Selection Considerations

The weight of the sensor needs to be aligned with the payload capacity of the UAV. Many manufacturers produce combined units - several multispectral imagers or multiple cameras - in an attempt to fit more capability into a small package.

Higher quality data (e.g. high-resolution images) typically require larger sensors and hence an increased sensor weight. As such, an assessment of data quality requirements is a useful input into the selection of a sensor system for deployment on a UAV.

Data collection bandwidths are important for both transmission and storage of collected data. High-resolution, high-frame-rate video data, for example, may be required to be stored on an onboard hard-drive rather than an SD card due to the higher data bandwidth of the hard-drive.

2.5 Manipulation and End Effectors

Although the addition of arms (or other manipulation devices) are less common than sensors, university and company research is ongoing in this area. This ranges from the ability to grab items in flight, to take samples from man-made or natural environments, and to spray liquids or foams. The agricultural industry is particularly involved with precision spraying of insecticide, particularly for hard to reach areas.

2.5.1 Effector Selection Considerations

The particular challenge with effector-type payloads is controlling the UAV while the activity is being carried out. Manipulation or spraying introduces a moment of force that means control of the UAV's flight can be extremely difficult.

[1] α-radiation typically does not penetrate the distance between source and UAV to be reliably detected.

The weight of the component is also a challenge due to payload considerations and reduces both the equipment capability and what it can be used for.

2.6 Other Aspects

2.6.1 Safety Systems

2.6.1.1 Collision Avoidance/Tolerance

Some UAVs have incorporated LiDAR sensors in conjunction with appropriate flight control software to prevent a UAV from colliding with objects whilst in flight. Vendors also provide accessories for UAVs such as cages and bumpers to help protect vulnerable parts from damage. A different approach in UAV design is called collision tolerance (e.g. Elios UAV), whereby the UAV system is designed to operate while in contact with surfaces or other objects during flight.

2.6.1.2 Parachutes

Parachute systems are available to save a UAV that has failed mid-air. If a sudden failure in the flight systems is detected, a parachute is deployed that allows the UAV to float back to the ground rather than crashing.

2.6.1.3 Fault Tolerance

Many UAV platforms are being designed with in-built redundancy and fault tolerance so that it can operate even when something has failed. The ability to fly with one less propeller is such as example.

2.6.1.4 Counter UAV Systems

Counter UAV (CUAV) systems are systems that can detect and/or bring down or otherwise incapacitate a UAV and are a recent (and fast growing) area for security services. Detector systems may use video or RADAR data to detect UAVs, though these may require operator attention and experience to differentiate real and false detections (e.g. birds). Inhibiting systems may involve physically interfering with the UAV (e.g. through netting to tangle propellers, firearms to damage the airframe, or birds of prey to grab and disorient the UAV), or may affect the UAV’s onboard sensors (e.g. through laser interference with cameras, or radio interference with the control or GPS signals).

The potential for unintended consequences from the use of CUAV systems should also be recognised. For example, the deployment of electronic countermeasures may lead to interference with non-hostile critical systems e.g. safety systems onboard the UAV, or medical devices within the area of effect.

2.6.2 Software

There is a huge growth in software to support UAV applications, outside of direct flight control interfaces. This includes software to assist with tasks such as:

- **Air Traffic Management**. These systems allow users or agencies to track and monitor their UAV fleets in real time like an aircraft traffic control system. They are widely used in disaster response scenarios.
- **Fleet Management**. This software allows companies to keep track of their fleet for maintenance purposes. This may include total flight-time for particular UAV systems, battery histories, and pilot logs.

- **Data Management / Data Processing**. This software includes image stitching programmes, 3D mapping software, cloud-based data collection and management platforms, and data sharing & distribution systems.

2.7 UK UAV Regulatory Framework

This section covers an outline of regulations on the classification of UAVs, as well as the commercial use of UAVs in the UK. The Civil Aviation Authority (CAA) is the UK's specialist aviation regulator. Pertinent regulation from the European Aviation Safety Agency (EASA) and The Office of Communications (Ofcom) is also presented. In addition, an overview of the regulatory considerations for the use of UAVs on nuclear sites is given.

This section is intended to be an informative overview of relevant regulations. Full information and guidance should be sought from the regulatory bodies themselves.

2.7.1 Terminology

A list of relevant definitions used in the following section is given in Table 1 [1].

Table 1: List of definitions as given in CAP (civil aviation publication) 722 [1]. Additional text explanatory text is presented as *[italics within square brackets]*.

Term	Definition
Autonomous Aircraft	An unmanned aircraft that does not allow pilot intervention in the management of the flight.
Autonomous Operation	An operation during which an unmanned aircraft is operating without pilot intervention in the management of flight.
Commercial Operation	Flight by a small unmanned aircraft except a flight for public transport, or any operation of any other aircraft except an operation for public transport; which is available to the public; or which, when not made available to the public, in the case of a flight by a small unmanned aircraft, is performed under a contract between the SUA *[small unmanned aircraft]* operator and a customer, where the latter has no control over the remote pilot or in any other case, is performed under a contract between an operator and a customer, where the latter has no control over the operator, in return for remuneration or other valuable consideration. *[The key elements in understanding this term are '…**any flight by a small unmanned aircraft**…**in return for remuneration or other valuable consideration'.*** *The term 'available to the public' should be interpreted as being a service or commodity that any member of the public can make use of, or actively choose to use, (e.g. because it has been advertised or offered to someone).]*
Congested Area	In relation to a city, town or settlement, any area which is substantially used for residential, commercial, industrial or recreational purposes.

Term	Definition
Continued Airworthiness	The monitoring, reporting and corrective action processes used for in-service aircraft to assure they maintain the appropriate safety standard defined during the initial airworthiness processes throughout their operational life.
Continuing Airworthiness	The system of management of the aircraft and the scheduling and actioning of ongoing preventative and corrective maintenance to confirm correct functioning and to achieve safe, reliable and cost effective operation.
Highly Automated	Those systems that still require inputs from a human operator (e.g. confirmation of a proposed action) but which can implement the action without further human interaction once the initial input has been provided.
Initial Airworthiness	The system used to determine the applicable requirements and establish that an aircraft design is demonstrated to be able to meet these requirements.
Small Unmanned Aircraft (SUA)	Any unmanned aircraft, other than a balloon or a kite, having a mass of not more than 20 kg without its fuel but including any articles or equipment installed in or attached to the aircraft at the commencement of its flight.
SUA Operator	This, in relation to a small unmanned aircraft, is the person who has the management of the small unmanned aircraft.

2.7.2 UAV Classification

The CAA's policy for Unmanned Aircraft Systems (UAS) is that they must meet the same safety and operational standards as manned aircraft. According to the CAA, because some UAS manufacturers have limited aviation experience, prescriptive CAA guidance in this area is required.

UAS are currently split into three categories according to their mass:

- **20 kg or less, Small Unmanned Aircraft**: These normally have a reduced level of regulation associated with them, which is aimed at being proportionate to the risk and complexity of their operations.
- **20 kg to 150 kg, Light Unmanned Aircraft**: These are subject to all aspects of UK aviation law, although they may be exempted from many of the requirements. Approval to operate is normally given following the submission of a safety case to the CAA.
- **Over 150 kg. Unmanned Aircraft Systems**: Aircraft in this class will usually be subjected to the same level of regulatory approval requirement as would be used for traditional manned aircraft. They will normally be certified by the EASA.

Civil aviation publication (CAP) 722 contains a "Concept of Operations" (ConOps) approach for UAS approval requirements [1]. Approval categories are designated A, B and C, with Category A having the least stringent approval requirements, and Category C the most. Rather than focusing solely on the mass category of a UAS in order to determine its approval requirements, ConOps encompasses all function areas of a UAS's operation, including both technical and operation complexity issues. A conceptual starting point for CAA approvals for UAS is shown in Figure 1. 'Technical Complexity' pertains to how complex the UAS is (e.g. number of flight control modes, flight management systems, etc.) whereas 'Operating Environment Complexity' describes how complex the environment is (e.g. congested areas, complex airspace, etc.). There is some degree of flexibility in the approvals classification, which could potentially result in extension of Category A to higher masses than usual. For example, the dashed line in Figure 1 shows how Category A can be extended to masses greater than 20 kg; this can be achieved with sufficient lack of technical and operational complexity. Conversely, there could be cases where a very low mass UAS too is technically and/or operationally complex to be classified as Category A. The CAA state that early engagement from operators is essential to help ensure that the correct classification and approach are established for the UAS and its intended operating environment.

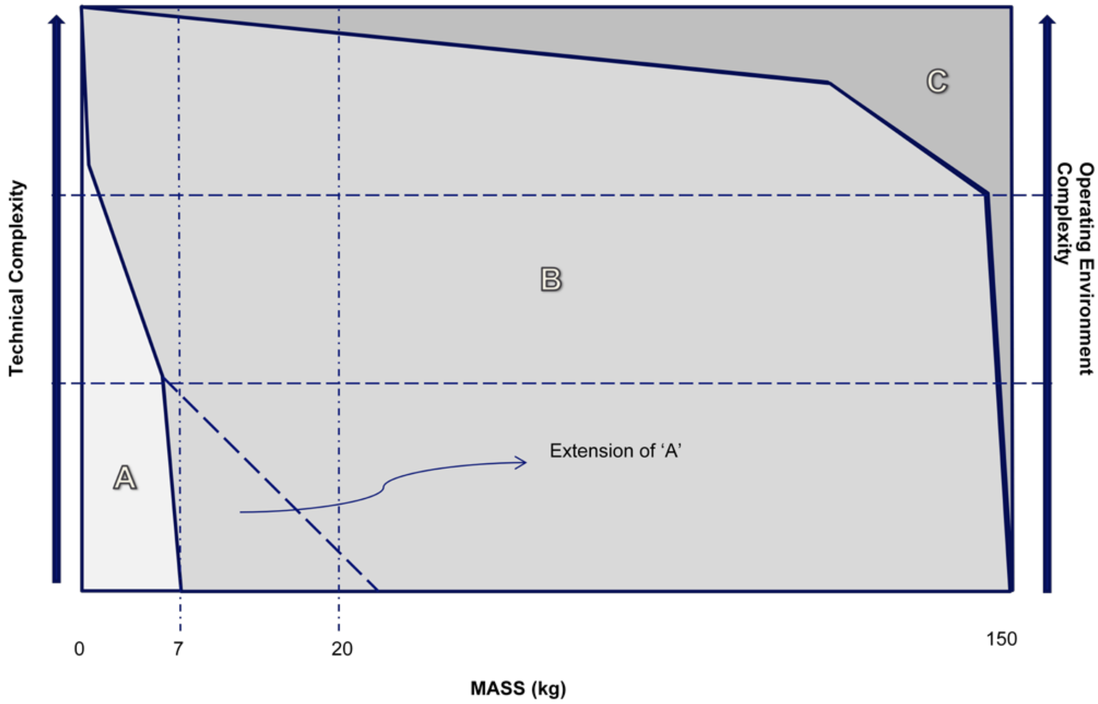

Figure 1: Summary of CAA classification for Unmanned Aircraft Systems. [1]

2.7.3 Autonomy in UAVs

The CAA also have the following definitions of UAS:

- **Highly automated systems**: systems that still require inputs from a human operator (e.g. confirmation of a proposed action) but which can implement the action without further human interaction once the initial input has been provided.
- **High authority automated systems**: systems that can evaluate data, select a course of action and implement that action without the need for human input. Good examples of these systems are flight control systems and engine

control systems that are designed to control certain aspects of aircraft behaviour without input from the flight crew.

The CAA consider an “autonomous” UAS to be a system that will do everything for itself using high authority automated systems. For example, it will be able to follow a planned route, communicate with Aircraft Controllers and other airspace users, detect, diagnose and recover from faults and operate at least as safely as a system with continuous human involvement.

Automation is the capability of a system to act using a set of pre-designed functions without human interaction (e.g. robotic manufacturing). A high authority automated system must be deterministic in that the system must always respond in the same way to the same set of data. Such systems are usually composed of a number of sub-systems used to gather data, evaluate data, select an appropriate set of actions and issue commands to related control systems. These systems can include flight management systems, detect and avoid systems, power management systems, etc. In an UAS a system can have authority over two types of function: general control system functions (e.g. flight control computers) and navigational commands.

High authority automatic systems can be applied to different degrees of system authority. Full authority pertains to where systems are capable of operating without human control or oversight; while there may be lesser levels of authority, where the system is dependent upon some degree of human input (e.g. confirmation of proposed actions). The level of authority a system can have with respect to navigational commands may vary during any flight, dependent upon the hazards the aircraft is faced with and the time available for the human operator to effectively intervene.

The CAA also notes that, in order to mitigate remote pilot workload (e.g. monitoring of UAS condition, awareness of static obstacles, identification of other UAS in the area, etc.), UAS are increasingly incorporating “advanced decision support systems”. As far as delivering a system that is safe, the CAA state that human factors expertise must also be taken into account, to ensure the correct level of pilot workload.

Section 3, Chapter 3 of the CAA CAP 722 deals specifically with autonomy [1]. At the current time, all UASs are required to perform deterministically: their response to any set of inputs must be the result of a pre-designed set of data evaluation output activation process. As such, there are currently no UAS related systems that are truly autonomous.

2.7.4 Commercial use of UAVs

At the time of writing there are no remotely piloted aircraft (RPA) licenses recognised in aviation law. However, it is essential that a pilot of any aircraft has a least a basic understanding of the applicable regulations, in particular those of the air navigation order [2].

Since the formation of EuroUSC, (the first UK & overseas pilot qualification, systems airworthiness, operational assessment and organisation accreditation company, within a national context) in 2003, the CAA took the decision to open up the market to other organisations wishing to operate UAV training facilities under the National Qualified Entity (NQE) programme.

Currently there are approximately 30 NQEs on the CAA registered programme, but it is only recently that some of these have begun to focus more on hands-on flight skills development training instead of classroom-based theory.

Working alongside some of the NQE organisations are a number of companies that have begun to specialise in scenario-based training, specific to meet the needs of industry. This primarily is due to the fact that, until very recently (2018), there was not a national standard for flight skills training, and the output from some the NQE organisations was not meeting the needs and higher standards expected by some regulated industries. The Engineering Construction Industry Training Board (ECITB) was one of the first (with support from a specialist working group) to develop a national pilot training standard.

2.7.5 Permission for Commercial Operations (PfCO)

Since the formation of the CAA UAV pilot accreditation scheme, there have been many changes in policy wording and requirements. The latest of these changes took place at the end of July 2018, with the introduction of the Air Navigation (Amendment) Order 2018 - Guidance for small unmanned aircraft users [3].

The main CAA policy documents that cover the use of UAVs currently are as follows:

- CAP 393 – Air Navigation Order 2016 [2]
- CAP 722 – Guidance Notes [1]
- CAP 1687 – Air Navigation (Amendment) Order 2018 [3]

A user or organisation wishing to operate a UAV for commercial gain (See 'Commercial Operation' in Section 2.7.1) must apply for Permission for Commercial Operations (PfCO). A permission from the CAA is required to be held if a user or organisation wishes to conduct a commercial operation with an aircraft (Article 94 [3]), or to fly an aircraft:

- at a height of more than 400 ft above the surface (Article 94A [3]),

and/or

- within 150 m of either a congested area or an organised open-air assembly of more than 1000 persons (Article 95 [3]),

and/or

- within 50 m of people or properties/objects that are not under the user or organisation's control (Article 95 [3])

An exemption from the CAA is required if a user or organisation seeks release from any other requirement within [3]. In both cases however, the CAA must still be suitably satisfied that the operation can be conducted safely. Permissions and/or exemptions are valid for up to 12 months and are subject to an annual renewal.

The greater the 'freedom of operation' that is required (in terms of locations, procedures and the duration of the permission), then the greater the amount of information which is required to be provided to the CAA (in terms of demonstrating that safe operation can be undertaken).

Two types of permission are available: Standard, and Non-Standard Permission.

2.7.5.1 Standard Permission

Standard permission enables a person or organisation to conduct commercial operations with a small unmanned aircraft and also permits operations within a congested area. Potential operators are required to provide evidence of pilot competence and an Operations Manual which details how the flights will be conducted.

2.7.5.2 Non-Standard Permission

Non-standard permission covers all other types of flight and addresses operations that contain a greater element of operating risk. In addition to the requirements for a Standard Permission, applicants are also required to prepare and submit an operating safety case (OSC) to the CAA. Full details of the pilot competence requirements and the OSC can be found in guidance document CAP 722 [1].

It should be noted that permissions and exemptions only authorise the commercial use of a UAV from a safety perspective. Operators are still subject to rules and regulations imposed by other bodies and organisations. These may include the emergency services, the Highways Agency, and local authorities. Before a commercial operation in a particular location, a permission holder should always check with all relevant bodies to establish what, if any, other restrictions apply. If applicable, operators should also understand and comply with rules around trespass and nuisance.

2.7.5.3 Application Procedure for PfCO

For a user or organisation to obtain PfCO, the following steps must be undertaken:

- Prove Remote Pilot Competence;
- Demonstrate a sufficient understanding of aviation theory (airmanship, airspace, aviation law and good flying practice);
- Pass a practical flight assessment (flight test);
- Develop basic procedures for conducting the type of flights which are intended and set these out in an Operations Manual; and
- If an intended operation requires an approval with greater privileges than in a Standard Permission, an Operating Safety Case will also be required to demonstrate that the intended operation is appropriately safe.

2.7.5.4 Current PfCO holders

The number of PfCO holders at the time of writing is 4961 based on information from the CAA on the 8th February 2019 [4].

2.7.5.5 Insurance

It is each applicant's/operator's responsibility to ensure they have appropriate insurance coverage, and this is a condition of each Permission, Exemption or any other form of operational authorisation.

Regulation (EC) 785/2004 requires air carriers and aircraft operators (which includes UAV operators) to "…ensure that insurance cover exists for each and every flight…" [5].

An applicant for a Permission, Exemption or authorisation must therefore have appropriate insurance on/at the date of the issuance of the Permission, Exemption or authorisation (to the satisfaction of the CAA) that meets the requirements of [5].

2.7.6 Ofcom

At the time of writing the licence exemption rules for radio control of the aircraft are 35 MHz and 2.4 GHz transmitting at 100 mW. Video transmitters operating at 5.8 GHz should transmit at 25 mW.

Using apparatus that does not meet the conditions of the licence exemption - or is not specifically licensed - is an offence.

Some offences can attract an unlimited fine and/or six months imprisonment. The courts can also confiscate anything used in connection with the offence.

2.7.7 Indoor Flights

For clarification, the applicability of the regulations regarding flights within buildings has been updated recently. Under the CAA Act 1982, the Air Navigation Order is made for the purposes of regulating air navigation. Flights inside buildings are not counted as ‘air navigation’ because they can have no effect on flights by aircraft in the open air.

As a result, flights within buildings, or within areas where there is no possibility for the unmanned aircraft to ‘escape’ into the open air (such as a ‘closed’ netted structure) are not subject to air navigation legislation. Persons intending to operate UAVs indoors should refer to the appropriate Health and Safety At Work regulations.

Having clarified the above, however, much of the existing guidance for external flights can be seen as general best practice, and while it is not a requirement to comply with external flight regulations while conducting internal flights, there are safety benefits in adopting best practice when operating any aircraft.

2.7.8 Automation on Nuclear Sites

The Office for Nuclear Regulation (ONR) is the nuclear regulator in the UK, responsible for the regulation of nuclear safety and security. The ONR has a goal-setting, non-prescriptive approach to regulation. An important point related to the ONR’s approach is that, in contrast to some other nuclear regulatory organisations, such as the United States Nuclear Regulatory Commission, the ONR does not carry out any “certification” activities.

The ONR uses Safety Assessment Principles (SAPs) and Security Assessment Principles (SyAPs), in conjunction with Technical Assessment Guides (TAGs) to guide regulatory judgements and recommendations; the SAPs, SyAPs and TAGs are available on the ONR website.

The ONR recommends the following classification for safety functions[2]:

- **Category A** – any function that plays a principal role in ensuring nuclear safety.
- **Category B** – any function that makes a significant contribution to nuclear safety.
- **Category C** – any other safety function contributing to nuclear safety.

The method for categorising safety functions should consider:

- the consequence of failing to deliver the safety function;

[2] Note that these ONR safety function classifications are distinct from the CAA’s approval requirement classifications.

- the likelihood that the function will be called upon; and
- the extent to which the function is required, either directly or indirectly, to prevent, protect against or mitigate the consequences of initiating faults.

Methods for classifying the safety significance of structures, systems or components should be based primarily on deterministic methods, complemented where appropriate by probabilistic methods and engineering judgement. A "proven in use" philosophy will, by itself, not be adequate. The methods should account for factors such as:

- the category of safety function(s) to be performed by the item;
- the probability that the item will be called upon to perform a safety function;
- the potential for a failure to initiate a fault or exacerbate the consequences of an existing fault, including situations where the failure affects the performance of another system, structure or component; and
- the time following any initiating fault at which, or the period throughout which, it will be called upon to operate in order to bring the facility to a stable, safe state.

The safety scheme recommended by the ONR is:

- **Class 1** – any structure, system or component that forms a principal means of fulfilling a Category A safety function.
- **Class 2** – any structure, system or component that makes a significant contribution to fulfilling a Category A safety function, or forms a principal means of ensuring a Category B safety function.
- **Class 3** – any other structure, system or component contributing to a categorised safety function.

ONR documents [6,7] do not currently make any reference to "autonomous" systems. Rather, Para 4.4 gives an over-arching definition of "automation", which encompasses automation of control and cognitive functions that have traditionally been carried out by humans, including diagnosis and decision-making. Para 4.4 also states that "automation is changing through the use of intelligent systems that have typically been controlled by operators", thereby introducing an ONR acknowledgement of "intelligence". Considering that there is no cross-sector consensus on how to define an "autonomous" system, the ONR's use of "automatic", coupled with "intelligent", provides flexibility to encompass a wide variety of systems (and is fully consistent with the ONR's non-prescriptive approach).

Compared to other sectors, the ONR more consistently uses the concept of "Allocation of Function" (AoF), which is: "When designing systems, dependence on human action to maintain and recover a stable, safe state should be minimised. The allocation of safety actions between humans and engineered structures, systems or components should be substantiated."

Human Factors (HF) and Control and Instrumentation (C&I; also incorporating software-based systems) are both major issues in the nuclear sector. The ONR has a clear approach of allocating the "human" parts to HF and the "machine" parts towards C&I and emphasising the need for a joint regulatory assessment. This approach ensures there is nothing missing in terms of "what is done by machine" and "what is done by humans". A statement that the "AoF is considered on a systems basis; in the total system, humans remain in overall control" further ensures that ONR encompasses all combinations of human and machine contributions.

In common with some other sectors, the ONR declare the concept of "situational awareness", recognising that, by reducing the level of interaction with the machine system, automation may increase the risk that operators can no longer identify what the system is doing.

ONR declare a specific link between automation (or computerised support) in respect of reliability or integrity. This is a specific issue, which should be evaluated jointly between C&I and HF inspectors. The duty holder also has to demonstrate that any failure modes of the automated system displays and controls will be revealed. The duty holder must also consider the implications for "team dynamics". Feasibly, the "team" could be to defined to consist of machines and operators; however the context of this statement (of situational awareness) is that the "team" is considered to be humans only.

Duty holders should be aware of the different types of technology that deliver functions as part of the nuclear security and safety related equipment and software operating at sites.

3 Summary of Case Studies of UAV deployments across the NDA Group

This section presents a summary of UAV deployments across the NDA Group and AWE. This information was collected through interviews with key personnel in each organisation involved in the deployment and consideration of UAVs, and covers: Sellafield Ltd., Dounreay Site Restoration Ltd., Magnox Ltd., LLW Repository Ltd. and AWE. These interviews were conducted and compiled during Q4 of 2018.

A list of the UAV deployments summarised in this section is given in Table 2. Details on each individual case study are presented in the Appendix.

Table 2: List of UAV case studies discussed with Site Licence Companies (SLCs)

SLC	Site	Description	Year
AWE	Aldermaston	Initial proof-of-concept flight	2018
Dounreay Site Restoration Ltd.	Dounreay	Integrity inspection work	2017-present
	Dounreay	Assistance with ‘Hidden Britain by Drone’ documentary	2018
LLW Repository Ltd.	LLWR	Survey of pile cap	2015
	LLWR	Assistance with civil engineering inspections	2016-present
Magnox Ltd.	Trawsfynydd	Trial inspection of Safestore building exterior	2013
	Winfrith	Inspection of SGHWR Cladding	2014-2015
	Winfrith	Internal flight through SGHWR for PR material	2014-2015
	Winfrith, Bradwell, Harwell	High-level video surveys of site	2015-present
	Hunterston A	RISER demonstration	2016
	Sizewell A	Visual inspection of various assets around site	2016-2017

SLC	Site	Description	Year
Sellafield Ltd.	Sellafield	University of Warwick PhD UAV demonstration	2012
	Sellafield	Photomapping of Wastwater pipeline	2012
	Sellafield	University of Bristol radiation mapping demonstration	2014
	Sellafield	RISER demonstration (Phase 1 and Phase 2)	2015
	Sellafield	Photographic survey of Braystone beach and Calder Hall Turbine building	2016
	Sellafield	External and Internal survey of site assets	2017
	Sellafield	Innovation Lab effector task	2017
	Sellafield	Internal inspection demonstration and training	2018
	Sellafield	LINC Blimp demonstration flights	2018

3.1 Reasons for use of UAVs and degrees of success

The majority of UAV deployments across the decommissioning sites to date have been to support or supplement routine visual inspection tasks. UAVs have been used to gather digital image and video data from difficult-to-access areas across several sites, such as building cladding, roofs and off-shore structures. Key benefits to this approach, as opposed to direct personnel access, have been to decrease deployment costs (e.g. of mobile elevating work platforms (MEWPs)), to decrease the time required to conduct the survey (e.g. no requirements to set-up potentially extensive scaffolding deployments), and to decrease risk to personnel (e.g. by reducing the requirement to work at height, or to enter hazardous environments).

In contrast to their use in detailed asset inspections, UAVs have also been used to gather high-level site overviews, either for use in overall project monitoring (i.e. tracking the development of a site during a project), for project planning, or for use in publicity materials.

In one instance a UAV was deployed to collect survey grade data of an on-site structure (pile cap on LLWR site) using laser scanning payloads, in order to reduce the dose risk associated with a traditional survey.

In addition to UAVs deployed to support sites and SLCs directly, UAV deployments have also been used to demonstrate and assist with the development of UAV technologies themselves, or site protocols and procedures. Technology demonstrations have included radiation detection and mapping, internal LiDAR mapping, a demonstration of different effector payloads, and a demonstration of a lighter-than-air flight methodology.

3.2 Procurement routes

UAVs were procured from two main routes: either direct procurement, whereby each organisation or site procured the UAV system with full ownership; or sub-contracted procurement, whereby a sub-contractor provided the UAV flight as a service. A notable exception to this was a demonstration flight undertaken as part of a PhD programme which was part funded by Sellafield Ltd., where a live demonstration of the UAV technologies developed during the PhD was undertaken on the Sellafield site [8].

3.3 Description of UAV(s)

There are several different UAV systems which have been used across the NDA Group. The vast majority have been rotary style UAVs, with only a single case where a fixed-wing UAV has been utilised, and a single case where a lighter than air (LTA) UAV has been deployed.

Typically, where UAVs have been deployed to capture external digital images and videos across sites, ‘consumer-grade’ commercially available UAV quad-copter systems have been used. These have comprised UAVs manufactured by DJI, either Phantom or Inspire models, and these have generally been deployed when the UAV deployment was conducted in-house. External visual inspections carried out by sub-contractors have also used DJI UAVs, as well as Intel’s Falcon 8 UAV, a two-rail 8-propeller system. For survey-grade laser scanning data, a Leica Aibotics Geosystems X6 was employed. Internal visual inspections have used Flyabilty’s Elios UAV system, a small quad-copter with an integrated carbon-fibre safety cage, affording protection from collisions during flight.

UAVs deployed as technology demonstrations have been generally more bespoke systems. The RISER UAV system is a quad-copter design with integrated propeller protectors for indoor flights. The University of Bristol’s UAV system was designed in-house and is an 8-propeller, 4-armed system, with the propellers arrange in pairs for failure tolerance. A University of Warwick PhD programme developing UAV control technologies utilised a commercial UAV platform in a hex-copter configuration, with bespoke flight systems and control software using LiDAR systems.

The only deployment of a fixed-wing UAV across the NDA Group has been a SensFly Swinglet CAM, used to conduct a visual mapping survey at the Sellafield site.

The only LTA UAV deployed at a site has been to support development of the LINC blimp UAV at Sellafield.

3.4 Control systems

Almost all UAVs deployed across the NDA Group have been controlled remotely using direct radio-control. These UAVs were controlled directly by a pilot using various flight control hardware, typically a twin-joystick controller. External flights were conducted within VLoS of the support team, though some systems used video feedback (e.g. FPV) from the UAV to assist the pilot with flying. Internal flights out of VLoS (e.g. into difficult to access areas) were conducted using video-feedback from the UAV.

An exception to the directly controlled UAVs was the deployment of the fixed-wing SensFly Swinglet CAM, where the flight instructions were programmed into the UAV before flight, and the progress of the flight was monitored during deployment through a base station.

3.5 Payloads

The different UAV deployments across the Group have used numerous different payloads. The vast majority have been sensor type payloads, with the only effector type payloads having been deployed as part of a research demonstration.

For visual inspections, high-definition cameras have generally been used, able to collect high-definition digital images and video; resolutions of up to 4k (4096 x 2160 pixels) have been collected. These cameras are typically mounted on a gimbal, able to be controlled independently from the UAV itself. High definition visual data are typically stored on-board the UAV, either on SD card or hard drive; compressed versions of the data are transmitted to the control team for assessment, e.g. to ensure that the correct area has been photographed.

Thermal cameras have also been deployed, and are a standard payload for the Flyability Elios UAVs, typically used for internal flights. The image resolution is 160 x 120 pixels, at 9 frames per second.

Radiation sensors have also been deployed as a UAV payload. These have all been γ-ray detectors, and have been used during demonstration or test UAV flights, rather than for routine inspection tasks. In all demonstration deployments the γ-ray measurements have been combined with location data, collected through either GPS (for external) or LiDAR (for internal) measurements.

LiDAR systems have been deployed in two main usage cases. The first has been in demonstration flights of the RISER UAV system for Sellafield Ltd. and Magnox Ltd., and has used LiDAR to map indoor areas for both external data output, as well as to assist with internal flight control (e.g. obstacle avoidance, navigation, etc.). The second has used laser-scanning during an external flight to collect survey-grade data of a pile-cap at LLWR, used as inputs to project planning.

Effector payloads have only been deployed as part of an R&D programme at the Sellafield Ltd. Innovation Centre, specifically to assess the viability of UAV effectors. An egg-pricker for ecology management, an aerosol can spray head, and a robotic arm were separately installed onto a test UAV platform, and preliminary proof-of-concept flights were undertaken.

3.6 Support team

The UAV systems deployed across the Group have all been controlled by at least a single pilot. Certain systems (generally DJI Inspire UAVs) have had the additional option for the payloads, typically the camera systems, to be controlled independently by another operator, allowing the pilot to focus on flying the UAV rather than collecting data. In addition, the RISER UAV demonstration was undertaken with a second pilot acting as ‘back-up’. The direct flight team has thus typically been 1-2 people.

In addition to the direct flight team, marshals and observers have typically been employed to assist with either monitoring the UAV during flight (a CAA requirement for external deployment of a UAV), or with ensuring that personnel do not enter the flight area during deployment. Depending on the motivation for deployment, site technical specialists (e.g. inspection engineers) may also have taken part in the deployment to advise on the data collection during flight.

3.7 Safety considerations

Where UAV flights have been conducted in-house by SLC staff, the SLC has obtained PfCO from the CAA. This requires submission of an operations manual, as well as proof of pilot training and competency, in addition to appropriate company insurance. Risk assessments, site inspections, flight records and battery records are all also commonly prepared for each UAV deployment.

The CAA maintains flight exclusion areas around nuclear sites, on behalf of the sites themselves. For a UAV deployment within restricted airspace, a request must be made to the CAA to clear the flight. This procedure is typically straightforward, as the site is, in essence, requesting permission from itself through the CAA to conduct a flight. This clearance may be granted for a set period (e.g. a year) if repeat flights are to be undertaken.

UAV flights are generally conducted within a personnel exclusion zone, maintained by marshals during the flight. If this is within a building, entry is either restricted, or personnel are clearly informed about the flight, and guided by the marshals.

Where possible, UAV flights have taken place on weekends to take advantage of the decreased staffing levels on site, and thus the decreased risk for harm in the event of an accident.

3.8 Security considerations

Where data collected by the UAV included photo and video data, these are generally vetted by security personnel before being released. Where UAVs have networking capability, this has generally been disabled or isolated to networks which have no internet connection.

In order to facilitate a flight which was undertaken on a paired site (Sizewell), the sister site was engaged early in the planning stage in order to address concerns over the collection of data on the sister site's boundary (i.e. security fences).

3.9 Information management

Data gathered by the UAVs during the flights have generally been stored on-board the UAV (e.g. on SD card or hard drive), transmitted to the UAV controller, or both.

For flights conducted by external sub-contractors, data were either vetted by security personnel after the flight had concluded, before being sent on for external analysis (if required, e.g. for LiDAR survey), or were recorded directly onto site-owned SD cards or hard drives, and transferred to site-ownership after the flight, with no data leaving the site boundary. For data collected in-house by an SLC, but with a flight team from another site, data were retained on the site from which it was collected.

3.10 Incidents

In all the UAV deployments across the Group there have been no significant reported incidents resulting in harm to personnel or damage to assets. Some deployments, however, have resulted in damage to the UAV system, or in forced emergency landings. These have been caused generally by hardware, software, or pilot errors.

Hardware errors have been encountered after flying a quad-copter in a dusty environment which causing one of the motors to glitch, forcing an emergency landing. Interference from local radio sources or sources of magnetic interference have also caused problems for flight control. Interference in GPS signals, often used by UAVs to assist with flight, have also been observed due to canyoning[3] effects between large buildings, or when flying internally.

Significant software errors have generally only been encountered in 'in development' UAV platforms undergoing demonstration flights. Problems with the onboard collision avoidance system caused the RISER UAV to crash into a structural beam and then

[3] Whereby a UAV cannot detect a sufficient number of GPS satellites due to signal blocking from nearby buildings.

drop to the floor during a demonstration at Hunterston A, though it is unclear if this was strictly a software malfunction or if the collision avoidance system was accidentally deactivated (i.e. pilot error). A software error in the University of Warwick's UAV positioning system during an off-site demonstration flight for Sellafield Ltd. caused the motors to cut out and for the UAV to fall to the floor, though only minor damage was sustained. An error in the Aibot X6 system caused it to automatically land during a test flight in an unplanned area due to a low-battery warning, this error was corrected by the vendor. Less serious issues have been observed while using the SensFly Swinglet CAM's data-shunt communication, whereby there was intermittent loss of data connection during the flight, though this did not affect the avionics (i.e. flight control systems).

Piloting errors have seen UAVs tip over on landing during training and deployment flights, particularly exacerbated in inclement weather (i.e. wind-speeds too high for operation).

3.11 Limitations

A limitation that is common to all UAV deployments across the Group has been the duration of a single flight, which is typically less than 30 minutes. This limitation has generally been worked-around by using several swappable battery packs during a deployment, and conducting it as a series of individual flights.

To comply with CAA regulations, all external deployments of a UAV must be conducted with the UAV within VLoS of the flight team; this may be an observer rather than the pilot. In addition, the pilot must be in control of the UAV at all times; automated flights have not been carried out.

In contrast, internal UAV deployments have not required VLoS of the UAV, as internal flights are not within the remit of CAA regulations. In certain environments, however, signal interference or blocking by the building structure has meant that remote operation of the UAV has not been possible.

For AWE in particular, concerns over data security with certain commercial UAV manufacturers (notably DJI) has led to a suspension of their intended UAV programme until guidance can be obtained as to MoD approved UAV platforms.

The use of UAVs to conduct visual inspection of some site assets, e.g. concrete and fastenings, has been found to be insufficient to accurately assess their condition in some instances; tactile inspection was suggested to be necessary in these situations.

3.12 Existing learning from experience

If UAVs are to be deployed by in-house pilots, consideration of the availability of deployment opportunities should be considered, given that each UAV pilot will be required to maintain their piloting skills and qualification by accruing a set number of flight-hours per year. If too many pilots are trained, and there are insufficient opportunities to deploy a UAV on the site, then the pilots will be required to undertake otherwise un-productive practice flights in order to maintain their qualification.

Experience with deploying UAVs on site has suggested that a team of marshals in communication (e.g. *via* radio) with each other and the flight team is highly recommended, as the amount of foot or vehicle traffic attempting to access the fight area is easy to underestimate.

Clear site-wide communication about UAV deployment has been found to be beneficial, and has the benefit of allowing site workers to differentiate between UAVs used in planned deployments, and UAVs which may represent a security risk (i.e. flown in from outside). In particular, close organisation between the flight team and local site workers (e.g. the building managers of a survey location) has allowed on-site knowledge to assist with inspection deployments, as well as to demonstrate the utility of the UAV to on-site stakeholders.

Some sub-contracted UAV deployments have required significant administrative procedures, including financial, security and regulatory related steps, before the UAV was able to be deployed on site. It has been highlighted that one of the key benefits of UAV use, i.e. the reduced time to deployment, may thus be counteracted by the administrative overhead required for deployment. As such a holistic view on UAV deployment should be taken when assessing its benefits, which includes the administrative work to authorise it.

While operating close to the ground, UAVs have been seen to produce significant downdraught. This may have implications in areas where there is loose radioactive contamination present, and the suitability of a UAV to be deployed in such an environment should be assessed.

Due to concerns over the suitability of a UAV system to fly within a waste storage area, an alternative monitoring system was designed by installing a sensor package onto the *in-situ* crane assembly. This highlights that a UAV system is not automatically the most appropriate solution, and should be assessed objectively by its merits and detriments as the situation requires.

Where UAVs have been deployed on a paired site, early dialogue with the sister site was found to be beneficial, as the nature of UAV deployment on one site may be a security concern for the other, particularly if the UAV is deployed close to a shared boundary.

Weather conditions have been seen to have a significant impact of a UAV’s deployment. Generally, a site’s operating procedures for UAV deployment will specify an operating envelope of conditions within which it is safe to fly the UAV, relying on ground-based assessment of factors such as windspeed or rainfall. It has often been observed, however, that the windspeed at the operating altitude of the UAVs can be significantly higher than that at ground-level, which may cause problems during the deployment. A robust assessment of flying conditions is therefore required before deployment. It is also highlighted that the number of viable flying days in a year are significantly impacted by the weather, with one estimate being ~200 viable days out of 365, or ~55% [9].

As nuclear sites have restricted airspace, as maintained by the CAA, certain models of UAV which use GPS data to monitor their flight may not allow themselves to operate within these areas, either refusing to fly beyond the boundary if from the outside, or refusing to take off if inside. These limitations can often be overcome, such as by a registration programme, or through dialogue with the UAV manufacturer. The restrictions on each UAV system should be assessed as part of the UAV system selection.

4 UK UAV Market analysis

4.1 Overview

The UAV market is generally considered to be a fast-growing and disruptive sector, benefitting both from technology advances encouraged by external markets (e.g. miniaturisation of cameras, electronics and battery technology by the mobile phone and IT sectors) as well as opportunities for applications in existing established sectors, such as oil & gas, construction and agriculture. A survey of 411 environment, health and safety (EHS) decision makers conducted by Verdantix found that 52% of firms expect to use UAVs in 2019 in some capacity [10]. Furthermore, Verdantix predicts that the period 2018-2023 will be one of accelerated UAV global market growth, with a compound annual growth rate (CAGR) of 27% [10].

Table 3 shows the top five market sectors for UAV usage in 2018, and those predicted in 2037, ranked on revenue and spend [10]. Generally, infrastructure inspections and site surveys/mapping will be key areas of interest for the commercial use of UAVs.

Table 3: Top five market sectors for UAV use across Europe and the USA, ranked by spend value [10].

Rank	2018	2037 (predicted)
1	Site/volumetric surveys	Environmental mapping
2	Infrastructure inspection – Vertical	Infrastructure inspection – Vertical
3	Infrastructure inspection – Horizontal	Site and volumetric surveys
4	Environmental mapping	Infrastructure inspection - Horizontal
5	Motion pictures and promotional photography	Agriculture and ecology inspection

Focusing on the UK commercial market, as of February 2019 there were 4961 UAV commercial license holders (PfCO) in the UK. In May 2018 there were 4068, in January 2017 there were 2380, and in 2014 there were only ~150 [11]. Furthermore, it is worth highlighting that the CAA's list of PfCO holders (CAP 1361) underwent three revisions in the period 18/01/19 - 08/02/19 (version 75 to 78), whereas it is nominally expected to be updated 'every 3 months', suggesting a larger than expected volume of new PfCO holders in this period [4]. It is interesting to note, however, that the most recent PfCO holder listed in CAP 1361 (Glanville Cleansing Limited, PfCO issued 06/02/19) has CAA ID 8424, suggesting that ~3500 companies have not renewed their PfCO. This proportion is in line with a similar assessment carried out in 2017 which suggested that 40% of PfCO holders had not renewed their licence, either as the result of supplier consolidation or of suppliers leaving the market [11].

The vast majority of PfCO holders in the UK are small, one or two-person enterprises undertaking relatively simple visual inspections and mapping exercises. In a rapidly saturating market a race to the bottom is expected. However, the UAV sector, whilst expanding in numbers in this micro-enterprise arena, has also seen a rapid expansion at the other end of the scale, primarily focussed on the diversity of payloads and UAVs offered, such as high-tech sensor systems (e.g. ultra-high definition cameras, survey grade LiDAR, or optical gas imagers) or specialist UAV platforms.

Table 4 presents a non-exhaustive selection of suppliers available within the UK UAV supply chain, including small to large businesses, and a range of service areas. This list is intended to be indicative of the range and breadth of services available, and does not cover all companies and organisations discussed within this report.

Table 4: Sample list of suppliers of UAV services in the UK, and the services and/or products offered.

Company	Business Function	Product	Service
Intel / Topcon	Manufacturer and supplier of inspection and surveying equipment, including UAV technology.	✓	✓
Flyability	Manufacturer of collision tolerant drones for inspection.	✓	
Aerialtronics	Manufacturers of state-of-the-art commercial UAV technology, including payloads and software.	✓	
Aeryon Labs	Manufacturers of state-of-the-art commercial UAV technology, including payloads and software.	✓	
3D Robotics	UAV technology manufacturers and software developers for the analytical, mapping and modelling market. Early suppliers of UAV technology long before the consumer market. Provides cloud-based support services.	✓	✓
Precision Hawk	End-to-end solution provider.	✓	✓
DJI	Chinese technology company that manufactures UAV platforms and camera technology, primarily for the pro-consumer market in support of aerial filming.	✓	
Parrot	Primarily a telecoms business but has acquired senseFly, AIRINOV, MicaSense and PIX4D as a provider of UAV hardware and software.	✓	
Yuneec / Intel	Manufacturer of manned electric aircraft that have diversified into the manufacture of multi-rotors for the pro-consumer market.	✓	
Cyberhawk Innovations	Provides industrial site aerial inspections and land surveying primarily for the oil & gas market.		✓
Strat Aero	Aerospace services company offering UAV technology for law enforcement, military pilot training and reconnaissance.		✓

Company	Business Function	Product	Service
Texo Drone Survey and Inspection	Scaffolding company that has diversified into the industrial inspection market and now offers UAV technology rental. Also involved in UAV research and development.		✓
Autel Robotics	Manufacturer of pro-consumer drones for photographers and other industries.	✓	
Vulcan	Manufacturers of heavy lift UAV technology for the professional filming industry.	✓	
Microdrones	German manufacturer of UAVs and supplier of integrated systems, specifically aimed at the professional market.	✓	
FotoKite	Manufacturer and developer of tethered solutions for the consumer, inspection and news reporting market.	✓	
Sky Futures	UAV solutions service provider, specialising in data management for inspection reporting and scenario-based pilot training. Oil & gas, Blue light services are their prime markets.		✓
EneffTech UAV Services	End to end UAV technology solution provider, offering consultancy and scenario-based training to the nuclear decommissioning, utilities and infrastructure markets.	✓	✓
Elistair	Manufacturer and developer of tethered UAV solutions.	✓	
UAVTech	End-to-end UAV technology solution provider, offering consultancy and tethered systems to the armed forces.	✓	✓
UAV Shop	Distributor of Vulcan UAV technology and reseller for other UAV technology manufacturers.	✓	
Quadcopters	Distributor and reseller to the pro-consumer and hobbyist market.	✓	
HeliGuy	Distributor and reseller to the pro-consumer and hobbyist market	✓	

In order to offer further insights into the UK UAV market, two formal analyses are presented.

4.2 Porter's Five Forces

A Porter's Five Forces analysis is a technique to assess a market from the perspective of a prospective entrant (i.e. a commercial company) to predict key factors which will affect the success or failure of the business. These factors are grouped in to 'five forces':

- ***Threat of new entrants***
  Factors affecting the likelihood that additional businesses (competition) will enter the given market
- ***Threat of substitution***
  Factors affecting the likelihood that the currently offered service or product will lose value compared to a new technology or technique
- ***Bargaining power of customers***
  Factors which affect the balance of power between the customer and the business
- ***Bargaining power of supplier*s**
  Factors which affect the balance of power between the business and its suppliers
- ***Competitive Rivalry***
  Factors which affect the likelihood of commercially aggressive or competitive behaviours arising from other businesses within the same market

The following Porter's Five Forces analysis is conducted from the point of view of a supply chain organisation intending to offer UAV services in the UK, specifically to a decommissioning organisation. Each of the five forces are ranked either 'High', 'Moderate' or 'Low', depending on the risk they pose to the commercial operation of this theoretical organisation.

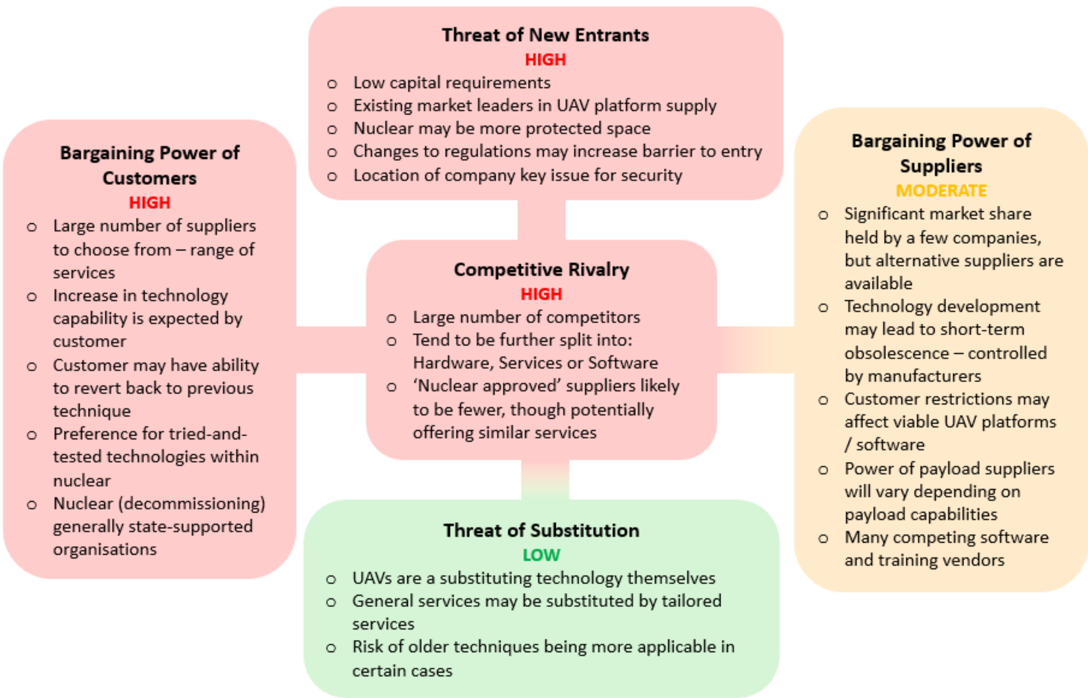

Figure 2: Porter's Five Forces analysis of the UK UAV market, with consideration of the nuclear sector.

4.2.1 Threat of new entrants

There is a high threat of new entrants for UAV platforms themselves as the capital requirements for design and construction of UAVs are relatively low. There are (mostly) insufficient economies of scale to reduce costs because, although the market size is large and growing, there are an increasing number of suppliers.

However, there are a few companies who appear to be leading in platform supply such as DJI and Yuneec, and these would have the capability of retaliation against new entrants either with lower prices, enhanced product differentiation or disrupting existing distribution channels. Concerns over the security of UAV platforms from international companies, however, such as DJI, may limit the ability for these companies to operate within the UK nuclear market. Intellectual property (IP) laws may also prevent new companies from entering the market – from a technological perspective – with similar products to those already offered.

Providing UAV services other than the UAV platforms themselves (e.g. payloads, piloting, flight or inspection services, data analysis) is likely to be a more viable entry path into the UAV market, and so is more likely to lead to new entrants. In addition, fewer IP issues are likely to arise for companies offering services rather than technologies, though IP relating, for example, to data processing, etc., may still act as a barrier to entry for service-type companies.

Governmental and legal barriers are likely to be increased through changes to regulation, which may decrease the viability of new entrants in the short term while buyers adjust. It may also affect the UAVs available to purchase - particularly for Government Agencies.

The location of a company may be a key issue, particularly where security vetting of equipment or personnel is required to be undertaken. As such, the threat of entry from international companies may be reduced in ‘protected’ sectors such as nuclear.

4.2.2 Threat of substitutes

There is limited threat of substitution since UAVs are themselves substituting human and more labour-intensive methods. UAVs can be significantly cheaper than existing methods and it unlikely that a step-change in new technology will replace them in the short-term.

One aspect to consider is the threat of substitution of general or generic UAV services or platforms by bespoke UAV systems or services, which are more suitable, or even tailored to address specific issues arising in the UK nuclear or decommissioning sector. Such bespoke systems may be more attractive to buyers for issues such as data security, or radiation tolerance.

In addition, substitution by ‘lower-tech’ methods may be a factor for specific deployment cases (e.g. gathering imaging data from a roof by either a UAV, or a camera on an aluminium pole), and there may be more stability for a business in offering a service within which a UAV is a tool, rather than offering the UAV itself.

4.2.3 Bargaining power of customers

Buyers have an ever-increasing supply chain offering everything from full turnkey services to straightforward product purchase. Costs for products are expected to fall while the products will offer more features so increasing their value for money considerably.

Suppliers will therefore try and move more into services where they can protect their profitability better in offering “added value” integrated services, such as data analysis or hosting. The decision of a customer to outsource UAV requirements or to develop in-house (Make/Buy decision) will depend on many factors including the volume, frequency, sensitivity, security and safety aspects of their site or sites.

In addition, as UAVs are generally used to replace older techniques, the customer is usually able to revert back to the pre-existing technique if they wish, though it should be noted that for some usage cases the benefits of deploying a UAV compared to having personnel perform the same task are sufficiently great (in terms of cost, speed or safety) that re-adoption of older techniques may be unlikely.

For the nuclear and decommissioning sectors, a preference for tried and tested technologies and techniques, as well as being generally state-supported rather than purely commercial organisations, allows significant bargaining power.

4.2.4 Bargaining power of suppliers

The bargaining power of suppliers to UAV businesses is expected to be moderate. While there are large commercial companies which have a majority market share in supplying UAV platforms (e.g. DJI and Yuneec), there are also a significant number of other vendors for comparable products, which may offer greater ability to customise platforms to the required usage case, though are likely to require increased costs to purchase. Products or technologies, however, may be protected by IP, and therefore only available from particular vendors – it is expected that this will be more common for more specialised items.

In terms of technology development, there is a concern among businesses which use UAVs that the fast-paced change in UAV platform designs may lead to swift obsolescence of an existing asset, forcing a UAV business to regularly upgrade its hardware to remain competitive. There is a desire to move to more modular systems, which may allow high value components (e.g. cameras) to be moved to an upgraded UAV platform at some point in the future. This is currently recognised by UAV platform suppliers, and there have been noises to moving towards ‘enterprise’ type platforms by DJI.

Supplier bargaining power will be greatly affected by any restrictions placed on their products by customers, e.g. over data security issues. In the UK, the MoD is expected to maintain a list of vetted UAV systems which may be operated on its sites, which will drastically decrease the supplier power of any system manufacturer which is not included in these scenarios. Conversely, the supplier of an approved system will gain significant bargaining power in these scenarios, although, again, is likely still to have competitors within this space.

Suppliers of sensor payloads will have a mixed level of bargaining power. Common sensor systems, primarily digital cameras, are expected to be readily available across the market, though there may be problems in interfacing certain sensor payloads and UAV platforms, particularly if proprietary sensor payloads are also offered by the UAV platform manufacturer. Suppliers of more novel or bespoke sensor systems (e.g. γ-ray detectors) are expected to have more bargaining power resulting from decreased competition and potentially IP protected technologies. Competition is expected to increase, however, due to the growing market for UAV sensor systems.

For UAV control and logistical software, there are a large number of suppliers and resources, some open-source, available. Similarly, there are increasing numbers of NVQ courses available to conduct UAV pilot training, as well as to assist with PfCO applications.

4.2.5 Competitive Rivalry

There is intense competition with a huge number of companies in the marketplace. Product differentiation and price reduction is occurring at a fast pace which places intense pressure on supplier profitability. Establishment and protection of IP may be used to support product differentiation, e.g. DJI's foldable Mavic UAVs [12], or Intel's V-shaped Falcon 8 UAV [13]. DJI have, for example, filed a patent infringement lawsuit against Yuneec in 2016 related to target tracking technology, and payload mounting platform design [14].

Though there are a large number of suppliers in the UAV market, suppliers offer a range of services. Three main business models are:

- UAV Hardware
- UAV Services
- Software Vendors

Some suppliers will be reliant on others for their own business model, e.g. UAV Service providers are likely to procure the UAV hardware they use externally. Collaborative partnerships between companies to complement delivery are also expected.

Furthermore, there are fewer suppliers who are 'nuclear approved', or appropriately vetted to gain access to UK decommissioning sites. As such, the competitive space within nuclear UAV is likely to be significantly smaller than the wider UAV sector.

4.3 PESTLE Analysis

A PESTLE analysis is a method of assessing external factors which may affect a commercial business. They are themed into the following groups:

- Political
- Economic
- Social
- Technical
- Legal
- Environmental

The following analysis is conducted form the point of view of a decommissioning organisation using (or considering using) UAVs to support site work. Table 5 shows the summary statements for each theme of the PESTLE analysis, which are explored in further detail below.

Table 5: PESTEL analysis from the perspective of a decommissioning organisation using (or considering using) UAVs.

Political	Economic	Social	Technical	Legal	Environmental
Protectionism over nationally funded technologies Alignment with cost-savings of Nuclear Sector Deal State security considerations	Reliance on continued support from UAV market Good consumer position in market Both Make and Buy are viable from available market UAVs likely to realise cost savings compared to traditional techniques	Stakeholder perception of UAVs UAVs are 'news headline' technology – increased scrutiny Increased safety of workforce Expand SQEP of workforce for work using UAVs	Potential for swift obsolescence Technical improvement of available UAVs likely OTS systems cheaper with more features Security of data-transfer from UAV to base-station Software requirements for control and UAV fleet logistics Problem may not require high-tech solution (UAV)	CAA only regulates external (not internal) flights PfCO required for own ('Make') flights Compliance with nuclear legislation Security of data gathered on nuclear site IP rights considerations for in-house ('Make') solutions	External flights weather dependent Flights over nuclear sites In line with ALARP Supports risk-based approach to decommissioning

4.3.1 Political

Difficulty in accessing technological UAV solutions from other countries may arise due to a protectionist mentality, which may arise from either side. The typically national nature of the nuclear and decommissioning sectors in countries around the world may lead to a reliance on 'in-country' solutions to challenges, which may otherwise have a degree of commonality across nations. As such, there may either be little desire to look 'abroad' for existing solutions, or little assistance given to leveraging a technology outside of its originating country.

Linked to this, and potentially one aspect fuelling this protectionist approach, is a lack of trust in technologies developed out of country from a security perspective. There may be concerns over involving technologies developed in other countries in national infrastructure projects, or in sensitive sites.

A key political aspect to consider for decommissioning is the Nuclear Sector Deal, which commits to cut the cost of decommissioning by 20% by 2030; the use of UAVs to assist with decommissioning works is likely to be a particularly viable cost-saving measure, and so may assist a decommissioning organisation in meeting this level of cost-saving.

4.3.2 Economic

While it is likely that the commercial UAV market will grow and continue to offer a range of services, it should be recognised that the use of UAVs to assist with decommissioning work is particularly reliant on the market supporting it. At present there are good opportunities to support both Make (purchasing UAV platforms to use in-house) and Buy (employing a UAV service company) decisions, which are likely to be more affected by the specialism of the task than by the availability of suppliers. Furthermore, it is likely that the favourable position of a consumer in the UAV market will remain as the market develops, with a large number of suppliers and services expected to be readily available.

As discussed with the Nuclear Sector Deal, the use of UAVs to support decommissioning activities is expected to realise cost savings, though both decreased deployment times and lower costs of equipment and personnel (e.g. compared to scaffolding).

4.3.3 Social

A key factor in the use of UAVs, particularly on a site with a sensitive public perception such as a nuclear site, is their perceived safety and reliability. Many members of the public will more commonly associate ‘drones’ with consumer models which are not piloted by professionals, and there have recently been several reported instances where UAVs have been reported in proximity to larger passenger planes, notably causing London’s Gatwick airport to close for a period of three days in December of 2018. As such there is a risk that any incident which could combine the headline buzzwords of ‘drone; and ‘nuclear’ may damage public perception of either. This being said, there are potentially significant real safety benefits to the use of UAVs in situations to replace human access, e.g. in areas of increased radiological or chemical hazard, or in working at height.

The adoption of UAV systems within an organisation will also aid in expanding the capabilities of existing workforce, if they are trained to pilot the UAV systems. This may be an increasingly transferrable skill to other parts of the business, and societally, if the use of UAVs in commercial settings becomes more widespread.

4.3.4 Technological

The expected high pace of technological advancement and innovation within the UAV market has two key aspects for a decommissioning company. The first is that it is very likely that any UAV systems or technologies will, within a few years, be either obsolete or superseded by advanced systems, which may result in a continual investment from a company in up-to-date technologies. Linked to this, however, is the expectation that the technical capabilities of available UAV systems will increase with time, making available systems and services more valuable as time goes on.

Consumer grade off the shelf (OTS) UAV platforms are expected to deliver good value at lower prices, arising from their mass-produced nature. These systems also benefit from improving in-build features (e.g. collision avoidance, location detection) used to differentiate UAV platforms from competitor offerings. Bespoke systems are also available at a higher price point, and have the benefits of being able to be tailored more to a specific usage case, as well as having a greater degree of transparency in their hardware and software systems which may have significant benefits in terms of assuring data security.

Control and monitoring of a UAV system should be considered, both during flight, as well as in monitoring a potential fleet of assets. Information such as total flying time (by UAV platform and pilot for maintenance and training records, respectively), battery charge state, location and state of any data storage media, etc. are all key metrics to track from both safety and security perspectives. Technical solutions (software) to many of these issues are available commercially.

Finally, a key technical consideration on the use of UAVs in decommissioning (and more broadly) is whether or not a UAV system is the correct solution to a particular problem; there may be other lower-tech solutions available, such as placing a sensor on an extended pole, or it may be that a UAV is not suitable for carrying out the required task, such as a tapping inspection of concrete.

4.3.5 Legal

In the UK, the CAA controls regulations for external UAV flights, i.e. flights which may conceivably interfere with other aircraft. Furthermore, companies wishing to employ UAVs in commercial work must hold PfCO authorisation from the CAA, fulfilling the corresponding safety, competency and insurance criteria. These restrictions are not applicable to flights conducted indoors, and it may be a viable usage case for an organisation to 'Make' internal flights using in-house UAV systems and pilots, and to 'Buy' external UAV services where external deployment is required.

In addition to regulations arising from the CAA, regulations relating to the use of remote technologies on a nuclear site must also be complied with. From this perspective, bespoke UAV systems may be beneficial in that there is greater transparency in their software and hardware components, particularly in terms of how data are collected and stored.

An additional aspect to consider if pursuing the development of internal UAV technologies for use within an organisation would be existing IP, as held by technology or service providers; the development of an in-house UAV platform or service may infringe existing IP. For example, Patent GB2511754 – 'Radiation detection device and method' is held by the University of Bristol, and pertains to the co-collection of both positional and radiological data from an unmanned vehicle [15]. An understanding of existing relevant IP may therefore be required if pursuing internal creation of bespoke UAV systems.

4.3.6 Environmental

A particular consideration as to the viability of external UAV deployment is the weather, with unfavourable weather events (excessive wind, rain) sufficient to either ground a UAV flight, or sufficiently interfere with the UAV to make flying inadvisable. As such the number of successful deployments within a year may be significantly fewer than expected.

Accident situations should be carefully considered, particularly when operating a UAV on a nuclear site, and likely accident scenarios should be planned for and mitigated against.

Generally, however, the use of a UAV is expected to conform to the ALARP approach to risk. It is recognised that there will be accidents and incidents in operating a UAV system, but that these will generally be minor, and the benefits to using a UAV in place of, for example, personnel working at height, is expected to be significant.

4.4 Summary of the UK UAV market

The UK market for UAV services is expected to be active and growing, with multiple suppliers available for a range of different services and products. Generally, this will be beneficial to consumers for UAV services and technologies, who will have plenty of options between competing suppliers.

For the nuclear sector the number of suppliers is expected to be more limited due to security vetting requirements, though still sufficient that nuclear consumers will benefit from sufficient choice. Innovation and technological development are expected to increase the capabilities of UAV services and technologies as time goes on. From the perspective of a decommissioning organisation, both Make and Buy options for UAV utilisation are viable, and well supported by the market.

5 Future Developments in Unmanned Aerial Vehicles

5.1 Methodology

Information on UAV deployments and research was gathered from a range of sources, including academic papers and press-releases from UAV research groups, universities, research funding bodies and private aerospace and UAV companies, as well as from general and special interest news outlets. Information was also incorporated from presentations given at the Commercial UAV Show, 2018, a yearly UAV tradeshow held in the UK; from the Cogentus Ideas Catalogue, a technology solutions database; and from expert judgement from the project team. References for each example of UAV deployment or research development are provided below.

Different UAV deployments and research developments were then grouped into broad developmental themes. These themes were then assessed as either short-, medium- or long-term developments with respect to the estimated severity of barriers to their realisation in a UK decommissioning context. Specific timeframes (e.g. <5 years) were not used for categorisation to avoid the appearance of a predictive analysis. The guidance criteria used are listed below:

- **Short-term (straightforward implementation)**
  Technologies or systems which are currently in use in the wider nuclear or non-nuclear industry, but not yet employed in service on UK decommissioning sites.
- **Medium-term (some barriers to implementation)**
  Technologies or systems which are either in development with a medium to high technology readiness level (TRL), but are not widely commercially available; or technologies and systems which are commercially employed in an industrial context in other countries, but have some barriers (e.g. regulatory changes) to deploy in a UK decommissioning context.
- **Long-term (significant barriers to implementation)**
  Technologies or systems which are either in development with a low TRL, or that would have significant barriers (e.g. significant regulatory changes, or changes in public perception) to deploy in a UK decommissioning context.

It should be noted that several developmental themes will have aspects which fit into more than one of the above categories (e.g. improvements to UAV automation). In these cases the theme has been classified into the category where a technology ‘step-change’ (i.e. where a significant change in the way the technology is used) is estimated to occur.

In addition to the above categories, regulatory developments are also separately discussed, as these will have bearing on all categories of technological developments.

A summary of the developmental themes, and their categorisation, is presented in Figure 3.

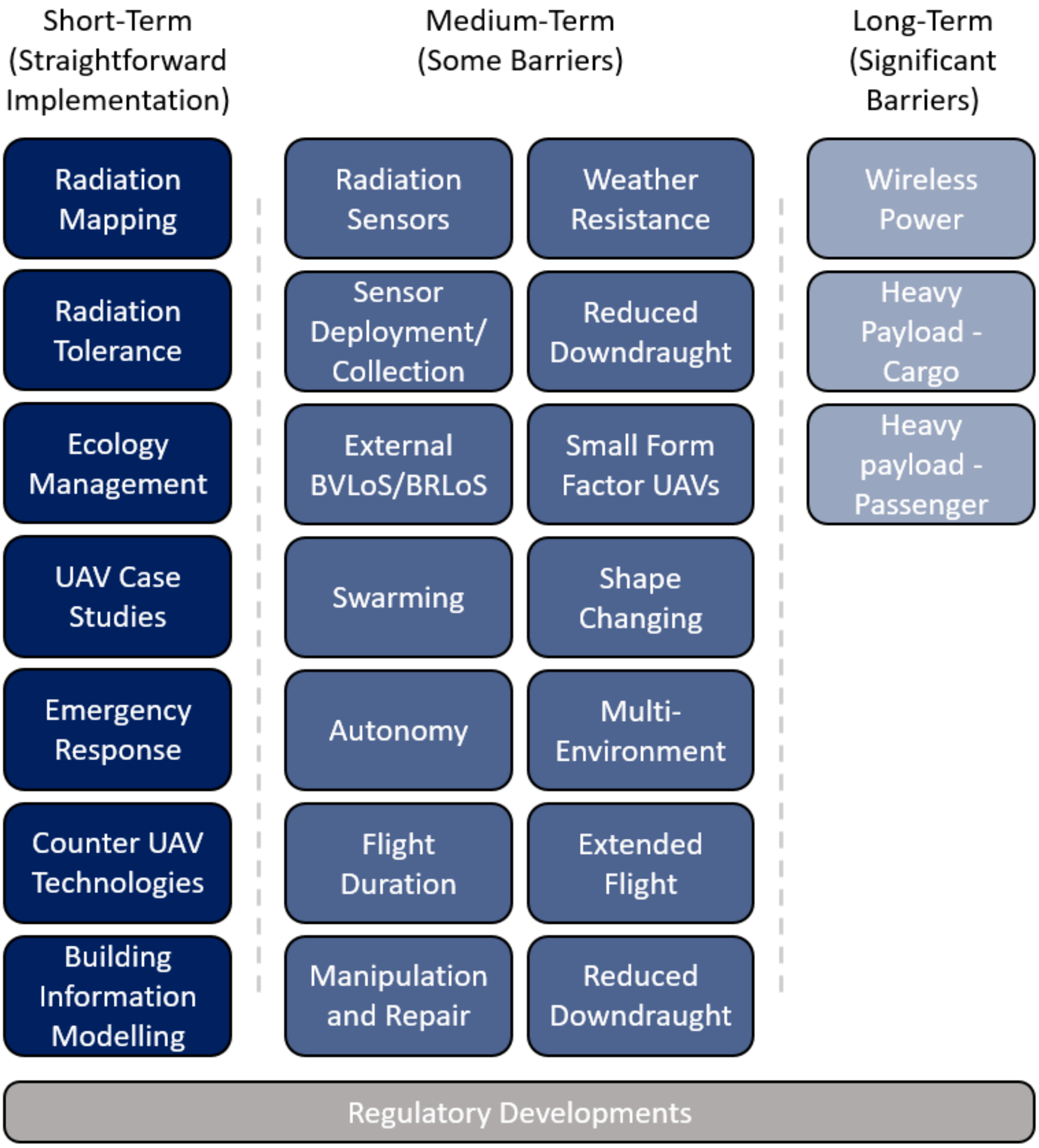

Figure 3: Summary of developmental themes for UAVs, categorised by the estimated severity of barriers to their deployments on UK decommissioning sites.

5.2 Regulatory developments

Developments in the regulatory environment for UAVs in the UK, and within the nuclear sector, are likely to be a key barrier or enabler to realising future UAV developments on decommissioning sites. As an example, while current UAV technology will allow BVLoS and BRLoS (beyond radio line of sight) flights, through signal relaying and on-board automation, such flights are prohibited in the UK by the CAA at the present time, which requires all external flights to be conducted within VLoS.

Within the UK, the CAA is generally seen as a pro-active and engaging regulator and has established a dedicated team to deal with issues related to UAVs in the UK. One area of pro-activity is in noting the potential of learning or self-modifying systems (i.e. that use data related to previous actions in order to modify their outputs such that their results are closer to a previously defined desired outcome) to be employed within UAV systems. Due to overall system safety requirements, however, it may not be possible to use such systems to their full potential. It is however noted that, at some future point, the aviation industry may consider the use of non-deterministic systems to improve overall system flexibility and performance, and that current regulations do not intrinsically prohibit the use of such systems, only that “a number of system and operational safety assessment issues that will need to be addressed before the use of this type of technology could be accepted for use in aviation”.

In terms of regulation for the nuclear sector, the ONR’s current approach to regulation is non-prescriptive and, in itself, does not inhibit the development or uptake of UAVs. There is scope, however, to further encourage uptake of UAVs, including modification of commercial off-the-shelf systems, through sustained engagement between decommissioning organisations, such as individual SLCs or the NDA, and the ONR, the CAA and even the MAA, to consider the possibility of introducing some form of standardisation on how UAVs are classified for the nuclear sector. Although this approach could be seen as prescriptive, and therefore contrary to the ONR’s general approach, the potential benefit is that it would result in better confidence in nuclear site licensees and supply chain companies in respect of UAV development.

For example, a case could potentially be made that “very small” UAVs (however “very small” may be defined) could be operated without needing a safety case but with “due regard” as per MAA guidelines. An outcome such as this could potentially spur on further development of UAVs in the nuclear sector, as there would be greater understanding, standardisation and cooperation between organisations about what is (and what is not) required to deploy UAVs on a nuclear site. If UAVs for the nuclear sector could be more specifically categorised, as is done by the CAA and the MAA, then this could help reduce the amount of regulation that is needed on a case-by-case basis at the current time, so there would be a potential for cost savings to the nuclear site licence companies if they could procure and then deploy technology solutions which had already been approved in advance.

One interesting aspect of regulatory development is that it can be, at times, reactive to external events. After the Gatwick Airport UAV incident in December 2018, for example, where reports of a UAV within the restricted flight zone caused the airport to shut down for a number of days, there were calls to extend the exclusion zone around airports from 1 km to 5 km. As such, there is a greater element of uncertainty in predicting regulatory developments in the future.

5.3 Short-term Developments

Viable developments in the use of UAVs in nuclear decommissioning over the short-term are primarily drawn from an assessment of case-studies of UAV deployments in other industrial scenarios, both in the UK and the rest of the world.

5.3.1 Wide Area Radiation Monitoring

The demonstration of UAVs for the detection and mapping of radiation doses is well established within the nuclear industry, with UAV systems from both the University of Bristol and the BlueBear-Createc collaboration being deployed in the UK and abroad [16, 17].

The events at Fukushima have led to an increased level of interest / opportunity to use UAVs for wide area radiation monitoring; in response to the events at Fukushima the European project ANCHORS (UAV-Assisted Ad Hoc Networks for Crisis Management and Hostile Environment Sensing) was established. ANCHORS used UAV mounted γ-dose monitoring, but went further by incorporating in a network of vehicles which could be deployed in the region of a radiological incident. Land based ROVs were used to launch and recover UAVs as well as carrying analysis arrays for the assessment of near ground contamination and further examination of hotspots [18].

Both the Chiba Institute of Technology and JAEA, Japan, are developing UAV systems for radiation surveys in and around the Fukushima reactor buildings and area, including the use of Compton cameras to visualise γ-ray hotspots from a distance [19, 20].

5.3.2 Protection of UAVs from Radiation

When working in the nuclear environment it is important that the impact of radiation on electronic componentry is considered. Radiation-hardened electronic components and camera systems are produced specifically for use in the nuclear industry, to allow equipment to be deployed in areas of high γ-dose. Simple electronics such as motors, wiring, solenoids and switches for example are very radiation resistant, however diodes and silicon chips are for more susceptible to malfunction in higher dose environments. In remotely operated vehicles this is often mitigated by shielding the componentry, or in the case of tethered ROVs having the sensitive electronics away from the ROV in the control box. Both approaches are impractical due to weight constraints in the case of shielding and the dependence of UAVs on electronics for flight stability, even if they could be operated through a tether. It may be possible to consider older technologies for electronic componentry with larger transistors, however these technologies introduce bulk and current consumption, which would seriously impact on UAV performance.

Dose assessment modelling, using codes such as MCBEND or MCNP, has been carried out by Wood to establish the dose levels that an ROV may receive whilst developing a system, in the same way they would for human dose assessments. In the short term such modelling could also be applied to UAV systems to assess likely dose limits and areas of potential failure, informing UAV design choices.

Information on dose tests are limited but work by Toshiba and Flyability has looked at the impact of dose on UAVs. In the case of Fukushima, Toshiba were asked to develop UAVs that could withstand up to 73 Sv and operate for 5 day periods [21]. However, these UAVs were seen to malfunction in less than one day, but with some areas significantly exceeding 73 Sv this was to be expected.

Flyability have tested their Elios UAV with and incremental increases in radiation exposure, up to 800 Rem/Hour (8.0 Sv/Hour) which the Elios was able to perform as normal for a 10-minute flight [22]. The cumulative exposure, during the test procedure, was more than 180 Rem (1.8 Sv), which is 90 times higher than the maximum dose allowed for a classified worker in the UK (0.02 Sv).

5.3.3 Site Ecology Monitoring

Costain, in collaboration with Thames Water, have used a UAV equipped with a thermal camera to monitor nesting birdlife on a site during the breeding season, which was undertaken to coordinate working ground teams such that there was a limited ecological impact during planned works [23]. Duke University have used a fixed-wing UAV to monitor seal populations *via* thermal imaging [24], and Vancouver Aquarium have found the collection of photogrammetry data on killer whales to be an effective method to monitor the animals [25]. In addition to ecology monitoring, UAVs have been used in crop spraying in New Zealand [26], where the terrain has made land access difficult. UAVs have also been deployed with a dart-gun to deliver tranquilising rounds to animals (Haevic) [27].

In such a role, UAVs may be used on sites in similar roles of ecology management, such as surveying populations of animals within the site boundary, as well as in proximity to the site. They may also be used to assist with site vegetation management.

5.3.4 Building Information Modelling (BIM)

The use of UAVs to assist with the collection of survey grade building information modelling (BIM) data, whereby computer models of the condition of an asset at a point in time can be recorded, has been undertaken by several companies. Plowman Craven undertook a survey of the Poultry Market in London using UAVs to collect data on the roof, where personnel access was not possible [28]. Costain have collected survey data for motorways, as well as worksites to compare ‘as-built’ assets to CAD plans [23]. A 3D model of the statue ‘Christ the Redeemer’ in Rio, Brazil, has also been generated by Pix4D using photogrammetry gathered by UAV, as an alternative to ‘survey’ grade data [29]. In addition to building surveys, stockpile surveys (e.g. soil, aggregates, etc.) have also been carried out by Skanska by UAV during work on the A14 road between Cambridge and Ellington to monitor project resources [30].

For decommissioning, the monitoring of site assets over their lifetime is a key responsibility for the SLCs, and the technology and analytical capability to automate this process through the use of UAVs is currently in use in other industries. In addition to asset monitoring, the monitoring of construction projects, which will be of relevance to sites at different stages of their decommissioning schedules, will also benefit from the use of BIM. There are challenges associated with managing large data sets, so it may not be practical to survey a whole site at high resolution, however when it comes to plant modification or decommissioning significant benefits may be gained from accurate site and building plans.

5.3.5 UAVs for Emergency Response

UAVs have been trialled and deployed by several organisations for use in emergency disaster response. The Fort Bend County Office of Emergency Management, USA, has used several different UAV platforms to acquire fast reconnaissance of areas affected by flooding [31]. Costain has used UAVs to record the state of a work site after an accident occurred, allowing analysis of the state of the site at the time of the accident, and thus to identify the root cause [23]. In addition to reconnaissance, UAVs have been used to deliver emergency payloads, such as a lifejacket at the Port of Sagunto to a swimmer in difficulty [32], and medical supplies by Swiss Post, Switzerland [33], and the Rwandan Government [34].

For decommissioning sites, UAVs may be deployed for fast reconnaissance of accident or incident sites. This may have particular benefits if there is the potential for the release of hazardous chemicals or substances. In addition to reconnaissance, UAVs could potentially be deployed to areas of the site to deliver emergency supplies, e.g. medical equipment, respirators, communication equipment, etc., in the event that regular access is impeded, or extant supplies are unavailable. It should be noted that for this capability to be more fully realised, exterior BVLoS flights may be required, which are currently not allowed by the CAA. This is discussed further in Medium Term Developments.

5.3.6 Counter-UAV Technologies.

As the use of UAV systems becomes more commonplace, it is likely that the requirement and capability to defend against them (from physical or data security threats) will also develop.

Tracking systems for UAVs currently rely on a number of different sensor technologies (acoustic, visual, RADAR, etc.) working in parallel to complement each other, and it is likely that improved sensor combinations, or automated data processing routines will develop with time [35]. Recent developments in visual monitoring of potential UAV threats, for example, has included the use of static cameras with overlapping FoV, as opposed to separated mobile cameras, as the speed of a UAV is typically greater than the tracking capability of a mobile camera.

Many modern UAVs will 'return to home' if they lose contact with their ground station. Devices which sufficiently interfere with the RF links between UAV and ground station will stop many commercial UAVs, and are currently employed at secure sites in the UK, e.g. prisons to prevent UAVs from delivering contraband items [36]. These systems may be installed such that the physical border of the site is coincident with the RF jamming barrier. Note that these systems will not cause the same effect on UAVs controlled manually, i.e. with no automation or GPS inputs.

While devices and systems to physically interfere with a UAV are available (nets, projectile weapons, birds of prey), there is opportunity to better increase the accuracy and reliability of such systems.

5.3.7 Increasing UAV Deployment – Additional Case Studies

UAVs are a fast developing technology and market, and there are a significant number of industries and businesses which are adopting their use across the world. It is expected that this increased exposure will assist in accelerating their use further, as more organisations and sectors will have additional case studies on UAV deployment on which to draw, and to assess the benefits for their own usage cases.

5.4 Medium-term developments

The following subsections discuss likely areas of development in the medium-term. These are typically areas in active R&D, both academic and commercial, which are not in commercial or common deployment. Some development areas which are currently in commercial or common deployment are included when there are judged to be barriers to their implementation in the UK decommissioning sector (e.g. regulatory).

5.4.1 Ionising-Radiation Sensor Development

The ability to carry out radiation surveys using UAVs has hinged on the development of light-weight detectors, the biggest development being the increased availability of medium-resolution γ-spectrometers, which have a better spectroscopic resolution than the lower-resolution NaI detectors. These detectors also operate at ambient temperature and are significantly smaller, than higher-resolution γ-spectrometers (e.g. HPGe detectors). The Kromek GR1 CZT detector is a very good example and is part of the University of Bristol and RISER systems. Mirion Technologies and Wood have worked to develop small medium-resolution γ-spectrometer systems based on the technology, which can be used for non-destructive analysis, and identification and quantification of gamma emitting radionuclides.

The continued development of UAV technologies will yield benefits to the nuclear industry, but it is possible that the development of sensors that can be mounted on UAVs may yield the most benefit. If sensor systems can be developed that are light enough, which include collimation, automated UAVs could be used for more detailed characterisation of plant assets by bringing sensors within proximity of surfaces. The bigger challenges are presented by radionuclides with a low γ-yield, with potential α and β emitting radionuclides, in such cases it may be possible for UAVs to bring sensors or swabs into contact with surfaces. Combined with detailed LiDAR and dose surveys, UAVs have the potential to collect data throughout the decommissioning of plant to track progress, bring efficiencies to decommissioning and waste management.

5.4.2 External Flight Beyond Visual/Radio Line of Sight

At present, BVLoS flight is restricted by the CAA, which requires all external UAV flights to be conducted within VLoS of the control team. Current UAV systems are capable of being flown BVLoS, e.g. Alphabet's Project Wing in Canberra, Australia [37]. In addition to flights BVLoS, the capability to deploy a UAV BRLoS (i.e. a pre-programmes flight with no live monitoring of the UAV) is also technically achievable. A barrier to more common implementation of these flight modes is the hardware used in the UAV systems, which may be more 'hobbyist', and thus does not conform to aerospace standards. For nuclear sites specifically, requirements for failsafe and redundancy implementations are a key barrier.

5.4.3 Autonomy

At present, UAV systems incorporate autonomy in systems such as position management – based on internal sensors such as GPS, ultrasonic proximity, gyroscopes, etc. These systems allow the UAV to be operated at a higher-level of control abstraction, i.e. by the pilot specifying position, height and orientation; rather than by the pilot having to monitor and control every motor or control surface of the UAV. It is also common for UAV systems to have a failsafe system whereby, if direct contact from the control station is lot, the UAV will automatically return to a designated landing-zone.

An increase in the level of autonomy is a likely area of development for UAV systems. In the short-term these developments are likely to better assist direct piloting, with an improvement in both the collection of local environmental data, as well as their interpretation and reaction (e.g. detecting and avoiding a falling object, or another UAV). In addition to assisting with general flight, these systems allow GPS denied flights to take place, e.g. within buildings, or locations with poor or unreliable GPS signal.

Over the longer-term, automation may allow for UAVs to be deployed from a base-station to a specified location, automatically navigating between the two. For decommissioning this may be utilised during a site inspection, where an inspector requires visual records of an out-of-reach area; the UAV can be called to collect the data, and then return to the base-station when it is not needed. Another deployment case may be for a UAV to be automatically deployed in response to a site alarm, through which incident response or security could view footage of the incident location. Related to these deployment cases, a UAV may automatically return to a charging-point if it detects that its battery is running out of charge, and be automatically replaced by another UAV. This level of autonomy will require networked communication between several UAV systems, and a control system to organise the UAVs. Such a system is currently being demonstrated in Canberra, Australia by Alphabet's Project Wing, where UAVs are being used for automated package delivery [37]. H3 Dynamics' DRONEBOX [38] and Massachusetts Institute of Technology's automated battery swapping station [39] are also good examples of the components of this system. Key barriers to the deployment of this kind of system on a decommissioning site are regulatory and safety related.

Greater levels of autonomy would allow a system to automatically deploy a UAV and collect data from it, either for recording purposes, or to analyse and take actions on itself. Such a system may deploy a UAV to take photogrammetry and survey data of buildings on a site, in a periodic manner, such that the state of each building is recorded yearly. It may also be used to send a UAV (or series or UAVs) along a site perimeter at regular (or irregular) intervals for security monitoring and deterrence. Building photogrammetry and surveying are currently able to be undertaken by UAV, as is visual monitoring of an environment. The barrier to implementing these systems is ensuring that automated systems are sufficiently robust to deal safely with the different scenarios in which the UAV may find itself. In addition, the regulatory environment must be such that fully automated UAV deployments (i.e. take-off time, flight decisions, landing time and location, emergency protocols) are allowed to be taken by an automated system rather than a human pilot.

5.4.4 Increased Flight Duration

Key factors which will lead to an increase in UAV flight times are:

- Improved battery technology
- Miniaturisation of electronics and payloads
- Improvement of UAV aerodynamics

Battery developments of relevance to UAVs, particularly lithium-polymer batteries, drive towards the combined qualities of increased energy-density and decreased weight. This will also include the development of fuel-cell technologies. Similarly, development of electronics will tend toward further miniaturisation and weight reduction, which will benefit both payloads and internal UAV systems. Both of these development trends are driven by external factors, e.g. smartphone technology, rather than by the UAV sector itself. Improvements in UAV aerodynamic design (i.e. lighter materials, decreased air resistance), on the other hand, will be more driven by the UAV sector, though will also benefit from inputs from sectors such as materials research. EPFL in Switzerland, for example, has developed a UAV which incorporates 'feathers' along the wings, allowing for increased precision in controlling its aerofoil surface, and so better precision over flight [40].

5.4.5 Aerial Manipulation and Repair

The ability for UAVs to not just act as sensing platforms, but to be able to affect their environment through 'effector' payloads is a likely development for UAV technology in the future. The benefits would be to extend the utility of UAVs, allowing the operator to remotely interact with an environment. This may be an operation to move an object, e.g. to clear small debris or to collect a sample, or to apply a tool to an object or mechanism, e.g. to drill a hole or tighten a bolt. Repair operations may also be carried out with specialised effectors, e.g. cement filling or polymer spraying.

Effector type payloads have been demonstrated at an R&D proof-of-concept level as part of a graduate programme at the Sellafield Ltd. Innovation Centre, supported by EneffTech UAV Services. A novel manipulation system for use on a hex-copter is also the subject of research at Purdue University, USA [41]. Tapping inspections by UAV deployed hammer have been explored by Los Alamos National Laboratories, USA [42]. The FlyCroTug is a UAV system developed at Stanford University, USA, which is designed to move objects across the ground by attaching a winch to the object, and then anchoring itself to the ground and pulling the object [43]. The University of Bath, UK, has undertaken research into low-mass applicators for cementitious pastes for use on UAVs [44]. Imperial College London, UK, has also conducted research on additive manufacture using UAVs, as well using a UAV to deploy 'tensile structures' of distributed cable [45]. The Aeroarms project out of the University of Seville, Spain, has designed a range of different flying robots with multi-joint manipulator arms to work together on grasping, transporting and depositing parts safely and efficiently [46].

Key barriers to implementation are technical. By nature, for a UAV to physically interact with an object it must be in close proximity, which may result in an increased risk of collision between the object and the UAV. In addition, for the UAV to exert a force on an object requires a good level of feedback and control of the UAV flight system. For example, a UAV should react to a change in barrier properties (e.g. pushing a block over), as well as a change in its own physical properties (e.g. changing mass and centre of gravity when lifting an arbitrary object).

5.4.6 Reduced Downdraught Systems

Rotary UAV systems typically produce a significant downdraught, equivalent to their weight. This may present a hazard in certain environments, where air disturbances are desired to be kept to a minimum (e.g. areas of loose radioactive contamination). UAV systems with reduced downdraught are presently in development, including LTA systems, as well as novel airframe designs. A LTA blimp system has been demonstrated at Sellafield Ltd, UK, using helium gas to provide lift to the system, and so requiring only small amounts of thrust for movement and direction. The SmartBird, Festo, Germany, is a novel flight technology based upon the flight patterns of the herring gull; its low weight and wing motion act to reduce the downdraught it generates and can be manoeuvred within medium sized internal environments [47]. The DelFly Explorer is a research project based on a similar idea, from TU Delft, Netherlands [48].

A key consideration for these systems is the weight of the required payload. The carrying capacity of a blimp type UAV, for example, will depend on the volume of gas within its lifting envelope, which may be constrained by its size requirements. The viability of these systems in specific scenarios may require the development of decreased mass payloads and control systems (batteries, motors, etc.).

5.4.7 Increasing Deployment Envelope – All-weather flying

At present, weather is a key factor in the viability of an external UAV flight, and has been directly reported to have influenced UAV deployments in UK decommissioning tasks, either by grounding a flight or by causing damage to a UAV during landing.

Typically, larger UAVs have better capabilities against wind, due to their greater inertial mass. In terms of developments, smaller more 'acrobatic' aircraft may be a viable avenue, which can be perturbed by gusts and then use an increased power to weight ratio to get back on course quickly. This would be at the expense of endurance. Regarding rain, commercial companies such as DJI have already started selling weather resistant UAVs [49]. It should be noted, however, that the development of weather resistant payloads is required in parallel to make these systems viable.

5.4.8 Deployment and Collection of Static Sensors

A common usage case for UAVs is to position a sensor suite (e.g. video or thermal cameras, ionising-radiation detectors) in a location which would otherwise be difficult to access. As an extension of this, where monitoring over a long period is desired, a UAV may instead be used to deploy and later retrieve a self-contained sensor package to a location, allowing for longer-term monitoring.

Although the technology for all the components within such a system is currently available (UAVs with cargo payload capability, sufficient motor control to deploy and collect payload, technology for self-contained sensor packages), the authors of this report are not aware of such a system being deployed.

For a UK decommissioning site, a useful application may be the deployment of radiation sensors for long-term monitoring of a set area during a particular stage of decommissioning work (e.g. dose measurements within a stack during demolition works).

5.4.9 Small Form-Factor UAVs

These are UAVs which are sufficiently small and manoeuvrable to easily navigate within buildings, or restricted spaces.

Key barriers to this technology are the need for small, lightweight yet energy dense power sources, so that the small UAV may maintain flight for a serviceable period of time (e.g. 10-20 minutes). In addition, the UAV should be able to accept a payload, such as a camera, in order for its utility to be realised. As such the design and realisation of small, lightweight payloads sufficient to be carried by a small-form factor UAV is required. Development of the Microrobotic Fly and the Robobees systems at Harvard University, USA, has studied this technology [50].

For decommissioning, the utility of such a UAV system would be in inspection of difficult access areas, such as narrow pipework, or areas where access is restricted by the building structure, or by debris.

5.4.10 Extended Flight

Notwithstanding developments in battery and fuel cell technology, UAVs designed for extended flight times (i.e. days or longer) are another area of UAV development. Massachusetts Institute of Technology, for example has developed a petrol powered UAV able to sustain flight for up to 5 days [51]. Facebook is researching solar-powered UAVs designed to fly for months, broadcasting internet connections [52].

For use in UK decommissioning, such systems could provide medium- to long-term surveillance of a decommissioning site from a safety and security perspective, monitoring site workers while outdoors, as well as any activities near the site boundaries. Such UAVs may also be used to provide communication relays in situations where on-site networking infrastructure is not accessible (e.g. at particular stages in a decommissioning programme).

5.4.11 Multi-Environment UAVs

While the focus of this report thus far has been on UAV systems designed for flight only, there is also the possibility for systems to be deployed which are able to navigate through additional environments, i.e. over land, or through water. EPFL, Switzerland, are developing DALER (Deployable Air Land Exploration Robot), which is able to both fly and walk across the ground [53]. Imperial College London, UK, have developed AquaMav, a UAV which can travel through both air and water [54].

For decommissioning deployments, there may be opportunities to deploy a multi-environment UAV in locations where the exact nature of the environment is unknown, for surveying purposes. The flight capabilities of such a system would be beneficial to overcome large obstacles, while movement along the ground may offer better control while passing through low gaps. The ability to traverse through liquids may also be a required ability.

5.4.12 Shape-Changing UAVs

These are UAV systems which are able to significantly alter their shape during flight, to allow for greater versatility during deployment. These changes may be made to allow the UAV to better fit through obstacles, to better position its control surfaces for increased manoeuvrability, or to change its aerodynamic properties to allow more efficient flight. CNRS, France, is developing a Quad-Morphing Drone designed to better navigate congested spaces [55]. Another system, Dragon, by the University of Tokyo, Japan, is also designed to morph during flight, again to better navigate internal environments [56].

The utility of such systems to assist with decommissioning activities may be in navigating congested internal areas, where the ability to adapt somewhat to an unknown range of obstructions would be beneficial.

5.4.13 Swarming UAVs

Swam UAVs are designed to operate as part of a collective, with all (or most) of the UAVs deployed and flying in parallel. The UAVs rely heavily on autonomy and communication between each system to organise their deployment. ETH Zurich, Switzerland, is developing swarming UAVs as part of the sFly project, designed to produce UAVs for use within a city environment [57]. PowerBee UAVs, by Powervision Robot Inc, China, are designed to be used in swarms to create static or dynamic images within the sky [58]. Multidrone is a Horizon 2020 programme to develop swam technologies to control a 4-10 UAV team to record outdoor media events [59].

Swarm UAVs could be deployed on decommissioning sites to act as automated marshalling notification or traffic management, using several small UAVs to mark an area where, for example, heavy machinery is transiting or temporarily working. A UAV swarm may also be used to provide security surveillance across a large site, capturing video data from multiple different angles and locations.

5.5 Long-term developments

The following areas of UAV development are assessed to require significant technical or regulatory work and development, or changes in public opinion before their use on a UK decommissioning site.

5.5.1 Heavy Payload UAVs – People Transport

UAVs are being developed with an ability to carry ever increasing payloads, some of the larger projects are highlighted in this section. The use of large UAVs as taxis is currently being considered, and there are hopes to deploy such vehicles soon. UAV taxis were planned for deployment in Abu Dhabi in the UAE, where the government is working with Chinese UAV maker EHang. The deployment did not take place as planned in 2018, but manned test flights did take place in 2018, during tests in China where the system was trialled in a range of conditions, including heavy fog and Force 7 winds. A 8.8 km flight has been achieved, reaching altitudes of 300 m [60].

A German prototype Volocopter has also been considered for use in the UAE, and has also been involved in test trials in the UAE [61]. Once fully charged (2 hours charge time), the Volocopter is able to fly at 30 miles per hour. Safety is considered, with redundant battery systems, propellers, motors and flight controls, and for worst case scenarios emergency parachutes can be deployed.

Both Boeing and Airbus are also looking to develop UAVs capable of transporting people, with their Vahana [62] and Aurora Flight Science projects [63]. Both are looking to enter the unmanned taxi arena within the next 10 years.

The use of such systems on a decommissioning site may conceivably be to replace current ground transport methods (i.e. cars or similar vehicles), where transport infrastructure (roads) have been removed as part of the decommissioning plan. There may also be opportunities for workers to viably operate across multiple sites in close proximity (e.g. Berkeley, Oldbury and Hinkley Point) if the transit time between them is sufficiently short by UAV.

5.5.2 Heavy Payload UAVs – Cargo UAV

Larger UAVs are now being developed that can carry significant payloads. Some have been deployed in military operations and are based on helicopter-type designs with one or two rotors. Others are similar to those previously discussed for people transport. Although these UAVs are being considered in cargo lift scenarios, some can and do also carry people.

The gap between small electrically powered UAVs and conventional helicopter systems is decreasing, with several companies developing automated systems. When used for purposes other than defence, systems like the Lockheed Martin K-MAX and SARA are being flown with a pilot in attendance to comply with flying regulations. In the defence arena, systems like the K-MAX and Northrop Grumman MQ-8C Fire Scout, for example, are in routine use in unmanned reconnaissance missions.

The K-MAX was deployed in an unmanned state by the U.S. Marine Corps in Afghanistan, to shift cargo away from attack-prone ground to re-supply convoys [64]. The K-MAX averaged 5 to 6 missions a Day, and flew itself autonomously between pre-designated waypoints, controlled from one Tough Book laptop.

The Cormorant, formerly Air Mule, was developed for the Israeli Defence Forces, who needed a vehicle that could fly unmanned behind enemy lines to rescue wounded personnel [65]. The Cormorant can take off and land in a foot-print that is 1/5 of that of a helicopter, making it suited towards emergency medical services, where it is often difficult to fly traditional helicopter systems. The use of ducted fans as opposed to rotors means it has the same capabilities as helicopter systems without the operational limitations of the associated rotor blades. A detailed discussion on the use of UAVs for Medical Evacuation (MediVac) or Casualty Evacuation (CASEVAC) is presented in the NATO STO Technical Report TR-HFM-184, published in 2012 [66].

There is clearly potential for some of the UAVs described above to provide support in the event of a nuclear incident, to remove materials or people from high risk areas. As seen for military operations, where there is a need to remove pilots from high risk environments, systems like K-MAX, SARA and Cormorant could be used.

K-MAX has been used for firefighting operations in the US (although a pilot was present if needed) [67], and it is also proposed that the Cormorant, due to its stability, could be used to deliver firefighting foam in the event of fires in high rise buildings. Although developed for Medivac the manufacturers of the Cormorant believe it will see more use for cargo transport, construction, and inspection, once certification is achieved.

The push to use heavy lift UAVs as taxis will mean that there will, and are, significant changes being made to improve safety systems to allow unmanned flight for non-military activity. It can be assumed that this will translate to the ability to use UAVs on construction or decommissioning sites in the nuclear industry. In particular, there may be benefits in using heavy lift UAVs to transport radioactive wastes from decommissioning sites to a GDF or a storage facility, particularly in terms of avoiding populated areas, removing the need for existing logistical infrastructure and in decreasing the dose risk inherent in more traditional road or rail transport. To facilitate this, however, significant developments in the safety and reliability of autonomous heavy-lift UAVs would be required, as well as public support for such a transport system.

5.5.3 Power Delivery

The development of on-board power technologies (e.g. battery technologies, fuel cells) has been discussed. An alternative to on-board power, without the restrictions of power through integrated cable, is wireless power transmission through the broadcast of electromagnetic waves from a base station to a target. Systems able to transmit power over significant distances are in development. Imperial College London, UK, have developed a small UAV which can be powered using wireless transmission technology [68].

The benefits to UAVs powered by such a method are that the UAV system would, in theory, never require recharging directly, as long as it was deployed within the area of effect of the wireless charger, which would allow continuous flight. In hybrid systems where the UAV still retains a high-capacity battery pack, wireless power transmission may be used to augment the battery charge, allowing the UAV to operate for longer periods than allowed by the battery pack alone.

6 Summary and Conclusions

This report has collated information on the current use of UAV systems within the NDA Group and AWE, with the aim of sharing experience and learnings between organisations in different stages of their own UAV programmes. In addition, an assessment of the UK UAV market has been presented in order to assist decommissioning organisations assess their own strategies in approaching the procurement of UAV services. Lastly, potential future developments and opportunities for UAV technologies in decommissioning have been explored, both to highlight short-term opportunities of UAV use cases currently used in other industries, as well as to showcase potential avenues of development in the medium- and long-term.

In terms of the current uses of UAVs within the NDA Group, the following conclusions can be drawn:

- The Estate has already successfully deployed UAV systems to assist with visual inspection of site assets, and there is a strong interest across the Group in benefitting from the use of UAVs;
- UAV deployment has decreased costs, decreased deployment time, and increased safety, compared to the same surveys undertaken by engineering inspectors;
- UAVs have been deployed both in-house by SLCs, as well as through sub-contractors;
- Decommissioning sites can act as proving grounds for the demonstration of in-development UAV systems, which can benefit their adoption or further development; and
- There is a range of experience levels across the Group in terms of UAV deployment, from sites which have never used a UAV, to sites which have been using them to assist with regular inspections for a year. Sharing this inherent experience across the Group is likely to be an excellent opportunity to develop the Group's UAV capability.

In terms of the UK UAV market:

- The market is expected to grow with time, and offers a wide range of UAV services and technologies, which will improve in capabilities as technology and innovation progress;
- Although the nuclear market is expected to have a reduced number of suppliers due to vetting requirements, it is expected to be a buyer's market due to the expected range and variety of services available; and
- Both Make and Buy options are available from the market for a decommissioning organisation.

Future developments within the UAV sector in terms of regulation, and in the short-, medium- and long-term, were assessed based on the use of UAVs in other industries, on R&D work currently ongoing, and with a view to potential challenges faced by the UK decommissioning sector.

- Regulatory developments are likely to be a key barrier / enabler to the deployment of advanced UAV technologies.

- While the UK is generally seen as having a pro-active and measured regulatory authority in the CAA, the tendency for regulation to be affected by external events (e.g. accidents) should not be underestimated.
- In the short-term, the likely uses for UAV on UK decommissioning sites will be to assist with the collection of BIM data for site assets, to assist with site infrastructure monitoring. In addition, the ability for UAVs to collect data on the location and intensity of ionising-radiation will also likely be leveraged.
- In the medium-term, UAV will likely be able to be undertake external BVLoS flights due to changing regulations, which will allow for remote operation from a central control area. In-hand with this, the automation systems within UAVs will allow for higher-level control by the pilot, with the UAV system automatically avoiding obstacles, or reacting to changes in the environment. Longer flight durations are likely, due to improvements in battery technology, payload design, and UAV materials. The use of effector payloads will also likely be more common, e.g. systems to repair or patch structures, or to remove obstructions. The ability for UAVs to act together as part of a swarm system is also likely to be an increasingly common usage case.
- In the longer term, UAVs may be able to automatically transport large payloads, such as personnel, or even radioactive waste within a site, or from a site to a GDF, or storage facility. Novel methods of power delivery may also be used to grant UAVs an effectively indefinite flight-time.

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Appendix

Initial proof of concept flight at Aldermaston, AWE, 2018

Summary

Proof of concept flight of a UAV (DJI Inspire 2) to demonstrate suitability to assist with site asset inspections tasks, modelling, monitoring and photograph/video support; the flight to demonstrate these capabilities was deemed a success, though due to potential data security issues the demonstrated UAV was later determined to not be a suitable platform.

Reason for use of UAV and degree of success

AWE is exploring the potential to use UAV platforms to assist in various site activities, including rooftop and stack inspections, Geographic Information System (GIS) mapping, media support to decommissioning and new project works and general ‘look-see’ response to emerging issues or concerns. To support the use of UAVs on site, a demonstration flight was given using a commercially available ‘professional’ grade UAV (DJI Inspire 2). The test flight itself was successful. The specific UAV platform however, has been deemed unsuitable for use across AWE due to data integrity concerns.

Procurement route

The UAV was procured for use in-house by AWE.

Description of UAV(s)

The DJI Inspire 2 is a ‘professional’ grade commercially available quadcopter, and is used as the main inspection UAV for the asset care programme. It is ~650 mm across, including propellers, and weights 3.4-4.2 kg, depending on payload. The main payload is a gimbal camera mounted underneath the UAV. A fixed, front-facing camera is also installed to allow a ‘first person view’ to the pilot. Flight time is ~25 minutes, with GPS positioning available. The landing legs are incorporated underneath the propeller mounts, and the two flight arms hinge above the main body of the UAV during flight to remove the landing legs from the camera FoV.

Control systems

The UAV is are operated within VLoS of the pilot or observers, *via* radio controller. It supports live video feed to a connected tablet or smartphone, from the foreword facing build-in cameras. The UAV can be flown in GPS assist mode, and is designed to be flown with two operators, one to pilot, and one camera operator.

Payload

The payload for the DJI Inspire 2 is a 3-axis gimbled camera attached underneath the UAV. The payload weight is <1kg.

Type, quality and communication of outputs

As this was a demonstration flight, no ‘real’ data were captured.

Support team

The flight crew consisted of two CAA-approved pilots (one pilot, and one camera operator during each task) and spotters as required to monitor airspace and people/vehicle movements.

Safety considerations

AWE operates in conjunction with its CAA-approved Operating Manual and Task-based Risk Assessments

Security considerations

Approvals for future UAV's subject to MoD, Defence Nuclear Security Regulator and AWE's own Security function

Information management

Not applicable for this test flight

Incidents

No incidents were reported

Limitations

UAV platforms must be on a MoD approved list.

Existing learning from experience

There are potential data security issues in using DJI UAV platforms to gather data from nuclear sites.

Integrity inspection work at Dounreay, DRSL, 2017 - ongoing

Summary

Ongoing support of asset inspection work at Dounreay using a team of in-house UAV trained inspection engineers. DSRL have a fleet of two UAVs, both commercially available, one consumer grade (DJI Phantom 3) and one 'professional' grade (DJI Inspire 2). 92 inspection (30 flights) have been performed since the start of the programme (August 2017). The use of UAVs has resulted in an estimated saving of £110k in direct inspection costs.

Reason for use of UAV and degree of success

The use of UAVs to replace manual inspections for asset care was pursued, primarily for cost and safety considerations. After a year of inspection programmes, key benefits have been:

- Cost savings of UAV deployment vs. scaffolding/Mobile Elevating Work Platforms (MEWPs) and personnel costs for comparable inspections;
- Safer access to areas which were either out of reach, or had high associated risks to inspection personnel;
- Release of inspection supervision staff, as well as MEWP staff and equipment to other programmes; and
- Quick access (24 hour notice to site) to areas requiring inspection, i.e. to assess storm damage.

Procurement route

Both UAVs are commercially available systems, one 'professional' grade (DJI Inspire 2), one consumer grade (DJI Phantom 3), and were procured for use in-house for DSRL. 6 inspection engineers were trained as pilots by Commercial Drone Training Ltd. (CDT), who visited the Dounreay site to supply the training.

Description of UAV(s)

The asset inspection fleet comprises two UAVs: a DJI Inspire 2, and a DJI Phantom 3.

The DJI Inspire 2 is a 'professional' grade commercially available quadcopter, and is used as the main inspection UAV for the asset care programme. It is ~650 mm across, including propellers, and weights 3.4-4.2 kg, depending on payload. The main payload is a gimbal camera mounted underneath the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~25 minutes, with GPS positioning available. The landing legs are incorporated underneath the propeller mounts, and the two flight arms hinge above the main body of the UAV during flight to remove the landing legs from the camera FoV.

The DJI Phantom 3 Standard is a consumer grade commercially available quadcopter, and is used as a training UAV, as well as offering backup to inspections. It is ~350 mm across, weighing ~1.2 kg. The payload is a gimbal camera, mounted on the bottom of the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~20 minutes, with GPS positioning available.

Control systems

Both UAVs are operated within VLoS of the pilot or observers, *via* radio controller. Both UAVs can support live video feeds to a connected tablet or smartphone, from the foreword facing build-in cameras. Both UAVs can be flown in GPS assist mode. The DJI Inspire 2 is usually flown with two operators, one to pilot, and one camera operator. The DJI Phantom 3 is flown with a single operator.

Payload

The payload for both UAVs is a gimbled camera attached underneath the UAV.

The camera for the DJI Inspire 2 is an unknown high definition digital camera, mounted on a 3-axis gimbal. The payload weight is <1kg.

The camera for the DJI Phantom 3 Standard is a 1/2.3" CMOS sensor on a 3-axis gimbal.

Type, quality and communication of outputs

Digital video and photographs are able to be recorded from both UAVs.

For the DJI Inspire 2, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs from are video at 6k, 30 fps, and photographs at 24MP. Full size photographs and video are stored on the onboard SD card, or onboard hard-drive, depending on the quality of data required (data requiring high transfer bandwidth is stored on the hard-drive). Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

For the DJI Phantom 3 Standard, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs are video at 2.7k at ~30fps, and photographs at 12MP. Full size photographs and video are stored on the onboard SD card. Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

Support team

The flight team typically comprises two members, one pilot, and one camera operator/observer[1]. The pilots are inspection engineers with UAV piloting qualifications, and there is a pool of 6 trained pilots. Additional site personnel may assist as observers, or marshals to keep flight area clear of personnel.

Pilot training was carried out by a NQE (Commercial Drone Training Ltd.) who visited Dounreay site to conduct the training.

Safety considerations

DRSL holds PfCO from the CAA, through maintenance of a Flight Operations manual. Each flight is risk assessed and documented.

Pilot competencies and PfCO status are monitored by the CAA, and pilots require a certain amount of flight / flight time per year to maintain competency.

A Flight Prohibited area surrounds the Dounreay Site, the CAA regulates this and the Site liaises with the CAA on any permissions sought to operate within this zone. Specific consideration is given to wildlife, particularly birds, as part of the flight assessment.

[1] The DJI Inspire 2 allows the camera payload to be separately controlled by another member of the flight team, this feature is not present on the DJI Phantom 3.

Security considerations

UAVs are kept ‘off-network’ due to security concerns with DJI data transfer. Data are stored on an on-board SD card, which is removed from UAVs at the end of the flight.

Information management

Data are recorded by DRSL, and so owned by them. Data are uploaded to a central database that inspection engineers, as well as commercial personnel, can access.

Incidents

During training flights, two tip-overs of the UAV were reported after landing. No significant damage occurred to the UAV.

A flight near the Dounreay Fast Reactor experienced significant interference with the UAV on-board compasses, due to the significant quantity of ferrous material in the area. This resulted in manual flying to be undertaken for sections of the flight, without automated support. The flight was safely completed.

A flight close to a facility known to produce RF transmissions caused the UAV to change control mode to ‘Attitude control’, away from the original control mode the pilot had set. This lasted for less than five seconds, and the flight was continued. .

During a flight collecting video footage in a dusty environment, the Port Rear motor of the UAV experienced a glitch, resulting in unexpected flight behaviour (the UAV pitched up and to the left). The UAV was landed and had diagnostics carried out (technical log analysed by Heliguy, Colena Ltd.). The cause of the glitch was assumed to be due to operating in a dusty environment. The motor glitch has not been observed again, after testing at the off-site training location.

Limitations

Inspection flights are limited to gathering external visual information (images, video), and must take place within VLoS of the pilot or observers. The current UAVs are also not suited to internal inspections, due to their size and design; internal inspections have been conducted, though it was remarked that smaller UAVs would have made the task easier.

Existing learning from experience

Due to the requirement for each pilot to maintain a given level of experience (i.e. recording a set number of flights / flight-hours per year), thought should be given to the expected work-load that a ‘UAV team’ will undertake in a year. Having an insufficient number of ‘working’ flights per year may lead to pilots undertaking extra training flights (i.e. non-profitable time) in order to maintain their piloting competency to a suitable level.

Pre-flight assessment should include an assessment of the electromagnetic (e.g. radio) environment, to minimise risk of disruption, interference, or override of control signals between the UAV and the pilot, and the UAV and other telemetry (e.g. onboard compass, GPS).

The surface of bodies of water may not be apparent in dim environments from the UAV cameras, and inspection from numerous angles may be required before a good perspective is achieved (i.e. observing reflected light-sources in the water surface).

Nuclear Decommissioning Authority

Channel 4 documentary filming 'Hidden Britain by Drone' at Dounreay, 2018

Summary

Footage captured of Dounreay site by TV production company. UAV was flown by DSRL SQEP staff for filming within the site licence boundary.

Reason for use of UAV and degree of success

Footage of the Dounreay site was taken as part of the Channel 4 TV series 'Hidden Britain by Drone', a program which explored restricted or typically inaccessible parts of the UK using UAVs to capture and video footage.

Procurement route

Not applicable, external TV production company applied for permission to record footage of Dounreay site.

Description of UAV(s)

Unknown – assumed commercially available quadcopter, hexacopter and oct-copter UAVs with professional grade camera payloads.

Control systems

Unknown, assumed single pilot controlling the UAV through a radio controller within VLoS, with separate camera operator controlling through dedicated system.

Payload

Digital cameras for video capture, specification unknown.

Type, quality and communication of outputs

Digital video was captured suitable for TV broadcast, though the exact quality is unknown. The method of data transfer (i.e. recorded to on-board memory, or transmitted to ground-station) is also not known.

Support team

It is assumed that the flight team consisted of a pilot and a camera operator.

DSRL personnel took responsibility for flying the UAVs on the Dounreay site, with programme production staff flying the UAV off-site.

Safety considerations

Unknown, assumed to follow existing DSRL procedures to comply with PfCO on Dounreay site.

Security considerations

Images and video were vetted by DSRL before release.

Information management

Footage (after security vetting) is assumed to belong to the filming company.

Incidents

No incidents were reported

Limitations

High-level visual inspection of Dounreay site for PR purposes.

Existing learning from experience

None available.

Surveying of pile cap at LLWR, LLW Repository Ltd., 2015

Summary

LLWR purchased a UAV to perform a BIM level survey of LLWR pilecap, to reduce dose risk to survey team. Flight was conducted in ~30 minutes, with survey data sent to 3rd party survey company after security vetting.

Reason for use of UAV and degree of success

An engineering survey of the pile cap at LLWR was required in order to inform a planned work programme. It was recognised that conducting a manned survey would expose surveyors to a dose risk. A UAV was instead used to gather BIM level point cloud survey data with a camera and laser scanner. This was undertaken over two consecutive flights, totalling ~ 30 minutes, capturing data of suitable detail to be sent to 3rd party survey company for use.

Procurement route

The UAV and associated systems were procured for LLW Repository Ltd. Procurement also included a specialist pilot training course hosted in Germany, which was attended by a member of LLW Repository Ltd..

Description of UAV(s)

The UAV was an Aibot X6, a hexacopter with in-build rotor guards and capacity for top and or bottom mounted payloads.

Control systems

The UAV was operated by a single pilot, controlling the UAV with a radiocontroller. The UAV was operated with GPS assisted flight within VLoS, at a maximum distance of ~80m.

Payload

Payloads were a camera to capture visual images, and a laser scanner to capture topology data. The combined UAV and payload weight was ~6-7 kg.

Type, quality and communication of outputs

Data were captured as photographs and as a topological 3D point cloud, which were combined after the flight to create a 3D model of the pile cap area.

Support team

The UAV was flown by a single pilot, with two on-site supports, and additional observers. The pilot received training from UAV vendor for 1 week as part of purchase. Two flights of ~12 minutes each were conducted sequentially, with the break taken to replace the UAV batteries.

Safety considerations

LLWR created a Flight Operations Manual to comply with CAA regulations (permission for commercial operation, PfCO). A risk assessment was undertaken for the flight, and the LLWR site was notified of the flight *via* e-mail. Site personnel were kept out of operations area during flight.

Security considerations

Data captured during the flight was stored on an on-board SD card. After the flight was finished, the SD card was secured and monitored until the data were transferred from it. The data were assessed and vetted for any security issues, before being transferred off-site to the 3rd part survey company.

Information management

The raw data were collected and is owned by LLW Repository Ltd. Status of processed survey data (i.e. after having been sent to 3rd party survey company) is unknown.

Incidents

During an initial test/training flight, a low battery response caused the UAV to automatically fly back to its home site and land. A system issue led to the UAV flying in the opposite direction from the designated home site, and subsequently landing. LLWR contacted the system manufacturer to report this issue which resulted in a software fix

Limitations

Flight was conducted within VLoS. Flights were limited to ~12 minutes per battery pack, requiring a battery change during the operation to complete the data capture.

Existing learning from experience

Although the flight time to gather the required data (~30 minutes) was significantly faster than would have been required using a manned survey team, this does not capture the administrative overhead for obtaining flight approval, flight planning, and other related activities.

Nuclear
Decommissioning
Authority

UAV assistance with civil engineering inspections, LLW Repository Ltd., 2016-onwards

Summary

Use of a commercially available consumer UAV (DJI Phantom 4) to assist with monthly structure inspections with photo and video capture at LLWR.

Reason for use of UAV and degree of success

A UAV is in use to assist with regular (monthly) asset inspections, to enable visual data to be gathered from areas where man-access would be difficult, or hazardous.

Procurement route

Commercially available consumer UAV procured by LLW Repository Ltd., through unknown vendor.

Description of UAV(s)

DJI Phantom 4 – a consumer grade quadcopter with front facing (static) and gimbled cameras. Weight ~1.4 kg, ~400 mm across, including propellers. Can use GPS positioning.

Control systems

UAV controlled through radio-controller. Flight can be either GPS assisted, or through manual control. Live view (from the static front camera) can be transmitted to tablet computer or smartphone mounted on the flight controller.

Payload

The gimbaled camera is a 1/2.3" CMOS, with resolution of ~12MP.

Type, quality and communication of outputs

Photo and video outputs can be collected. Photos have resolution of ~12MP. Video can be recorded up to 4k (4096x2160) resolution at maximum of 25 fps, with lower resolutions able to be recorded at higher frame rates (i.e. 120 fps at a resolution of 1920x1080).

Support team

Single pilot, undertook UAV flight training at a NQV in Edinburgh. Survey personnel provide operational support.

Safety considerations

Flights are undertaken under the existing LLW Repository Ltd. Flight Operations Manual (CAA compliant, updated annually). Each flight requires a new risk assessment to be undertaken and submitted for approval. Personnel are kept out of the operations area.

Security considerations

Due to the potential for data acquired on by DJI UAVs to be automatically uploaded to DJI when the UAV is connected to the internet, the UAV is operated off-network. Images and data are stored on the on-board SD card.

Information management

The data are collected and owned by LLW Repository Ltd..

Incidents

A strong gust of wind on landing has caused the UAV to tip over. No significant damage was reported.

Limitations

Inspection is limited to exterior visual inspections (e.g. roofs).

Existing learning from experience

Reliable assessment of flying conditions (i.e. weather, particularly wind) is important in establishing a suitably low-risk flight operation.

Nuclear
Decommissioning
Authority

RISER deployment at Hunterston A SRU, Magnox Ltd.: Hunterston, 2016

Summary

Demonstration deployment to assess suitability of RISER UAV to operate on a Magnox Ltd. site. UAV was deployed in indoors environment (steam riser unit) to collect simultaneous LiDAR and radiation dose data. During the third demonstration flight a problem with the collision avoidance software caused the UAV to crash, ending the demonstration.

Reason for use of UAV and degree of success

This was a test flight to assess the ability of the RISER UAV system to be to measure the radiological environment within a building, as well as to capture video and photographic data to inform inspection requirements. The test flight was conducted inside the Steam Riser Unit (SRU) at Hunterston A. Without the use of a UAV this would otherwise have required scaffolding access to difficult areas of the SRU.

Procurement route

The RISER system was deployed on site by Createc. The direct procurement route is not known, but it is thought that Magnox Ltd. initiated contact in order to assess the deployment of the RISER system on site.

Description of UAV(s)

Remote Intelligent Survey Equipment for Radiation (RISER), a UAV developed by Blue Bear and Createc. This is a quadcopter with propeller guards, and onboard cameras, LiDAR sensors and radiation detection equipment.

Control systems

The RISER UAV was controlled by a single pilot through radio communication. An observer / backup pilot was also employed with a separate control system. The flight was undertaken using both visual line of sight (VLoS), and by first person view using live, onboard telemetry. There were also autonomous systems incorporated to aid flight, such as collision avoidance systems, which were employed for the flights.

Payload

The key sensor payloads for the RISER UAV are:

- Video camera
- Gamma spectrometer
- 2x LiDAR systems (vertical and horizontal).

Type, quality and communication of outputs

A 3D point cloud of the SRU was created by taking positioning and LiDAR data during flight. These 3D point cloud data were combined with radiation dose measurements (Figure A1).

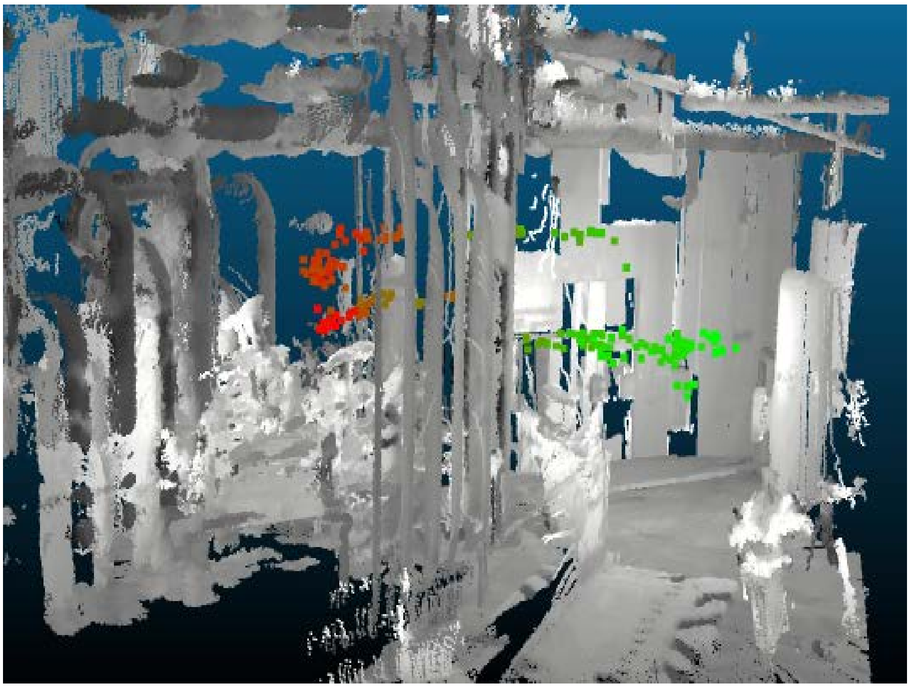

Figure A1: Example of 3D LIDAR (greyscale) and radiation (green-red points) data collected by RISER platform inside Hunterston A SRU. [1]

Data were streamed from the UAV to a base-station, and was able to be viewed in real time during collection.

Support team

The core flight team consisted of one pilot, and one observer who also acted as a co-pilot if required. There were 4-5 additional members of the support team to assist with the test flight, not including Magnox Ltd. observers.

Safety considerations

The flight was undertaken within a controlled entry building, and the flight and observation teams were the only personnel present. The flight areas were designated as no-entry areas.

Security considerations

Unknown.

Information management

Unknown. Information collected was transferred to Magnox Ltd. after collection.

Incidents

During the last (3rd) flight, the automatic collision avoidance system for the UAV encountered a fault, which resulted in a collision between the UAV and the interior or the building. The UAV lost control, collided with a metal beam, and fell 5-10 m to the floor (steel sheet).This caused minor damage to the UAV, with no damage observed to the building.

Limitations

Test flight to assess viability of deployment on Magnox Ltd. sites. UAV took an initial flight period (minutes) to establish 3D LiDAR map of immediate surroundings before commencing main flight.

Existing learning from experience

Reason for failure of guidance system is not known (from surveyed sources). The RISER system performed well in the previous two flights, obtaining 3D LiDAR, radiological, and photographic data within the SRU, and there is good potential for this type of system to be deployed in future.

Concern over the flight failure observed in the 3rd test flight has led to alternative methods of data capture to be investigated. As part of this, a sensor package designed to be deployed on the ILW store crane has been developed.

Nuclear Decommissioning Authority

Inspection of SGHWR cladding at Winfrith, Magnox Ltd.: Winfrith, 2014 - 15

Summary

Test deployment of a UAV, flown using in-house pilot, to perform inspection of external cladding of SGHWR building. Deployment was a success, with cost savings realised compared to traditional inspection methods.

Reason for use of UAV and degree of success

Use of a UAV to facilitate inspection of external galvanised cladding to the Steam Generator Heavy Water Reactor (SGHWR) facility (~30x60x40 m). Use of a UAV was trialled to save costs on scaffolding (expected to be £50-60k for the entire building), as well as to reduce risk to personnel working at height. The UAV inspection was able to locate areas of concern in the cladding, for further manual inspection, as well as to detect issues in the concrete mural.

Figure A2: SGHWR building at Winfrith, with concrete mural shown on top right corner. Image captured by DJI Phantom 3. [2]

Procurement route

The UAV (DJI Phantom 3) was purchased for site use, and procured through a framework supplier. The choice of UAV was informed by the pilot's own experience with UAVs outside of work, as well as by the flight training school who provided the piloting course.

Description of UAV(s)

The DJI Phantom 3 Standard is a consumer grade commercially available quadcopter. It is ~350 mm across, weighing ~1.2 kg. The payload is a gimbaled camera, mounted on the bottom of the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~20 minutes, with GPS positioning available.

Control systems

The Phantom 3 was operated within VLoS of the pilot, *via* radio controller. The UAV can support live video feeds to a connected tablet or smartphone, from the foreword facing build-in cameras. The UAV was flown with GPS assistance, and was flown with a single operator.

Payload

The payload for the DJI Phantom 3 is a digital camera, mounted underneath the UAV on a 3-axis gimbal. The camera is a 1/2.3" CMOS sensor.

Type, quality and communication of outputs

For the DJI Phantom 3 Standard, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs are video at 2.7k at ~30fps, and photographs at 12MP. Full size photographs and video are stored on the onboard SD card. Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

Support team

The pilot was a Magnox Ltd. employee who had been identified as a drone hobbyist outside of work. Pilot attended a training course on UAV operations. Flight team was a single pilot, and an observer.

Safety considerations

Permission for Commercial Operations (PfCO) was obtained for Magnox Ltd. from the CAA, which required the submission of an up-to-date (yearly) Operations Manual. Company insurance also had to be updated by the NDA to meet CAA requirements of EC regulation No. 785/2004.

Flight specific documentation was prepared from flight team (risk assessment, site inspection, flight record, battery record, etc.), and site-side documentation (e.g. local risk assessment) was prepared by site.

Security considerations

Unknown

Information management

Video and photo data from the UAV are stored locally on a SD card, which was transferred to the required end-user before leaving site.

Incidents

No incidents or near-misses were reported.

Limitations

Visual inspection only. Total inspection time was 3-4 days.

Existing learning from experience

Visual inspection of galvanised cladding is sufficient to identify areas for further, manual inspection. Images taken down the side of the building were able to observe 'bumps' and other features standing proud of the wall profile, indicating areas of potential degradation.

Nuclear
Decommissioning
Authority

Interior flight through SGHWR at Winfrith for promotional video, Magnox Ltd.: Winfrith, 2014-15

Summary

A DJI Phantom 3 was used to capture promotional video footage of the SGHWR building at Winfrith, both externally, and internally. The UAV was flown inside the building without the need to stop all other works inside. GPS satellite navigation was not functional within the building, due to signal interference from the building structure, and sources of radio interference within the building prevented flights within certain areas.

Reason for use of UAV and degree of success

A UAV (DJI Phantom 3) was used to capture promotional video material around and inside the SGHWR at Winfrith. The UAV was able to quickly and cheaply capture video within a working facility from a range of perspectives, giving a general overview of building layout and work undertaken. The UAV was able to be piloted through large internal spaces, though flight through some human access routes (stairways, doors, corridors) experienced signal interference.

Procurement route

The UAV (DJI Phantom 3) was purchased for site use, and procured through a framework supplier. The choice of UAV was informed by the pilot's own experience with UAVs outside of work, as well as by the flight training school who provided the piloting course.

Description of UAV(s)

The DJI Phantom 3 Standard is a consumer grade commercially available quadcopter. It is ~350 mm across, weighing ~1.2 kg. The payload is a gimbaled camera, mounted on the bottom of the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~20 minutes, with GPS positioning available.

Control systems

The Phantom 3 was operated within VLoS of the pilot, via radio controller. The UAV can support live video feeds to a connected tablet or smartphone, from the foreword facing build-in cameras. The UAV was flown without GPS assistance due to limited satellite signal within the SGHWR building, and was flown with a single operator.

Payload

The payload for the DJI Phantom 3 is a digital camera, mounted underneath the UAV on a 3-axis gimbal. The camera is a 1/2.3" CMOS sensor.

Type, quality and communication of outputs

For the DJI Phantom 3 Standard, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs are video at 2.7k at ~30fps, and photographs at 12MP. Full size photographs and video are stored on the onboard SD card. Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

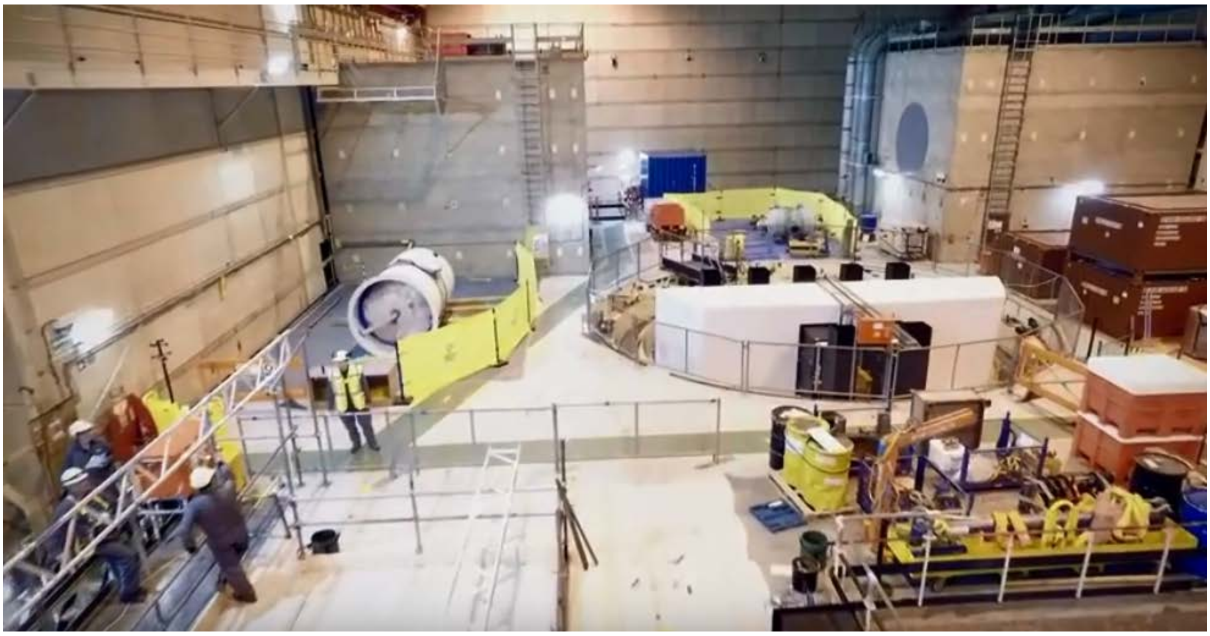

Figure A3: Image taken from promotional video of UAV flight through SGHWR building at Winfrith. [2].

Support team

The pilot was a Magnox Ltd. employee who had been identified as a drone hobbyist outside of work. The pilot attended a training course on UAV operations. Flight team was a single pilot, and an observer. Support was also given by onsite personnel.

Safety considerations

Permission for Commercial Operations (PfCO) was obtained for Magnox Ltd. from the CAA, which required the submission of an up-to-date (yearly) Operations Manual. Company insurance also had to be updated by the NDA to meet CAA requirements of EC regulation No. 785/2004.

Flight specific documentation was prepared from flight team (risk assessment, site inspection, flight record, battery record, etc.), and site-side documentation (e.g. local risk assessment) was prepared by site. Limited no-entry flight areas were established, though personnel were able to keep operating within the building.

Security considerations

Video footage was stored on an onboard SD card. Video data were vetted before being incorporated into promotional a video.

Information management

Video and photo data from the UAV are stored locally on a SD card, which was transferred to the required end-user before leaving site.

Incidents

No incidents or near-misses were reported.

Limitations

UAV was flown without GPS assistance, due to signal interference within building. Some areas were too narrow to fly successfully.

Existing learning from experience

Operations within buildings or other areas of signal interference may lead to loss of GPS signal, and so of any automated GPS flight assistance. A UAV may be deployed within a building successfully, though issues were encountered when attempting to traverse human accessways (stairs, doorways).

Video surveys of Winfrith, Bradwell and Harwell sites, Magnox Ltd.: various sites, 2015 onwards

Summary

Use of a commercially available consumer grade UAV (DJI Phantom 3) to gather regular site survey information (photographs, video), as well as to assist with prompt, restricted access asset inspection after potential weather damage. UAV is operated in-house, gathering video and photo data.

Reason for use of UAV and degree of success

Use of UAV to gather aerial view photography and video to assist with site surveys, allowing easier, faster and cheaper site monitoring via UAV than comparable techniques for gathering data (helicopter, satellite image, etc.). UAVs are also used for visual inspection of assets, i.e. after potential storm or other weather damage, as deployment of a UAV is quicker and safer than access (i.e. to a roof) by personnel. In both roles, the use of a UAV has benefited operations at Winfrith, Bradwell and Harwell.

Procurement route

The UAV (DJI Phantom 3) was purchased for site use, and procured through a framework supplier. The choice of UAV was informed by the pilot's own experience with UAVs outside of work, as well as by the flight training school who provided the piloting course.

Description of UAV(s)

The DJI Phantom 3 Standard is a consumer grade commercially available quadcopter. It is ~350 mm across, weighing ~1.2 kg. The payload is a gimbaled camera, mounted on the bottom of the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~20 minutes, with GPS positioning available.

Control systems

The Phantom 3 was operated within VLoS of the pilot, *via* radio controller. The UAV can support live video feeds to a connected tablet or smartphone, from the foreword facing build-in cameras. The UAV was flown with GPS assistance, and was flown with a single operator.

Payload

The payload for the DJI Phantom 3 is a digital camera, mounted underneath the UAV on a 3-axis gimbal. The camera is a 1/2.3" CMOS sensor.

Type, quality and communication of outputs

For the DJI Phantom 3 Standard, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs are video at 2.7k at ~30fps, and photographs at 12MP. Full size photographs and video are stored on the onboard SD card. Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

Support team

Flight team consists of a single pilot, with an observer. Site assistance may also be used, depending on operational requirement.

Safety considerations

Flights are covered under existing Magnox Ltd. PfCO. Each flight has a risk assessment, flight log, battery log, on-site assessment etc. Site-side procedures (i.e. local risk assessment) will also be undertaken.

Security considerations

Data saved to on-board SD card. Data were transferred directly to site after flight, and did not leave site with flight team.

Information management

Data owned by Magnox Ltd.

Incidents

None reported.

Limitations

'Survey' data are for visual / manual tracking, rather than for BIM or photogrammetry.

Existing learning from experience

Flight viability is significantly affected by weather (e.g. fog, windspeed), which needs to be factored in to any programme.

Nuclear Decommissioning Authority

Visual inspections of sites around Sizewell A (steam generator roof, off-shore cooling water intake, cooling water plant basement, interior building inspection), Magnox Ltd.: Sizewell A, 2016-2017

Summary

Visual inspection of various assets around the Sizewell A site which would have posed difficulties for regular access. Data was collected by a 3rd party company (Hexcam), who provided the UAVs and pilots. External inspections (Steam generator roof, off-shore cooling intake) were very successful. Interior inspections suffered from disruption to GPS signals, requiring more manual piloting to be undertaken. Data were captured to the on-board SD card, which was provided and owned by Magnox Ltd. The contractor handed over the card on completion of the job, before leaving site. Agreement with Sizewell B was gained before undertaking the UAV flights.

Reason for use of UAV and degree of success

UAVs were used to take video footage and photographs of a number of assets on the Sizewell A site, which would have presented difficulties in accessing with more traditional methods. These were:

- The offshore cooling water intake before and after modifications were carried out.
- The roof of the steam generator building, to inform demolition plans
- An internal building flight
- The Cooling Water Plant (CWP) basement area, to assess the viability of inspection after the manned-access ways had been removed.

Exterior inspections were judged to be a success, with good quality data gathered by the UAVs. The internal building inspection was also judged to be successful, though an intermittent GPS signal resulted in the pilot flying the UAV by direct visual feedback. The GPS signal also suffered interference undertaking the CWP basement inspection, requiring direct visual piloting; in this instance the flight was not considered successful due to the required pilot line of sight to the UAV, negating the benefits of remote operation in this environment.

Procurement route

The UAVs and operators were supplied by external company Hexcam, who were subcontracted by the Site Access contractor Actavo.

Description of UAV(s)

Two UAVs were deployed for the site inspections, a DJI inspire 2 and a DJI Phantom. The precise model of the Phantom is unknown, and is here assumed to the DJI Phantom Standard.

The DJI Inspire 2 is a ‘professional’ grade commercially available quadcopter, and is used as the main inspection UAV for the asset care programme. It is ~650 mm across, including propellers, and weights 3.4-4.2 kg, depending on payload. The main payload is a gimbal camera mounted underneath the UAV. A fixed, front-facing camera is also installed to allow a ‘first person view’ to the pilot. Flight time is ~25 minutes, with GPS positioning available. The landing legs are incorporated underneath the propeller mounts, and the two flight arms hinge above the main body of the UAV during flight to remove the landing legs from the camera FoV.

The DJI Phantom 3 Standard is a consumer grade commercially available quadcopter. It is ~350 mm across, weighing ~1.2 kg. The payload is a gimbal camera, mounted on the bottom of the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~20 minutes, with GPS positioning available.

Control systems

Both UAVs are operated within VLoS of the pilot or observers, via radio controller. Both UAVs can support live video feeds to a connected tablet or smartphone, from the foreword facing build-in cameras. Both UAVs can be flown in GPS assist mode. The DJI Inspire 2 is usually flown with two operators, one to pilot, and one camera operator. The DJI Phantom 3 is flown with a single operator.

Payload

The payload for both UAVs is a gimbled camera attached underneath the UAV.

The camera for the DJI Inspire 2 is unknown, but expected to be a high-definition digital camera, mounted on a 3-axis gimbal. The payload weight is <1kg.

The camera for the DJI Phantom 3 Standard is a 1/2.3" CMOS sensor on a 3-axis gimbal.

Type, quality and communication of outputs

Digital video and photographs are able to be recorded from both UAVs.

For the DJI Inspire 2, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs from the camera are video at 6k, 30 fps, and photographs at 24MP. Full size photographs and video are stored on the onboard SD card, or onboard hard-drive, depending on the quality of data required (data requiring high transfer bandwidth is stored on the hard-drive). Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

For the DJI Phantom 3 Standard, live flight visuals from the forward-facing cameras can be streamed to a tablet or smartphone. The highest resolution outputs are video at 2.7k at ~30fps, and photographs at 12MP. Full size photographs and video are stored on the onboard SD card. Data thumbnails can be previewed by transmitting to a linked tablet or smartphone.

Security considerations

Due to the close proximity of the site to Sizewell B, agreement was sought to the deployment of UAVs on the Sizewell A site to capture video and photographic data. This was agreed with Sizewell B, though there were some initial concerns over capturing visual data of Sizewell B assets security fences, etc.).

Information management

For the site inspections, Magnox Ltd. procured and supplied an SD card to the UAV operators, which was installed in the UAVs to which they could capture data. After the flight the SD card and data were returned to Magnox Ltd. This was explicitly agreed with the subcontractor before the flight.

Incidents

Poor GPS signals during internal flights led to the pilot controlling the UAV through direct visual feedback, though the flights were ended safely.

Limitations

Data were limited to visual inspections, though found to be suitable for the intended use. Loss of GPS signals within structures led to the requirement for flying with direct visual feedback.

Existing learning from experience

Deployment of UAVs on paired sites (Dungeness, Hunterston, Hinkley Point), and indeed on sites in close proximity to other unaffiliated secure sites, may require dialogue between the two sites before UAVs are operated.

Trial inspection of exterior of Safestore building, Magnox Ltd.: Trawsfynydd, 2013

Summary

Trial inspection of exterior of Safestore building, to assess if abseilers could be replaced for inspections. Agency worker brought in own UAV to take images of Safestore building. Image detail was good, but was not able to detect areas of concern (i.e. loose concrete).

Reason for use of UAV and degree of success

Trial inspection of external Safestore cladding, to replace use of abseilers for inspection for descaling operations. Photography of building sides was excellent, but no clear visual indications of loose concrete. Potential for record-keeping of building condition.

Procurement route

UAV belonged to Agency Supplied Worker, who was also hobbyist pilot. Worker was pilot for deployment.

Description of UAV(s)

Unknown – Quadcopter with rotor-guards, camera suspended underneath. Possibly DJI Phantom 1.

Control systems

Single pilot, flying in VLoS

Payload

Digital camera, type unknown.

Type, quality and communication of outputs

Photographs of Safestore building exterior walls.

Support team

Single pilot. Unknown support team.

Safety considerations

UAV flight was conducted at weekend, to take advantage of reduced site population. Flight area around Safestore building was marked out, with restricted access. Flight distance from building was 10-15 m.

Security considerations

Unknown.

Information management

Information recorded by Magnox Ltd.

Incidents

UAV was flown in a series of vertical descents from top of Safestore to bottom. On one landing the UAV clipped a fence on the landing. No significant damage to UAV or fence.

Limitations

Not sufficient to detect delaminated concrete from visual inspection

Existing learning from experience

Suggestion of a designated landing zone for each flight, instead of landing at the base of each wall scan, as this led to clipping a fence.

University of Warwick indoor mapping demonstration, Sellafield Ltd., 2012

Summary

A test flight of a UAV system in development at the University of Warwick as part of a joint Sellafield Ltd. – EPSRC PhD project. The project aimed to develop a UAV system for semi-autonomous inspection inside Sellafield Ltd. facilities. The test flight was successful in demonstrating the capability for UAVs to be used in this manner, though some issues in the control system were observed due to the developmental nature of the project.

Reason for use of UAV and degree of success

This test flight was part of a PhD project at the University of Warwick looking to develop automated on-board navigation systems for UAV platforms, with the intention to deploy them within hazardous and unknown environments for inspection work to be carried out. The developed navigation systems were generally effective, though some software bugs were observed and recorded.

Figure A4: Image of the UAV system during the demonstration test-flight at Sellafield. [3]

Procurement route

The PhD was funded by both Sellafield Ltd. and the Engineering and Physical Sciences Research Council (EPSRC). As project sponsors, Sellafield Ltd. were able to set out a list of system requirements for the research to develop. These included the typical operating environments (indoor containing unknown 'clutter'), inspection requirements (imagery, dosimetry, geometric), UAV platform requirements (primarily cost, flight time and size), and operation requirements (semi-autonomous, low barrier to use). Tests on the Sellafield site were organised a part of the system demonstration.

Description of UAV(s)

The UAV platform used for this work was a commercially available HexaKopter (HiSystems GmbH), a six-propeller multicopter airframe. This platform can carry a payload of ~2 kg, and has a flight time of 10-25 minutes, depending on payload weight (heavier payloads lead to shorter flight times).

Control systems

The control system for this UAV was developed as part of the PhD research, with a focus on improving semi-autonomous flight, with inputs from a pilot. The system maintains stable flight automatically, responding to control commands from the pilot (height, position, etc.)

The UAV is controlled and monitored through radio controller and a base-station. Flight data (position, height, live video feed) is relayed from the UAV.

Figure A5: UAV base-station. [3]

Payload

The sensor systems used on the UAV are listed below:

- LiDAR, 290 g – For gathering 3D topographical data of the UAV's environment
- Orientation, 65 g – To sense the angular pose of the UAV and LiDAR scanner
- SoNAR, ~5 g – To measure the height of the UAV when close to the ground (<6 m)
- Altimeter, ~5 g – Pressure sensor to measure height of UAV when out of range of the SoNAR sensor
- Camera, 190 g – Provides live video-feed to operator, and acquires images during flight for later analysis

It should be noted that, although one of the metrics of interest as defined by Sellafield Ltd. was local dose measurements, this capability was not explicitly developed nor demonstrated as part of this research.

Type, quality and communication of outputs

The main data outputs of the UAV are 3D LiDAR data of the UAV’s environment, and digital images captured by the on-board camera. The LiDAR data are reported to be able to detect a 13 Amp hanging cable at a distance of ~1.5 m during live flight. Post processing of the LiDAR data is also possible to create a higher density point-cloud measurement (Figure A6)

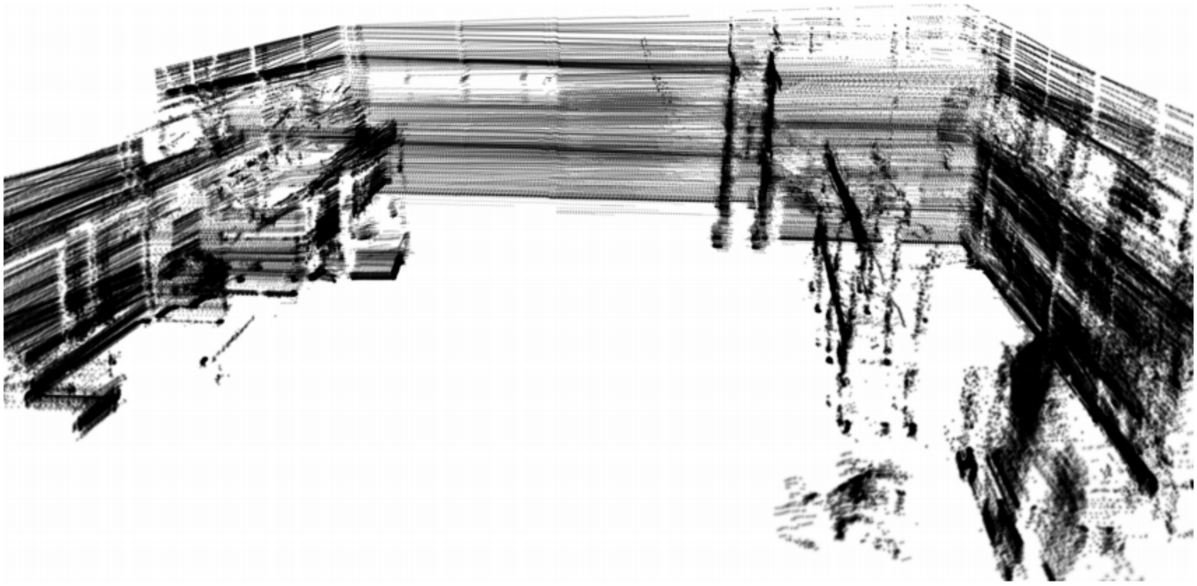

Figure A6: High density, post processed LiDAR map of the demonstration flight area. [3]

The digital camera used on the UAV was a ‘GoPro (HD) Hero 2’. This camera can take still images with up to 11 MP resolution, and video at a maximum resolution of 1920x1080. It was highlighted that the camera does not perform well in low-light.

Support team

The UAV was flown by a single pilot, and during the demonstration control was given to a number of individuals with varied UAV piloting experience, with the aim to demonstrate that the semi-autonomous control system could reduce the barrier to entry for inexperienced pilots.

Safety considerations

The demonstration flight took place within a designated building, and the flight area was marked as a no-entry zone for personnel.

Security considerations

The test flight was conducted in a pre-cleared building. Data captured by the UAV were vetted prior to release.

Information management

Information gathered during the test flight was used as part of the PhD research at the university of Warwick.

Incidents

During a test flight through a confined area, the UAV control software encountered a positioning glitch, causing control of the UAV to be lost, and the UAV to land heavily (height of ~1.5 m). No damage was reported to the UAV.

The automated collision avoidance system was also observed to be suitable to protect against objects in the lateral plane of the UAV, but not from objects above or below the UAV, i.e. the UAV was not prevented from climbing or descending into an object. This lack of protection was noticed by the operator without a collision occurring.

Limitations

The demonstrated UAV system was a system still in development, and as such experienced some software bugs and limitations. The system as demonstrated is not suitable for full deployment.

Existing learning from experience

The use of a UAV to gather LiDAR information and digital images of its environment, through semi-autonomous control has been demonstrated in principle.

Nuclear Decommissioning Authority

Photomapping of Wastwater pipeline, Sellafield Ltd., 2012

Summary

High level photomapping carried out to support a project involving the Wastwater pipeline at Sellafield site. A fixed wing UAV was used to gather photogrammetry data, which was stitched together and used in project planning.

Reason for use of UAV and degree of success

The reason for the use of UAV technology in this case, was to get a topographical overview of the project in question, this would be used for quality management, PR and project management purposes.

The project needed up to date information and better ground resolution that other conventional methods of the time, such as Google Earth, could not deliver.

The degree of success can be measured in the fact that the workflow output exceeded the expectations and had all the information Sellafield Ltd. required.

Procurement Route

The photomapping services were supplied through a 3rd party company (Enefftech). The procurement route for this project was by direct award rather than *via* any framework.

Description of UAV

The platform used to conduct the mission was a senseFly Swinglet CAM, electric fixed wing, weighing in at around 500 g with a wing span of 80 cm.

Control System

Since it is still illegal to operate a fully autonomous UAV within UK airspace, the aircraft was semi-autonomous using a GPS enabled flight controller with ability to take over the flight by the flick of a switch and fly the craft back manually. The radio transmission frequency was 2.4 Ghz.

The flight parameters were plotted on a laptops software and uploaded to the aircraft prior to the mission. During the flight the aircrafts position in relation to the take off point was being fed back to the ground station for the remote pilot to monitor and intervene if needed.

Payload

The Swinglet CAM 4 was using a compact 12 Megapixel digital camera wired directly to the flight controller to receive the necessary trigger commands.

Type, Quality and Communication of Outputs

The workflow output was a series of still 12MP images taken from approximately 300 feet above ground level (AGL) stitched together using software to produce a 2D ortho-mosaic, either as a GIF, TIFF or PDF file extension. The aircraft did not have any facility to receive and stream live video images. All data were stored on a SD card on board the aircraft. The data were not encrypted.

Support Team

The flight team included:

- 1 x BNUC's qualified fixed wing remote pilot

- 1 x Construction Engineer working for the client
- 1 x Post production individual to produce the workflow output

Safety Considerations

Flight were conducted in line with the company's operations manual for this aircraft, which include and not limited to:

- Pre-site survey report,
- On-Site Survey Report and risk assessment/method statement,
- Pre-flight aircraft checks
- Post-flight aircraft checks
- Ground signage
- Identification of emergency landing ground
- Communication with the nearest ATC if in restricted air space

Security Considerations

Data security was in line with SL requirements for operations outside the fence

Information Management

Data were stored on a third party computer during the post process stage. All data belong to the client and it is the client that owns the copy-write. Data analysis was performed by the client and used for project overviews by the construction team.

Incidents

While there was no CAA reportable incidents or aircraft damage, there was intermittent loss of data connection. This was not in connection with the radio communication for the avionics, but with connection to the telemetry data shunt back to the ground station that allows for the remote pilot to understand at all times where the aircraft is in relation to the uploaded flight plan.

Limitations

As this was an external flight, it had to comply with CAA regulations and while it would have been possible to have conducted the mission without the aircraft in site, it was conducted in visual line of site (VLOS) at all times.

Existing Learning From Experience

The challenges on the project were not technical, they were commercial as it took many months for a PO to be raised.

Nuclear
Decommissioning
Authority

University of Bristol X8 radiation mapping demonstration, Sellafield Ltd., 2014

Summary

An in-development UAV platform designed to record and map ionising-radiation in an external environment was demonstrated at the Sellafield site. Demonstration flights over two test areas were conducted, with the UAV flying in a set acquisition pattern above the sites, recording radiation data using a light-weight γ-ray detector, and correlating with location data from the on-board GPS system. Flights were successfully able to localise sources of radiation with minimal human dose risk.

Reason for use of UAV and degree of success

Demonstration flight of a UAV system able to detect and localise radiation doses. The system was able to spatially identify radiation sources found in two external sites on the Sellafield site. The demonstration of this technology at Sellafield allows the platform to be utilised in other areas (e.g. Japan)

Procurement route

The UAV was designed and constructed by the University of Bristol, who also flew the UAV on site.

Description of UAV(s)

The UAV was a purpose-built octo-copter in a X configuration, 1.2 m across, weighing ~7 kg. The UAV was capable of flight times of 30-35 minutes. The total payload capacity was ~5 kg, though a maximum payload mass of ~0.5 kg for the presented usage.

Control systems

Take-off and landing of the UAV was performed by pilot, controlling by a radio controller. Radiation mapping was undertaken by programmed flight-plan through pre-determined aerial waypoints using GPS signal.

Payload

The main sensor payload was a γ-ray spectrum scintillation detector (Kromek GR1). A miniature camera was also mounted on the UAV for piloting assistance. A laser rangefinder was also used to measure the height of the UAV above the ground.

Type, quality and communication of outputs

Location data (from the internal GPS sensor) and radiation data were captured during the flight. Data were acquired at 500 ms intervals. GPS data were captured to an accuracy of ±0.5 m. Height data were captured to an accuracy of ±5 cm.

Support team

One pilot. Unknown support team.

Safety considerations

Unknown.

Security considerations

Unknown

Information management

Data were vetted by Sellafield Ltd. and approved before dissemination (publication).

Incidents

None reported.

Limitations

Flight was undertaken within VLoS.

Existing learning from experience

The demonstration flight on the Sellafield site was used as relevant experience to demonstrate the system at other relevant nuclear locations (e.g. Fukushima, Japan).

Createc RISER indoor radiation mapping, Phase 1: Active demonstration, Sellafield Ltd., 2015

Summary

The RISER UAV system was successfully deployed in an indoor environment on the Sellafield site to assess its ability to collect internal LiDAR and radiation dose data simultaneously on a nuclear site. The system comprised a quad-copter UAV with LiDAR and γ-ray spectroscopy payloads, and was able to both internally map and record radiation doses during its flight. This testing state (Phase 1) was conducted with the UAV within VLoS of the operating team. The internal environment was successfully surveyed with decreased dose risk and decreased time required, compared to more traditional survey methods. Problems with the data connection between the UAV and the ground control station were encountered, which resulted in loss of radiological data, as well as an inability to pilot the UAV BVLoS.

Reason for use of UAV and degree of success

The use of a UAV system to remotely detect and map internal areas for radiological contamination would provide benefits in time, safety and cost to Sellafield Ltd. As such, a demonstration flight of an in-development UAV platform to simultaneously record the layout of an internal space, and record and map the radiation dose present within that space, was organised in order to both assist the development of the UAV system, and to assess its potential for eventual deployment on the Sellafield site. Although technical issues were identified during the test, the demonstration was a success both in that an internal area of the Sellafield site was successfully analysed by the UAV system, and that both Sellafield Ltd. and the Blue Bear Systems Research Ltd. and Createc Ltd. consortium gained valuable operating experience in the deployment of the RISER system on a nuclear site.

Procurement route

This was a demonstration UAV flight undertaken by Blue Bear Systems Research Ltd. and Createc Ltd., the UAV's developers, who provided the UAV system and pilot team.

Description of UAV(s)

The RISER UAV (Remote Intelligent Survey Equipment for Radiation) is a quadcopter system with in-built rotor guards, designed for use in internal environments. It was developed by Blue Bear Systems Research Ltd. and Createc Ltd., and weighs ~4.5 kg. The flight time was ~13 minutes per battery, with a maximum of ~20 minutes expected to be achievable.

Control systems

The UAV was operated by radio control by a pilot. The system was capable of operating BVLoS through a live camera feed which allows the pilot to control the UAV through FPV, though this control mode was not used in this demonstration (see Phase 2). The control system is maintained by two separate data-links for redundancy. The RISER UAV implements automated collision avoidance systems to assist when the UAV is controlled BVLoS.

Payload

The main sensor payloads of the UAV were a γ-ray spectrometer, and two LiDAR range-finders, one mounted to take horizontal data, one mounted to take vertical data.

Type, quality and communication of outputs

A point-cloud dataset was collected by the LiDAR payloads, with an accuracy of down to ±10 mm, or ±60 mm up to 30 m from the UAV. This was collected during the flight of the UAV.

A radiological spatial accuracy of ±25 cm was expected, and γ-ray spectra with sufficient resolution to identify ^{137}Cs were recorded.

The collected data were initially transmitted in real-time to the ground control station (a laptop computer), though later this was changed to allow the UAV to buffer the data connection in order to improve transmission reliability. Data were communicated through WiFi connection, though data connection issues were encountered (see Incidents).

Support team

In addition to the main pilot, a secondary support pilot was within view of the UAV during the flight, with the ability to take control of the UAV if required.

Safety considerations

Second UAV pilot was on standby to take control of UAV if required

Security considerations

Unknown

Information management

Unknown

Incidents

The initial plan for the demonstration flight had been to conduct two test flights, one within VLoS of the UAV, and the other BVLoS (i.e. with the pilot flying by FPV *via* the camera on the UAV). During the demonstration, however, problems with the data-link between the UAV and the pilot were observed, manifesting as latency in the image transmission to the pilot. As such it was decided that the BVLoS flight would not be undertaken at this stage.

During the flight, latency problems with the live data connection between the UAV and the ground control station resulted in a loss of radiation monitoring data through data corruption. This issue was resolved during the second flight by allowing the UAV to buffer the data before transmission. This, however, introduced a small delay in data acquisition.

Limitations

BVLoS flight was not able to be undertaken due to problems with the UAV data connection.

Existing learning from experience

Problems encountered with the data transmission system suggested that a WiFi connection was not a suitable method of communication between the UAV and the ground control station.

Commercial arrangements to engage companies for demonstration deployments were found to be inadequate to easily accommodate ‘zero value’ contracts.

Nuclear
Decommissioning
Authority

Createc RISER indoor radiation mapping, Phase 2: Beyond line of sight Pile 1 chimney, Sellafield Ltd., 2015

Summary

The RISER UAV system was successfully deployed in an indoor environment on the Sellafield site to assess its ability to collect internal LiDAR and radiation dose data simultaneously on a nuclear site. The system comprised a quad-copter UAV with LiDAR and γ-ray spectroscopy payloads, and was able to both internally map and record radiation doses during its flight. This testing state (Phase 2) was conducted with the UAV BVLoS, though the initial take-off and eventual landing of the UAV were conducted within VLoS. The internal environment was successfully surveyed with decreased dose risk and decreased time required, compared to more traditional survey methods.

Reason for use of UAV and degree of success

The use of a UAV system to remotely detect and map internal areas for radiological contamination would provide benefits in time, safety and cost to Sellafield Ltd. As such, a demonstration flight of an in-development UAV platform to simultaneously record the layout of an internal space, and record and map the radiation dose present within that space, was organised in order to both assist the development of the UAV system, and to assess its potential for eventual deployment on the Sellafield site. The demonstration was a success both in that an internal area of the Sellafield site was successfully analysed by the UAV system flying BVLoS, and that both Sellafield Ltd. and the Blue Bear Systems Research Ltd. and Createc Ltd. consortium gained valuable operating experience in the deployment of the RISER system on a nuclear site.

Procurement route

This was a demonstration UAV flight undertaken by Blue Bear Systems Research Ltd. and Createc Ltd., the UAV's developers, who provided the UAV system and pilot team.

Description of UAV(s)

The RISER UAV (Remote Intelligent Survey Equipment for Radiation) is a quadcopter system with in-built rotor guards, designed for use in internal environments. It was developed by Blue Bear Systems Research Ltd. and Createc Ltd., and weighs ~4.5 kg. The flight time was ~13 minutes per battery, with a maximum of ~20 minutes expected to be achievable.

Control systems

The UAV was operated by radio control by a pilot. The system was operating BVLoS through a live camera feed which allows the pilot to control the UAV through FPV, though the UAV was initially piloted into the demonstration area by a support pilot who was within VLoS of the UAV. The control system is maintained by two separate data-links for redundancy. The RISER UAV implements automated collision avoidance systems to assist when the UAV is controlled BVLoS.

Payload

The main sensor payloads of the UAV were a γ-ray spectrometer, and two LiDAR range-finders, one mounted to take horizontal data, one mounted to take vertical data.

Type, quality and communication of outputs

A point-cloud dataset was collected by the LiDAR payloads, with an accuracy of down to ±10 mm, or ±60 mm up to 30 m from the UAV. This was collected during the flight of the UAV.

A radiological spatial accuracy of ±25 cm was expected, and γ-ray spectra with sufficient resolution to identify ^{137}Cs were recorded.

The collected data were not displayed live at the ground control station for this flight, but were analysed at a later stage. Data from the UAV were communicated *via* WiFi to the ground control station via a transmitter relay which was positioned in proximity to the flight area.

Support team

In addition to the main pilot, a secondary support pilot was within view of the UAV during the flight, with the ability to take control of the UAV if required.

Safety considerations

The UAV was swabbed to monitor any contamination between battery exchanges. A second UAV pilot was on standby to take control of UAV if required.

Security considerations

Unknown

Information management

Unknown

Incidents

None reported.

Limitations

This was a demonstration flight to showcase the ability of the UAV to be operated BVLoS.

Existing learning from experience

The downdraught from the RISER UAV was sufficient to blow loose material around on the floor below. This should be taken into account when looking to deploy the UAV in areas of loose contamination.

During Health Physics screening the UAV was found to have picked up low levels of contamination. This was removed by surface cleaning (wiping) of the leading edges of the propellers and some of the internal surfaces.

Nuclear Decommissioning Authority

Photographic survey of Braystone beach and Calder Hall Turbine building, Sellafield Ltd., 2016

Summary

Use of an external UAV supplier (Furness Engineering and Technology Ltd., FETL) to conduct separate aerial surveys of Braystone beach (in proximity to Sellafield site), and of Calder Hall roof. A UAV was employed for technical benefits (ease of deployment, low cost compared to other methods), and to trial Sellafield Ltd.'s procedures for the use of a UAV outside and inside of the fence. Flights were successful, with actionable data gathered, and lessons learned for future deployments.

Reason for use of UAV and degree of success

The use of a UAV to conduct surveys of the Braystone beach area, and of the Calder Hall roof was motivated by two considerations. The first was that a UAV may allow easier access to areas of both locations than would be available with more traditional access routes. For Braystone beach, for example, surveying areas for erosion monitoring at low tide through traditional methods would require personnel to be working at the low tide mark for limited periods, with associated health and safety concerns. The second reason was to test the policies and procedures which Sellafield Ltd. had developed to allow the use of UAVs on site. The flights were considered a success, with useful data captured, and experiences gained in deploying UAVs externally around the Sellafield site.

Procurement route

The UAVs and pilots were supplied by an external supplier, FETL, who hold PfCO.

Description of UAV(s)

The DJI Inspire 2 is a 'professional' grade commercially available quadcopter. It is ~650 mm across, including propellers, and weights 3.4-4.2 kg, depending on payload. The main payload is a gimbal camera mounted underneath the UAV. A fixed, front-facing camera is also installed to allow a 'first person view' to the pilot. Flight time is ~25 minutes, with GPS positioning available. The landing legs are incorporated underneath the propeller mounts, and the two flight arms hinge above the main body of the UAV during flight to remove the landing legs from the camera FoV.

Control systems

The UAV was controlled by a single pilot, through a wireless control system.

Payload

The main payload of the UAV was a high quality digital camera, mounted on a gimble for 3-axis orientation.

Type, quality and communication of outputs

The exact model of the digital camera payload is unknown, but HD quality digital images were captured during the flight. Preview data were relayed back to the control station, with full quality data stored locally on the UAV.

After the flight, data from the Calder Hall roof were post-processed via photogrammetry to create a pseudo-3D model of the roof area, though it should be noted that no survey ground markers were used during the flight and that the model should not be considered ‘survey grade’.

Support team

Flight team consisted of a pilot and observer. Site marshals and additional observers were also utilised to make sure that flight area was clear of personnel and vehicles.

Safety considerations

Trial flights were conducted with a stepped risk approach. Braystone beach was chosen as a trial location as it was ‘outside the fence’ of the Sellafield site, but still within its restricted airspace. Calder Hall was then the next increment, as an area within the Sellafield site, but one designated to be a low risk.

Site communications were given about the UAV activity before it commenced, with opportunity for concerns to be raised. Personnel and vehicles were kept out of the flight area by marshals during the operation.

Security considerations

External suppliers (FETL) were vetted with appropriate clearance for work on a nuclear site.

Information management

All data were transferred to Sellafield Ltd. upon completion of the work.

Incidents

None reported.

Limitations

Visual inspections of external environments.

Existing learning from experience

Radio contact between the marshalling team and UAV operators was highlighted to be beneficial. More foot-traffic than originally expected was encountered during the flight, requiring active marsh ling to maintain a safe flight area.

JFNL photographic inspections of FGRP stack (external and internal) LAEMG Pipe bridges and site road bridge, Sellafield Ltd., 2017

Summary

External supplier (James Fisher Nuclear Ltd., JFNL) used to gather internal and external photography data on various site assets, to inform decommissioning plans and asset inspection tasks.

Reason for use of UAV and degree of success

UAV systems were used to gather photographic and video data of various assets around the Sellafield site, to inform decommissioning and asset management programmes. UAVs were deployed due to the difficulty in accessing particular survey areas (i.e. the FGRP stack) through traditional means. The data gathered by the inspections were able to inform the project engineers as to the state of the various assets surveyed.

Procurement route

The inspection services were provided by a 3rd party company (James Fisher Nuclear, in collaboration with WYG), who supplied the UAV systems and pilots.

Description of UAV(s)

Two different UAV systems were used for the inspections. An Intel Falcon 8 system was used for the external inspections. A Flyability Elios was used to perform the internal inspections.

The Falcon 8 is a professional grade V-shaped octocopter UAV. The eight propellers are arrayed in banks of four across two flight arms on either side of the main body. It is 1.2-2 kg, depending on payload, and is ~800 mm across. Its flight time is 16-26 minutes, depending on payload and flight conditions. It supports GPS tracking.

The Elios is a professional grade quadcopter UAV, designed to operate within enclosed spaces and indoor environments. It's key feature it the geodesic carbon fibre frame which protects the UAV inside, giving good collision tolerance. It is ~700 g, and the protective cage is ~400 mm. It has a ~10 minute flight time.

Control systems

Each system is controlled by a single pilot *via* radio controller.

The Falcon 8 controller is a single remote controller with integrated display, providing telemetry and live video feedback from the UAV. The UAV can be controlled manually, or with GPS assistance. Flight plans may be uploaded to the UAV prior to flight for survey or inspection requirements.

The Elios ground station is composed of a remote controller, a tablet and a purpose designed ground control application providing the pilot with live telemetry data, an SD live video stream captured by Elios and the information and controls needed to operate it efficiently and safely. In addition to having full control over the navigation of the drone, the pilot adjust can also adjust, in real time, settings of the camera head, such as exposure, lighting and pitch angle.

Payload

The payload for the Falcon 8 UAV was a digital camera, although the exact make and model is unknown.

The Elios is equipped with a low light capable, full HD camera, as well as an embedded uncooled FLIR camera core. The Elios also carries onboard lighting *via* 5 LED arrays.

Type, quality and communication of outputs

The camera model for the Falcon 8 is unknown. Available payloads can capture video and photo data between 20-42 MP. Full data are stored on the onboard SD card, and telemetry data (including live video feed) are transmitted to the controller.

The Elios HD camera captures photo and video data at a resolution of up to 1920 x 1080 at 30 frames per second. The embedded uncooled FLIR camera core has a resolution of 160 x 120 pixels, and can capture video at 9 frames per second. Full data are recorded directly to an SD card embedded in the UAV, and telemetry data (including live video feed) are transmitted to the controller.

Support team

One pilot, one observer, and site marshals

Safety considerations

Standard policies for UAV use on Sellafield site were followed. Personnel were kept out of operating area, and site communications were issued notifying employees of planned flight.

Security considerations

Unknown.

Information management

Data are owned by Sellafield Ltd.

Incidents

An incident of a heavy landing of the UAV was reported, causing damage to one of the struts. The cause is unknown.

Interference with GPS signals was observed when operating between certain buildings, expected to be effects of canyoning (i.e. buildings reducing line of sight between UAV and GPS satellites).

Limitations

Visual inspections.

Existing learning from experience

None reported.

Nuclear
Decommissioning
Authority

Internal inspection to support decommissioning of Primary Separation Plant, Sellafield Ltd., 2018

Summary

Internal deployment of UAV to assist with asset inspection, used to train Sellafield Ltd. staff on use of UAV systems for internal inspections.

Reason for use of UAV and degree of success

The underlying factor driving the use of remotely piloted unmanned aircraft systems (UAS technology) is the need for safer cost-effective solutions when needing to work in difficult to access spaces.

The business case proved that there was significant safety and cost savings to the project by implementing UAS technology and methodology. In fact, even when set against hiring in SQEP supply chain professionals through the preferred framework route and taking into account the initial capital cost of technology and training, the programme saved an estimated £150,000.00 over the life cycle of the project.

But this was no ordinary use case, the area that needed inspecting was the full height of a 60 m stack with a complete 'no man entry' exclusion zone in place, so by definition, being able to inspect a structure at height without having to enter the stack was a success in itself. The evidence gleaned from inside the structure allowed the programme schedule to be reduced along with the costs savings that resulted from this.

Further to the above, this approach to the problem has lasting benefits, as it now leaves individuals with knowledge, experience & skills that are transferable to other sectors and this is something that is difficult to quantify in terms of pounds and pence. The fact that the project has left a legacy of strength can only be a good thing and an example for other projects to follow.

There has already been interest from across the Sellafield Ltd. portfolio to utilise this safe, cost effective solution and avenues to deploy further afield are being followed with interest.

Procurement Route

The procurement route for this project was by direct award rather than *via* any framework, as there was a need to expedite the supply and training, if the project was to meet its milestones. As part of EneffTech UAV's reseller agreement with Flyability, they are the only reseller of this technology allowed to supply to the nuclear industry.

Description of UAV

The platform used to conduct the mission was a Flyability Elios Collision Tolerant Drone, that has a carbon fibre frame to protect the vital components, powertrain and propulsion system. The 400 mm (designed to fit through a standard man hole) protective frame is no ordinary one. It is decoupled on three axes from the inner frame - the drone - using a gimbal mechanism. This decoupling mechanism is what allows Elios to remain stable in the event of a collision.

Weighing in at only 700 g including battery and integrated payload, this is no heavy weight. Designed from a study of insect flight, the low inertia makes it the ideal tool for inspection in confined spaces.

Control System

Manually operated from a ground station using standard frequencies for the avionics as well as live digital downlink for beyond line of sight operation.

The Elios Ground station is composed of a remote controller, a tablet and a purpose designed ground control application providing the pilot with live telemetry data, and standard definition live video stream captured by Elios and the information and controls needed to operate it efficiently and safely. In addition to having full control over the navigation of the drone, the pilot adjust can also adjust, in real time, settings of the camera head, such as exposure, lighting and pitch angle.

Payload

The Elios is equipped with an excellent low light capable, full HD camera, capturing data at a resolution of up to 1920 x 1080 at 30 frames per second. In addition, the Elios features an embedded uncooled FLIR camera core with a resolution of 160 x 120 pixels at 9 frames per second.

The full HD camera offer a total fail of view of 215 degrees (130 horizontal) while the thermal camera offers a total field of view of 42 degrees (56 horizontal).

For inspecting in pitch dark environments the Elios carries onboard lighting. The intensity of the fully adjustable & directional 5 high efficiency LED arrays is enough to make the need for additional external lighting redundant.

Type, Quality and Communication of Outputs

Data are recorded directly to a micro SD card embedded on the aircraft. No post processing or specific software is required as the simple video files can be read on the ground station tablet or computer.

Using the Flyability Inspector Software, a review of the flight can be undertaken frame by frame along with the flight information recorded on the log SD card.

Points of interest (POIs) marked during the flight can also be recovered so as to only extract the still images of interest for the deployment. Recorded as well on the log SD card, is the video stream recorded with the thermal sensor. This is displayed as an overlay of the full HD video.

Support Team

The support team consisted of one SC cleared SQEP Elios pilot and instructor combined. The SL team ensured all arrangements were in place to conduct the training successfully and perform the first inspection using their own team.

Safety Considerations

While the CAA do not require UAS pilots to undergo the same level of training and process planning, the flights were conducted in line with the companies SLP and followed the rigorous planning process as external flight operations which include and not limited to:

- Pre-site survey report,
- On-Site Survey Report and risk assessment/method statement,
- Pre-flight aircraft checks
- Post-flight aircraft checks

- Ground signage
- Identification of emergency landing ground
- Communication with the site shift manager and local stakeholders

Security Considerations

Data security was in line with SL processes set out by the site Information Security team for operations inside the fence. The specifically developed processes for this new emergent technology is thorough.

With a number of iterations, a balance between risk appetite and usability was agreed. However, there is further scope to improve these protocols to simplify them for the pilot / UAS coordinator, ensuring the robustness of the management control processes are easily maintained.

The system was chosen as it was known NOT to have any "unauthorised data leak issues" that has resulted in the American Military removing some drone manufacturers equipment from their operations. The system has no GPS capability by design, therefore no metadata is stored on any imagery to pinpoint an internal structure surveyed by the Elios UAV.

Information Management

All data captured from the stack inspection remained the property of SL and at no time did this information leave the site boundaries, being firstly stored on micro SD card then transferred to a verified "clean" SL IT network system.

Incidents

While there were no incidents during the first SL team inspection of the stack, the aircraft did suffer from some minor damage during the pilot training programme. But this was repaired on site before the training was completed.

Limitations

As this was an internal building flight and by the nature of the task was performed beyond visual line of site (BVLoS). As this was a training session, the main limitations arose due to the (expected) inexperience of the trainee pilots.

The aircraft chosen can be used externally if the wind speeds are very light, but the aircraft is designed primarily for internal building inspection and it is the intention of the client to only use it for internal environments.

However, the initial primary function of this Elios UAS is to inspect inside of a stack. This stack as a natural 'stack draw' which generates air movement within the structure. The limitations of the UAS is that with high winds on the external of the stack, the draw is increased and the stability of the UAS is jeopardised. In an early flight the pilots had difficulty manoeuvring the UAS back out of the stack base against the air flow entering it.

Existing Learning From Experience

There was a significant delay in raising a PO for the work, which may need to be considered if one of the intended benefits of UAV deployment on site is its swift deployment.

Nuclear Decommissioning Authority

Innovation Lab graduate task: drone tooling (roof repair, manipulator, egg pricking), Sellafield Ltd., 2017

Summary

Graduate project to develop various effector payloads for use around Sellafield site. Payloads were designed, constructed, and installed on to a test UAV. Initial proof-of concept flights were undertaken to assess viability.

Reason for use of UAV and degree of success

The objective behind this project was to explore the feasibility and potential of UAV based tooling in support of infrastructure projects and tasks. To date most if not all UAV based technology is passive, but what if it could be active? This was the objective of the research.

Sellafield Innovation Centre were tasked and funded by their internal client (infrastructure) to come up with solutions for a number of challenges they are currently dealing with, they were as follows:

- Ecology Management (Issues surrounding the growing seagull population)
- Temporary Repair of damaged buildings above ground level
- Inspection of flat roofs
- Removal of debris from guttering and roof areas

A team of graduates were formed and given five weeks to come back with some working solutions, but as none of the team had any piloting experience, they needed a test pilot to ensure the project had the best possibility of success.

Success of the project was documented with respect to the fact that all five tooling solutions were developed to a very early technology readiness level, with at least one or two having potential commercial application.

Procurement Route

The procurement route for this project was by one-time vendor route *via* the innovation centre's own budget. Due the nature of the centres work, it was extremely important that they received value for money and could get things actioned within days if not hours of issuing a purchase request.

Description of UAV

The platform used as a donor vehicle was a used generic hexacopter (Tarot 680 Pro) complete with all the electronics needed for flight. The vehicle was built from commercially off the shelf components and assembled in a way to accept the tooling and robotic arm.

Control System

Manually operated from a ground station using standard industry accepted frequency for the avionics as well as live standard frequency digital downlink for the pilot and payload operator. Flown visual line of sight.

Due to budget constraints the flight controller used was a very early version ArduPilot APM 2.6 open source unit, supplied by 3D robotics which had full waypoint mission capability *via* the radio telemetry system and mission planner software.

The very early flights were conducted at a test facility at Kirkbride Airfield, but this was moved to a room inside the GEN2 facility at Lillyhall due to poor weather and a tight project completion deadline.

All flights were performed at low altitude (2 to 3 meters) above ground level (AGL).

Payload

The aircraft was equipped with a 160 x 120 thermal camera as well as a GoPro Hero 3 fitted to a 3 axis dampened gimbal to capture HD video and stills.

Other payloads tested were:

- Aerosol Can Spray Head - 3D Printed
- Egg Pricker
- Robotic Arm with End-effectors

Type, Quality and Communication of Outputs

Data were recorded directly to micro SD card embedded on the aircraft. No post processing or specific software was used as video data from the GoPro and thermal cameras were for test purposes only.

While the output footage was full 4K or 1080p video, the aim of the project was the suitability of UAV technology to interact with the environment around it and do tasks that would normally be done using conventional methods.

Support Team

Single pilot.

Safety Considerations

While every precaution was taken to protect individuals from harm, this was a flight test, so by definition took the aircraft beyond its design limits to document the outcome. All tests were conducted in controlled conditions (internally, restricted access during flight).

Security Considerations

As this was early research, security considerations were not taken into account, as it was proof of concept. Should the project have developed, then security considerations would have played a significant part of the development process.

Information Management

All data captured were stored on micro SD card on the payload, no other files were saved during the demonstrations.

Incidents

Despite the nature of the tests, incidents were minor, with some damage to propellers when landing after testing the pendulum effect that would occur should a robotic arm loose power. Some software issues were encountered from a corrupted flight controller not receiving packages of information as programmed, which led to a system failure.

Limitations

Lift capability for effector payload prototypes was constrained due to the UAV's size. Initial proof-of-concept demonstrations.

Existing Learning From Experience

The commercial process to organise this work was the same as used for much larger projects, and found to be not entirely suitable.

The lesson learned from this exercise was that there are many tasks that could be undertaken using drone-based technology that are currently not being considered and that if a little more research and investment money in this particular area could be arranged, this would result in large operational savings and a reduction of risk when having to work at height or difficult to reach areas. Especially when compared to current conventional methods.

There is potential for technical resources within SLC's to benefit the SME community, if there was a commercial mechanism to work together closer.

There is an opportunity to use the Sellafield site as a proving ground for new and innovative emerging technology.

LINC Blimp test flight, Sellafield Ltd., 2018

Summary

Development of a lighter than air UAV system (helium blimp) designed to operate in areas of radiological contamination with minimal disturbance. Initial test flights proved successful.

Reason for use of UAV and degree of success

This research study was driven by a number of factors, but primarily it was to prove that a lighter than air inspection vehicle fitted with a HD camera viable to gather inspection and swab data from a height without disturbing contaminated particles which may be present in the environment. The conventional method is suited manual intervention and the use of scaffolding.

Unlike rotary wing vehicles, a helium filled dirigible needs very little to no movement of air to climb, as the helium is producing most of the lift, with motors used for flight control. The high volume to carrying capacity ratio of such a vehicle, however (a 2.5 meter dirigible to lift a maximum capacity of 200 g), raises questions as to the practicality of such a design.

Therefore, a feasibility study was undertaken to capture the limitations and benefits including what payload would be best suited for the given objective.

Based on the trials and none destructive tests, this study was judged as a success in that it answered all the concerns and demonstrated quite clearly, in scenario conditions, that the concept was sound. However, it was clear that to have finer control over the aircraft some development of the platform would be required.

Procurement Route

This was a tender submission through the Sellafield LINC procurement route, with contract award to the most suitable tender submission.

Description of UAV

The platform used was a helium filled dirigible (Blimp) of approximately 2 meters in length with a volume of 1.5 m^3, complete with commercial off the shelf components and assembled in a way to accept a top mounted payload.

Control System

Manually operated from a ground station using 2.4 GHz frequency for the avionics. Flown visual line of sight with no computer aided flight. Main power was supplied by a 3S (3 cell) 11.1 V Lithium Polymer (LiPo) battery, with a discharge rate of 30C.

Lift, decent, forward and revers were produced by a brushless ducted fan unit, while the yaw (Left and Right) was produced by a brushed motor using a standard propeller.

All flights were performed indoors.

Payload

The aircraft was equipped with a GoPro Hero 3 fitted to a top mounted gimbal angled at 45 degrees to capture HD video and stills. Also fitted was a 360 degree camera to capture as much data as possible.

Type, Quality and Communication of Outputs

The output of the 360 camera could viewed from a tablet installed with suitable software. All data were captured on SD card, while some image data were stored on the tablet for analysis later.

Both HD video and stills were captured and compared against the sample given with the tender to make sure the objective had been achieved.

While it was not part of the work scope, modifications to take swab samples were judged to be viable.

Support Team

EneffTech UAV Ltd. and ROVTech Solutions Ltd worked together to deliver the project and document the results into a report.

Safety Considerations

As the vehicle had very little inertia, it posed minimal risk

As this was early research, security considerations were not taken into account, as it was proof of concept. Should the project have developed, then security considerations would have played a significant part of the development process.

Information Management

All data captured were stored on micro SD card on the payload, no other files were saved during the demonstrations.

Incidents

There were no incidents.

Limitations

The limitations revolve around lift capability, and the physical size of the aircraft when navigating around structures. Due to the low power propulsion system, this aircraft was limited to internal use only. Also there is no lateral manoeuvrability.

Existing Learning From Experience

This type of tooling has the potential to be very useful where Alpha contamination is an issue. Further development would be encouraged.

Nuclear Decommissioning Authority

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