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UNMANNED COMBAT AIR VEHICLES: OPPORTUNITIES FOR THE GUIDED WEAPONS INDUSTRY?

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On 6 June 2008, the UK Ministry of Defence announced that, for the first time, an RAF unmanned airborne drone had fired weapons on operations [1]. This watershed engagement was conducted remotely from the Nevada desert in support of coalition forces in Afghanistan and demonstrates that the UK has now joined an elite group of countries with operational unmanned air combat capabilities. The proliferation of Unmanned Combat Air Vehicles (UCAVs) is increasing, and supporters of the concept believe that these systems represent the future of air warfare.

The primary opportunities to the guided weapons industry are provided by integrating existing weapons onto UCAVs for the prosecution of ground targets. In the future there will be a broad range of UCAV systems, requiring a number of different weapon capabilities. UCAVs will use an array of novel weapon technologies, including micro-munitions, Directed Energy Weapons and weapons for air-to-air combat.

There are also technologies from guided weapons systems that could be applicable to the design of UCAV platforms. Traditionally, the development of UCAVs has been the domain of aerospace companies. However, the core technology issues are moving away from the airframe and greater emphasis is being placed on the on-board systems, such as the mission management and control systems, and the communication infrastructure. In these and other areas, technologies and expertise from cruise missile and loitering munitions systems can be transferred to UCAV systems.

Before analysing the opportunities that the UCAV market presents, it is necessary to discuss the UCAV concept and establish the potential future roles and capabilities of these systems.

The UCAV Concept

The concept of a UCAV is mature: an aircraft without an on-board human pilot which is able to attack targets and is recoverable and reusable. Current systems tend to be remotely ‘piloted’ by a ground controller, who is then also responsible for conducting any armed engagements. However, future concepts focus on UCAVs that can operate with higher degrees of autonomy, conducting missions with little controller influence following the input of mission information. The weapons employed from a UCAV are generally conventional air-to-ground guided munitions. In the future, micro-munitions, Directed Energy Weapons and weapons for air-to-air combat could be used from UCAVs.

Advantages of UCAVs

UCAVs have many advantages and provide significant operational benefits. It is a common argument that unmanned aircraft are better suited to ‘4D’ tasks: the dull, dirty, dangerous and deep. The dull aspect refers repetitive missions or missions that require persistence, and so are better suited to autonomous systems than humans. ‘Dirty’ refers to environments in which there are nuclear, biological and chemical threats. ‘Dangerous’ tasks are those in which there is a high risk to the aircraft and aircrew. ‘Deep’ tasks are those that are beyond the range of current manned aircraft.

UCAVs provide highly flexible operational capabilities and so can be used in a range of different roles. There are a number of types of UCAVs, with quite different characteristics, ranging from low-speed armed unmanned air vehicles (UAVs) whose primary role is intelligence gathering, to high speed, stealthy and agile strike UCAVs. It is possible, however, to make some general comments regarding roles in which UCAVs are suitable. High endurance means that they are also suitable for roles in which long-range or extended loitering capabilities are required. Systems that are relatively low cost and are perceived to be expendable are able to operate in high-risk, attritional environments. In general, the small and precise nature of their effects means that they can operate in complex target environments. The performance advantages of UCAVs are explained in more detail in Appendix A.

UCAVs have the potential to be more cost-effective than manned aircraft. In general, they are smaller, simpler aircraft (provided by new design freedoms), which reduces the design and manufacture costs. In addition, the training, operation and support costs for a UCAV are predicted to be lower than manned aircraft. A more detailed cost analysis of the different types of UCAV is also provided in Appendix A.

Challenges to UCAVs

Currently there are some significant issues associated with unmanned air vehicles. The main challenges are summarised by Air Chief Marshal Burridge, Commander-in-Chief Strike Command between 2003 and 2006:[2]

1. Interoperability of systems
2. Vulnerability
3. Limited capacity to address a wide area
4. Insatiable demand for bandwidth
5. Inability to deal with ambiguity in the same way as manned aircraft.

In the case of a combat UAV, the added complication of conducting engagements presents further challenges.

These issues must be overcome before UCAVs can be regarded as a universal replacement for manned aircraft. Therefore, for the foreseeable future, it is likely that unmanned aircraft will be used to complement the capabilities of manned aircraft. The challenges and disadvantages associated with UCAVs are expanded upon in more detail in Appendix B.

Proliferation of UCAVs

The first serious UCAV experiments were carried out in the 1970s, when the US Air Force conducted a series of remote-controlled strikes against simulated air-defence sites. However, these projects were constrained by the contemporary limits of computing power and significant command and control difficulties. In particular, communication links between the controller and the UCAV were extremely vulnerable to jamming and spoofing, and the required target accuracy was difficult to achieve due to navigation errors. Following two decades of technological advances in computer processor speeds and the robustness of communications, the UCAV concept was revived in the late 1990s.

Today, there are a small number of nations fielding operational UCAVs. Two prominent examples are produced in the United States by General Atomics Aeronautical Systems: the MQ-1B Predator is a ground attack UCAV armed with Hellfire missiles and the MQ-9 Reaper (formerly known as RQ-9 Predator B) is a hunter-killer UCAV that carries a payload consisting of a combination of Hellfire missiles, Laser Guided Bombs and Joint Direct Attack Munitions (JDAMs).

An MQ-1B Predator airborne in support of Operation Iraqi Freedom. *Photo courtesy of the Department of Defense*.

Both of these UCAVs have been used successfully by the US Air Force in the current conflicts in Afghanistan and Iraq [3, 4]. The UK has also recently procured three MQ-9 Reapers, which are being used in an armed capacity on current operations.[1] The first instance of an RAF Reaper firing its weapons occurred in June 2008, in support of coalition forces in Afghanistan [1]. Both the US and the UK aircraft are remotely controlled by 'pilots' located at the Creech Air Force Base, Nevada, more than 7,000 miles from the battlefield.

Several of the world's leading countries are presently undertaking advanced UCAV development or demonstrator projects, including the United States, Russia, China and several European nations. Whilst the UK's initial involvement in UCAV development has been modest, the UK Ministry of Defence and UK industry (led by BAE Systems) have now embarked upon a £124 million UCAV demonstrator programme, called Taranis [6]. The project, running from 2007 to 2010, aims to develop a future unmanned air combat military capability for the UK.

Types of UCAV Systems

The UCAV concept covers a wide range of systems with many different characteristics. For the purpose of this report, it is useful to distinguish between different systems by identifying a number of UCAV types. The Final Report of the NATO SCI-124 Task Group[2] identifies a range of UAV assumptions and defines six classes of UAVs [7]. Developing these ideas, it is possible to identify three types of UCAV:

1. Armed Intelligence, Surveillance and Reconnaissance (ISR) UAVs
2. Large, advanced, stealthy UCAVs
3. Small, agile, expendable UCAVs.

Identifying these three types of UCAV system provides a framework around which opportunities to the guided weapons industry can be analysed.

Armed ISR UAVs

Characteristics

Armed Intelligence, Surveillance and Reconnaissance (ISR) unmanned air vehicles are the first type of UCAV. These UCAVs are primarily used in ISR roles, but are armed to provide lethal effects if required. The primary characteristic of these UCAVs is persistence. They operate at medium or high altitudes, and are low speed and long endurance systems. They are unlikely to operate in extremely high risk environments due to their relatively high radar signature, low speed and low agility. Examples of this type of UCAV are the MQ-1B Predator and MQ-9 Reaper.

Roles and Missions

Air Chief Marshal Burridge underlined the role of armed ISR UAVs when describing the use of MQ-1B Predators in Iraq: 'the Predator had the ability to release small, relatively inexpensive missiles close to their targets to ensure accuracy, while flying in high threat areas where less manoeuvrable and larger aircraft were not the delivery platform of choice' [8].

Armed ISR UAVs are most suitable for the attack of mobile, time-sensitive, ground targets. Examples of time-sensitive targets may be enemy leadership personnel in an urban environment or mobile air defence assets. These missions require rapid target acquisition, identification and engagement. High accuracy is also essential to minimise collateral damage. For time-sensitive targets, the time from detection to strike will need to be extremely short; the platform will need to be close-in and possibly even over the target area. This will most commonly occur with platforms that are able to loiter and search above potential target areas.

With their high endurance and ability to loiter, these UCAVs are also able to provide protection to ground forces on the front line. The command and control of the UCAV would have to be flexible, allowing ground troops to request engagements as they require. This role is most suitable for UCAVs because of their long endurance and persistence capabilities.

Armed ISR platforms may also have maritime applications. UAVs are already used in ISR roles for escort operations, sea-lane and convoy protection and the protection of high-value and secure installations. In the future, it is possible that these systems could also prosecute maritime targets.

In addition to these examples of possible missions, there are several secondary or indirect roles in which the presence of these UCAVs may provide operational benefits without firing its weapons. For example, the presence of an airborne UCAV may act as deterrent, protecting assets, such as convoys, from attack without the need to use its weapons.

Large, Advanced, Stealthy UCAVs

Characteristics

Large, advanced, stealthy UCAVs are a second type of UCAV. These are highly sophisticated systems which are

[1] One of the RAF Reapers was destroyed following a crash on operations in Afghanistan on 9 April 2008 [5]. This leaves two of the three Reapers procured by the UK remaining in service.

[2] The role of NATO Systems Concepts and Integrations (SCI) panels is to advance knowledge related to advanced systems, concepts, integration, engineering techniques and technologies. NATO SCI-124 is concerned with architectures for the integration of manned and unmanned aerial vehicles.

An Armed ISR UAV: General Atomics Aeronautical Systems MQ-9 Reaper. *Photo courtesy DoD*.

A Large, Advanced, Stealthy UCAV: BAE Systems Taranis Concept. *Photo courtesy BAE Systems*.

A Small, Agile, Expendable UCAV: Lockheed Martin Minion Concept. *Photo courtesy Lockheed Martin*.

designed to be deep penetrating and stealthy strike aircraft. Typically these aircraft will be similar in size to existing fighter aircraft. In addition, they will be highly agile and supersonic, but with limited persistence. Carrier-based advanced UCAVs of this type have also been proposed in the US.

A number of large, advanced, stealthy UCAV are under development as technology demonstrator programmes, but operational systems are unlikely in the short-term. The Examples of this type of system include the UK Taranis demonstrator programme and the (now terminated) US Joint Unmanned Combat Air Systems (J-UCAS) programme. In the future, these systems could be fighter aircraft, performing air-to-air combat tasks in order to gain control of the airspace.

Roles and Missions

This type of UCAV can be used to perform long-range bombing campaigns against fixed ground targets. In this role, the UCAV may be used as a cost-effective alternative to piloted bombers. To conduct missions, the UCAV can follow predefined long-range flight paths, planned to avoid air defence assets. It can also be programmed with target identification and threat evaluation algorithms to alter this flight path if any unexpected threat is detected. If the UCAV is able to approach at close-range, low-cost bombs or guided munitions could then be deployed against ground targets. In highly attritional environments, advanced UCAVs may need to stand-off to ensure survivability and so will require more sophisticated weaponry.

A second class of mission is the suppression or destruction of air defence assets. These missions are slightly different from specialist bombing campaigns because they require the UCAV to search for targets and then acquire and engage once they are detected. While searching for air defence targets, the UCAV will be operating in an extremely risky environment so stealth and agility are essential capabilities.

A carrier-based version of this type of UCAV could be used to increase naval reach, conducting sea-based surveillance, naval strike and the suppression of enemy air defence missions.

In the long-term, this type of UCAV could be used to gain control of the airspace. These systems will be operating in very hostile environments in the quest for Air Superiority and Air Supremacy[3]. They would be required to conduct air-to-air engagements from long-range and also at close quarters. In this role, the UCAV is exploiting potential performance advantages, such as manoeuvrability, over manned aircraft. The absence of a pilot eliminates the risks to aircrew, such as injury, capture and loss of life in this role.

Small, Agile, Expendable UCAVs

Characteristics

Small, agile expendable UCAVs, with airframes similar to large, long-range cruise missiles, are potentially a third type of UCAV. They would be medium speed and agile and would be able to operate at low altitude, even executing terrain-following routes. They would be much smaller than other UCAVs, and so hard to detect and, unlike a cruise missile, they would be reusable. If such a system could be developed at low-cost, they could operate in extremely hostile environments as they would be expendable. Although no UCAV of this type has been developed into an operational system, this may present the optimum trade-off between cost, performance and expendability. An example of this type of system is Lockheed Martin's Minion concept [9]. The proposed system was a cruise missile-like, air-launched, unmanned aircraft, which was able to carry a payload of four precision-guided small diameter bombs or, as an alternative, an electronic attack payload. Engagements would be controlled from the launch aircraft, before the Minion returns to forward operating base, landing using its own retractable landing gear. The aircraft was estimated to cost substantially less than a Joint Air-to-Surface Standoff Missile (JASSM).

Roles and Missions

Small, agile, expendable UCAVs would be suitable for penetrating air defence systems and could deliver small weapons from close-range against an array of ground targets. This system could provide a broad spectrum of operational capabilities, including specialist bombing missions against fixed ground targets, the suppression and destruction of enemy air defence and the attack of time-sensitive and mobile ground targets. In the future, very advanced systems also could be used for air-to-air engagements to gain control of the airspace.

The UCAV Market

The UCAV market is growing both in the UK and across the world. Current acquisition programmes have focused on armed ISR UAVs, which are now part of the UK and US air inventories. In addition, many nations are funding the development of large advanced stealthy UCAVs in the form of technology demonstrator programmes, but

[3] The NATO Glossary of Terms and Definitions [10] defines Air Superiority and Air Supremacy as follows:

'Air Superiority': That degree of dominance in the air battle of one force over another which permits the conduct of operations by the former and its related land, sea and air forces at a given time and place without prohibitive interference by the opposing force.

'Air Supremacy': That degree of air superiority wherein the opposing air force is incapable of effective interference.

development of operational systems of this type is still some way off. A number of small, agile expendable UCAV concepts have also been proposed by industry.

The significant investment by the world's leading nations demonstrates a commitment to UCAV technologies and their future use. As a result, UCAVs provide a new growth market, which the guided weapons industry should explore for business opportunities. However, the UCAV market is constrained as a result of legal issues and voluntary agreements to restrict export opportunities.

Armed ISR UAV Programmes

The UK Ministry of Defence is purchasing armed ISR UAVs as an urgent operational requirement. So far, three RQ-9 Reapers have been procured by the UK Ministry of Defence and, in December 2007, the UK Government requested the possible procurement of a further ten RQ-9 Reaper UCAVs from the US [11]. The total value of the contract, which includes the aircraft as well as the associated equipment and services, is estimated to be US$1.071 billion. The UK request for further UCAVs is to provide the ability to defend deployed troops, perform regional security tasks and allow greater interoperability with US. It demonstrates intent for significant future UK investment in UCAVs.

The US Department of Defense (DoD) *Unmanned Aircraft Systems Roadmap 2005-2030* [12] details the future US procurement plans for the two main armed ISR UAVs currently operational: the MQ-1B Predator and the MQ-9 Reaper. In total, it is predicted that 200 Predator UAVs, which will be a mix of armed and unarmed variants, and 66 MQ-9 Reapers will enter the inventory of the US armed forces. These inventory numbers suggest that UCAVs will form a key element of US air power in the future.

Large, Advanced, Stealthy UCAV Programmes

The UK is also investing in research and development for advanced UCAV technologies. The Taranis technology demonstrator project, led by BAE Systems, will bring together a number of UCAV technologies, capabilities and systems at a cost of £124 million [6]. The Taranis demonstrator will be a long-range attack aircraft, which will be stealthy, fast, agile and highly autonomous. It will be able to attack a number of targets as well as defend itself against enemy aircraft. A similar technology demonstrator programme is being undertaken by a consortium of major European nations, including France, Sweden, Italy, Spain, Greece and Switzerland. This European project, named nEUROn, is led by Dassault Aviation.

So far, funding of €535 million has been secured to develop and test a highly stealthy UCAV, with the first flight trials scheduled for 2011 [13]. The project signifies a commitment by major European nations to advanced UCAV technologies and their potential operational use.

The US flagship advanced UCAV procurement programme was the Joint Unmanned Combat Air Systems (J-UCAS) programme. The programme was a joint US Air Force and US Navy procurement, which consisted of two separate unmanned vehicles: the Boeing X-45 and the Northrop Grumman X-47. Both of these aircraft were advanced deep penetrating stealthy strike aircraft. The US DoD *Unmanned Aircraft Systems Roadmap 2005-2030* outlined a six-year spending profile for the project, totalling US$4.7 billion [12]. However, the 2006 Quadrennial Defense Review stated a policy to 'restructure the Joint Unmanned Combat Air System (J-UCAS) program and develop an unmanned longer-range carrier-based aircraft capable of being air-refuelled to provide greater standoff capability, to expand payload and launch options, and to increase naval reach and persistence' [14]. Whereas the J-UCAS was designed to pave the way for manned aircraft by destroying enemy air defences, the new project focuses on targeting the enemy directly, flying extremely long-range bombing campaigns. The US is currently conducting feasibility studies into the unmanned long-range bomber.

Small, Agile, Expendable UCAV Programmes

The development of small, agile, expendable UCAVs has not been as widespread as armed ISR UAVs and large, advanced, stealthy UCAVs. However, the boundaries between cruise missiles and UAVs are blurring, and a number of hybrid systems are being developed. Typically, this type of system will have a long-range, and will be able to loiter above potential target areas. They will carry a payload of small conventional munitions or, in the future, micro-munitions.

Lockheed Martin is pioneering this concept and in recent times has unveiled two notable projects for small, expendable UAV systems that can engage targets. The Minion concept was for an unmanned aircraft that looked like a cruise missile, but housed an internal payload of four precision-guided small diameter bombs. The Minion system was designed for low cost, resulting in an estimated cost that would have been substantially cheaper than the Joint Air-to-Surface Standoff Missile (JASSM) [9]. A second Lockheed Martin project is the Surveilling Miniature Attack Cruise Missile (SMACM), which is currently under development. It is described as a 'long range, high endurance, expendable, unmanned air vehicle (UAV) that can be used in a reconnaissance role or in an armed version to attack moving or stationary targets' [15].

Most development and demonstrator projects of this type of UCAV are privately funded by industry. However, industry investment in these projects demonstrate that medium-term, these systems may form an important component of future air power.

Army and Navy Markets

The UCAV market is not only restricted to the Air Force community. Both the US Army and the US Navy have been exploring the capabilities provided by UCAVs.

nEUROn concept. *Photo courtesy Dassault Aviation*.

Boeing X-45A on a Test Flight. *Photo courtesy US DARPA*.

Northrop Grumman X-47A on a Test Flight. *Photo courtesy US DARPA*.

The US Army is funding the development of the General Atomics MQ-1C Warrior. The MQ-1C Warrior is based on the MQ-1B Predator and will provide US Army with a long-endurance, persistent ISR and tactical strike capability. General Atomics have been awarded a $214 million contract for system development and demonstration. The US Army intends to procure 132 Warrior UCAVs, with an expected total program cost of US$1 billion. The aircraft is expected to become operational in 2009 [16].

The US Navy did not commit to practical UCAV efforts until 2000, with the inception of the J-UCAS programme. The development of a carrier-based unmanned strike aircraft is now continuing as part of the US Navy's UCAS-D programme. UCAVs may have maritime applications in the future, conducting missions that protect and defend the seas.

Legal Issues and Constraints to the UCAV Market

There are a number of legal issues associated with UCAVs that may constrain the development of UCAV systems and limit the potential export market.

The first legal issue arises from limitations that are placed on the types of weapons systems that can be employed by military forces. The 'Principle for Humanity or Unnecessary Suffering' defines limits on the types of weapons that can be employed by military forces. In short, it states that weapons systems should not cause undue human suffering and places agreed limits on weapon characteristics, such as range and explosive power. Of particular relevance to the use of UCAVs is the 1988 Intermediate-range Nuclear Force (INF) Treaty[4], agreed between the United States and the Soviet Union. Although the UK is not bound by the INF Treaty, it is current policy to adhere to its principles. The INF Treaty prohibits the testing, production and launch of nuclear and conventional ground-launched cruise missiles with ranges of between 500 and 5,500 km. The debate hinges on whether UCAVs are classified as cruise missiles. The INF Treaty defines a cruise missile as an 'unmanned, self-propelled vehicle that sustains flight through the use of aerodynamic lift over most of its flight path … that is a weapon-delivery vehicle' [17]. Many critics believe that UCAVs conform to this definition, and so are outlawed by the INF Treaty.

A second legal point of note regards the Missile Technology and Control Regime (MTCR). The MTCR is an informal and voluntary agreement between 34 countries (including the UK, US and many other major nations), which 'restricts the proliferation of missiles, complete rocket systems, unmanned air vehicles, and related technology for those systems capable of carrying a 500 kilogram payload at least 300 kilometres, as well as systems intended for the delivery of weapons of mass destruction' [18]. UCAVs are Category I items and so are under strict export controls. The MTCR agreement states that there is a 'strong presumption' that the export of Category I equipment outside of the MTCR community will be denied. The export market for UCAVs is therefore constrained, which adds risk to any development programme.

There are a number of ethical and additional legal issues associated with the use of UCAVs and other unmanned or autonomous weapon systems. Most of these issues are concerned with the need for legal accountability for engagements under the Laws of Armed Conflict. As a result, it is likely that a 'man-in-loop' will be retained in all UCAV systems to authorise any engagements. These ideas are expanded upon in Appendix C.

UCAV Weapon Technologies

The critical function of a UCAV is the prosecution of targets, and this area presents the primary opportunities to the guided weapons industry. The applicable weapon technologies depend on the type of UCAV system and the role it will be performing. The current opportunities focus on arming UCAVs with conventional guided missiles and jamming systems. In the future, the employment of micro-munitions, E-bombs and Directed Energy Weapons from UCAVs will provide further opportunities to the guided weapons industry.

The opportunities can be categorised as either short-term, medium-term or long-term. Short-term opportunities are those that exist within the next 5 years. Medium-term refers to 5 to 10 years from now. Long-term refers to those opportunities that may occur after 10 years.

Short-Term Opportunities

The current opportunities are provided by arming ISR UAVs with existing weapon technologies. Applicable technologies for these systems are conventional air-to-ground cruise missile and jamming systems. The other types of UCAVs are relatively immature and are still under development, and so the related opportunities will be confined to the medium and long terms.

Conventional Air-to-Ground Cruise Missiles

Armed ISR UAVs will be operating in relatively benign environments in which air superiority conditions have been achieved. Therefore, they will be able to approach targets at close-range and so will employ low-cost and simple guided munitions. The payload capacity of a current armed ISR UAVs is much lower than manned aircraft.

Suitable conventional weapons for armed ISR UAVs should therefore be small, lightweight and precise in

[4] The INF Treaty is formally titled 'The Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Elimination of Their Intermediate-Range and Shorter-Range Missiles.'

delivery. Today, Hellfire missiles, Laser Guided Bombs and Joint Direct Attack Munitions (JDAMs) have all been successfully integrated onto the unmanned air platforms used by the RAF and the US Air Force. The MQ-1B is the armed configuration of the General Atomics Predator UAV, with two Lockheed Martin AGM-114 Hellfire missiles [19]. The larger MQ-9 Reaper is a medium-to-high altitude, long endurance UCAV, with its primary mission as a persistent hunter-killer. It has six wing stations for external carriage of payloads, and its armament can include a combination of Lockheed Martin's AGM-114 Hellfire missiles, Raytheon's GBU-12 Paveway II Laser Guided Bombs and Boeing's GBU-38 Joint Direct Attack Munitions [20].

Therefore, the primary short-term opportunities are provided by modifying and enhancing existing small air-to-ground conventional cruise missile and integrating of these weapons onto armed ISR UAV platforms.

Jamming Systems

The advent of small, lower-power jamming systems has provided the potential for UCAV-based airborne electronic attack capabilities, which could be used to suppress radar and communication systems. The power requirements for a UCAV-mounted system are significantly lower than those on piloted aircraft as a UCAV can operate close-in to targets. This has driven-down the size, weight and cost of jamming units.

UAV-based jamming systems are operational today. The US Hunter joint tactical unmanned aerial system is an example of an operational UAV that can conduct electronic attack missions. The Hunter has carried electronic countermeasures payloads, including a communications jammer and a radar jammer, supplied by Northrop Grumman [21]. Additional short-term opportunities are therefore provided by integrating the latest jamming technologies onto UCAVs.

Medium-Term Opportunities

The medium-term presents much greater opportunities, as UCAVs become more widespread and technological advancements drive improvements in weapon systems. Opportunities will be across all types of UCAV systems: armed ISR UAVs; large, advanced, stealthy UCAVs; and small, agile, expendable UCAVs.

It is predicted that in this timeframe the number of armed ISR UAV will have increased, expanding the opportunities associated with this type of UCAV. The medium-term may also see the full-scale development of large, advanced, stealthy UCAVs and the advent of small, agile, expendable UCAVs.

Medium-term advancements will provide UCAV applications for a number of new or enhanced weapon technologies, including conventional air-to-ground cruise missiles, micro-munitions, jamming systems, E-bombs and self-protection missiles.

Conventional Air-to-Ground Cruise Missiles

In the medium-term, the development of conventional air-to-ground missiles will focus on providing greater precision and more localised effects. This will improve the performance of conventional missiles launched from armed ISR UAVs.

There will be additional opportunities provided by large, advanced, stealthy UCAVs, which, in the medium-term, may have evolved from demonstrator projects to full scale development programmes for operational systems. Large, advanced, stealthy UCAVs will be very high value assets, and so will stand-off to ensure survivability and will require complex stand-off weaponry. They will have much higher payload capacities than armed ISR UAVs, but most will have internal weapon bays to improve the stealth characteristics of the airframe.

Further opportunities may also be provided by the development of small, agile, expendable UCAVs. These systems could carry a payload of small conventional munitions for the prosecution of ground targets.

It may be, however, that conventional air-to-ground cruise missile for UCAVs may be superseded by smaller missiles that are classed as micro-munitions.

Micro-munitions

The advent of much smaller UCAVs and a demand for greater stealth will drive the requirement for a new class of micro-munitions. Micro-munitions will be smaller and lighter than conventional missiles, and can also be carried internally, improving the stealth characteristics of the delivery vehicle's airframe.

Micro-munitions will have applications across all types of UCAVs. They will permit small and lighter payloads, for armed ISR UAVs and advanced stealthy UCAVs, therefore, reducing the size of these platforms. The range of micro-munitions may be limited, reducing their suitability for platforms that stand-off from targets. Micro-munitions may, in the medium-term, be a key driver for the development of small, agile, expendable UCAVs.

In general, micro-munitions may be intended for functional kills, aiming to disable critical systems rather than destroy the target. They have the advantage of being very difficult to detect and destroy and the small warheads lead to highly localised effects.

There are currently significant challenges associated with the development of micro-munitions. However, as Micro Electro Mechanical System (MEMS) and Nano Electro Mechanical System (NEMS) technologies mature, smaller avionics, navigation systems, sensors, fuzes and other systems will be possible. In addition, there is a requirement for miniature power and propulsion systems and there will also be system integration complexities. However, the advancement of micro technologies and the growth of this new class of munitions provide significant

Armourers unload an AGM-114 Hellfire Missile from a MQ-9 Reaper. *Photo courtesy DoD*.

Two AGM-114 Hellfire Missiles and a GBU-12 Paveway II Laser Guided Bomb under the wing of a MQ-9 Reaper. *Photo courtesy DoD*.

new opportunities to the guided weapons industry across many applications, including the armament of UCAVs.

Jamming Systems

In the future, technological advancements will drive down the size of jamming units and increase power levels. Reducing the size of jamming units means that they will be suitable for small armed ISR UAVs and small, agile, expendable UCAVs. Increasing power levels means that electronic attack missions can be conducted from longer range, providing the potential for jamming to be conducted from advanced platforms that will need to stand-off to ensure survivability.

An example of a cutting-edge jamming technology is the Jammer Cube, which has been developed as part of a US Marine Corps advanced concept technology demonstration called CORPORAL – Collaborative Online Reconnaissance Provider / Operationally Responsive Attack Link. The Jammer Cube unit is a 1kW jammer, weighing approximately 1kg and the size of a stack of compact disc jewel cases [22]. The jamming system uses an electronically steered conformal antenna that is integrated into the airframe of the UAV. In the medium-term, advanced jamming systems will become even smaller and more powerful than this example.

E-bombs

Electromagnetic bombs, or E-bombs, may provide an alternative to conventional warheads across all UCAV applications. Small E-bombs could be used to deliver extremely localised effects, emitting an electromagnetic pulse to disable electronic systems. The electromagnetic warhead is delivered in a projectile, similar to a conventional cruise missile. At an appropriate range from the target, a short and powerful burst of electromagnetic pulses (usually in the microwave range) is released. The weapon lasts for only a few microseconds, but is powerful enough to destroy the electronics of its target – a radar system, GPS system, radio system or a computer.
The main advantage of these systems is that the duration of the pulse is so short that they are potentially non-lethal: an attack could spare human lives and leave buildings undamaged. As such, E-bombs are ideal for use in urban environments, where the level of collateral damage is critical.

The technology associated with E-bombs is relatively simple, when compared with conventional anti-radiation missiles, such as Raytheon's AGM-88 HARM (High-speed Anti-Radiation Missile) and MBDA's ALARM (Air Launched Anti-Radiation Missile). Therefore, it is expected that E-bombs will be cheaper to develop and manufacture.

Information on the proliferation of E-bombs is highly classified. It is widely reported that the US Air Force used an E-bomb in 2003 in an attempt to shut down an Iraqi satellite television centre [23]. However, the Pentagon refuses to acknowledge the existence of the weapon. The technology required is mature, and so the development of E-bombs presents a further opportunity to the guided weapons industry. Electromagnetic warheads could be integrated into missile suites similar to GAMs (GPS Aided Munitions) and JDAMs (Joint Direct Attack Munitions).

Self-Protection Missiles

So far, all of the weapons technologies discussed have been ground attack weapons. In the future, there may also be a requirement for weapons that can provide self-protection to the UCAV platform and this area presents further opportunities to the guided weapons industry. In particular, self-protection missiles will have applications for large, advanced, stealthy UCAVs that are high-value platforms. They may also be used to protect armed ISR UAVs if they are operating in high risk environments.

Trials have been conducted where Raytheon's AIM-92 Stinger missile has been fired from MQ-1B Predator platforms [8]. Stinger is an advanced air-to-air missile and would give the UCAV a limited self-protection capability, rather than turn it into a fighter. Suitable missiles should be agile, supersonic and have advance guidance and control systems to maximise accuracy.

Long-Term Opportunities

As unmanned aircraft and weapon technologies evolve further, the UCAV market may provide even greater opportunities to the guided weapons industry. Long-term opportunities will exist across all types of UCAV systems.

UCAVs may be regarded as ideal platforms from which to deploy Directed Energy Weapons (DEWs). DEWs could be employed by all types of UCAVs, but significant technology advancements are needed to develop units that generate the necessary power but are also small and lightweight. If this can be achieved, DEWs could be used for the attack of ground targets and provide self-protection. Finally, in the long-term, UCAVs may be used to gain control of the airspace at the start of conflicts. To achieve this, advanced systems would be operating in very hostile environments and would be required to conduct air-to-air engagements from both long-range and at close quarters.

Ground Attack Directed Energy Weapons

Directed Energy Weapons (DEWs) deliver a beam of energy, usually as electromagnetic radiation, at the target instead of a projectile. These weapons require high accuracy and a line-of-sight between the deployment platform and the target. This is easiest to achieve from a low altitude, close-in airborne platform, such as a UCAV.

Whilst DEW technologies are fundamentally different to that of conventional munitions, the guided weapons industry has expanded into this area. There are several

Raytheon Humvee-mounted Active Denial System. *Photo courtesy DoD*.

Boeing Advanced Tactical Laser System. *Photo courtesy of Boeing*.

current and future technologies that, in the long-term, could be deployed from UCAVs, providing new operational capabilities to the military.

The current technology challenges facing industry are to provide DEW units that generate the necessary power but are also small and lightweight for deployment from a UCAV. However, if these challenges can be overcome, DEWs can provide significant advantages over projectile weapons. Electromagnetic radiation travels at the speed of light and so will transit from the UCAV to the target immediately. Therefore, there is no need to allow for target manoeuvre during weapon transit, and the target has no time to detect or evade. A further benefit is that the ratio of momentum to energy of electromagnetic radiation is negligible and so the operation of a DEW results in no recoil that could destabilise the UCAV's flight. The beam can also be focused on precise locations and without a blast, provides accurate effects with a lower risk of collateral damage.

A potential DEW technology for the future is high power microwave (HPM) weapons. A HPM weapon generates continuous or pulse microwave beams that could be directed at a target. A microwave beam operating at gigawatt power levels would turn any unhardened electronics into molten silicon. A HPM weapon could therefore be used to destroy any enemy electronic systems, including radars, computer systems and communications infrastructures. Raytheon is the industry-leader with respect to HPM systems, with two development programmes at advanced stages: the Active Denial System (ADS) and the Vigilant Eagle system. The ADS will provide a non-lethal crowd control method, using a HPM beam to heat the surface of human skin. The heating effect produces an intensely painful sensation while not actually burning the skin, avoiding permanent damage. Variants of the system have been mounted on Humvees, flat-bed trucks and static shelters. The development of an airborne version of the ADS has also started. Vigilant Eagle is a ground-based anti-missile defence system that uses a HPM beam to divert missiles. The system is intended to be deployed at airports to protect aircraft from man-portable air-defence systems (MANPADS) and other threats. Neither the ADS nor the Vigilant Eagle system provides the ground-attack capabilities required to destroy targets, but future advancements of HPM technologies could result in novel weapons for UCAV applications.

A second future DEW technology for UCAVs is high energy laser weapons. Chemical laser systems have military uses and are currently operating at megawatt power levels. However, before practical application from a UCAV is possible, significant development is required. These systems require large volumes of chemical fuels, and as such are being integrated into very large aircraft. Boeing's Advanced Tactical Laser System is a technology demonstration programme to develop a high energy chemical laser for engagements against ground targets [24]. Because large storage volumes are required, this system is deployed from a modified C-130H aircraft. However, the operation of high energy laser weapons from a UCAV is likely to be only possible in the long-term due to size and weight constraints.

There are a number of other technological challenges associated with the development of DEWs and these are discussed in greater detail in Appendix D.

Self-Protection Directed Energy Weapons

Some of the DEW technologies could be developed to provide self-protection, destroying or disabling any missiles fired at the UCAV. A major technological challenge, however, will be producing a pointing system that is able to direct an energy beam at a highly agile in-coming missile.

Air Superiority and Air Supremacy Weapons

In the long-term, advanced UCAVs could be used to gain control of the airspace. In this role, UCAVs will be acting as unmanned fighter aircraft, operating in hostile environments and aiming to achieve a situation of Air Superiority and then Air Supremacy. These aircraft will be very advanced, high performance systems, operating at high speed and agility and with a high degree of autonomy. They would be required to conduct air-to-air engagements from long-range and also at close quarters. This can be achieved by operating conventional air-to-air missiles that provide within visual range and beyond visual range capabilities.

Examples of Air Superiority and Air Supremacy weapons that are being integrated onto today's advance manned fighter aircraft are MBDA's ASRAAM (Advanced Short-Range Air-to-Air Missile) and Meteor (a Beyond Visual Range Air-to-Air missile). It is possible to envisage that these types of weapons could be integrated onto advanced UCAV platforms in the long-term.

UCAV Platform Technologies

Whilst the primary opportunities provided by UCAVs are associated with weapon systems, guided weapons technologies and expertise can also contribute to improved UCAV platform design. Expansion into this market would provide additional opportunities to the guided weapons industry.

The critical technologies for a UCAV platform are associated with mission management and control, and the related communications infrastructure. In both of these fields it can be argued that the guided weapons industry is at the forefront of technological advances. In addition, there are sensor, image processing, stealth and defence aid suite technologies that could be translated from guided weapons systems to UCAVs.

Placing timeframes on platform technologies is more difficult to achieve. Therefore, this section of this paper focuses on current and emerging guided weapon technologies that could be transferred to UCAV systems.

Mission Management and Control

Some of the fundamental technologies of a UCAV are associated with mission management and control. There are technologies and expertise in this area that can be transferred from cruise missile systems and loitering munitions systems that could improve the performance of UCAVs. Potentially, the entirety or any subset of mission management and control functions could be autonomous in future systems. Some of these functions are outlined in Table 1.

Today, the most advanced UAVs and UCAVs are partially autonomous, with mission management and control functions divided between UCAV systems and human operators. The US DoD *Unmanned Aircraft Systems Roadmap 2005-2030* [12] defines ten Autonomous Control Levels. Current systems operate between Level 2 and Level 3. At Level 2, the aircraft is remotely guided and reports real-time health and diagnosis to the ground controller. At Level 3, the aircraft is also able to adapt to failures and flight conditions. Systems such as the MQ-1B Predator and RQ-9 Reaper are still remotely 'piloted' by a ground controller in a control room using a joystick and other controls. These aircraft have a nose-mounted camera and other flight control instruments that provide imagery and data that is used by the ground controller to remotely fly the aircraft. A further discussion about UCAV autonomy levels and potential future capabilities is provided in Appendix E.

In the future, it is possible to envisage a scenario in which UCAVs are controlled by an operator specifying points in physical space, referred to as 'waypoints', through which the aircraft should pass. The navigation and flight control could then be performed by on-board systems, resulting in the aircraft flying through the waypoints without further human input. Technologies from the guided weapons could be applied to UCAVs to achieve this. Two types of system to consider are loitering munitions systems and long-range, stand-off air-to-ground missile systems.

Loitering munitions are ground-launched munitions that can be positioned in a de-conflicted volume of airspace for a significant period of time before rapidly attacking an appropriate land target. One such loitering munitions programme is Fire Shadow, which is led by MBDA. In general, loitering munitions are controlled by operators specifying a number of waypoints through which it should pass. A flight path is then generated by the on-board navigation systems. The guidance and control systems calculate the required flight control demands to autonomously follow this flight path. Loitering munitions also have the capacity to be re-tasked in-flight at any time; when new flight waypoints are uploaded to the munitions in the air, a new flight path is then generated and followed using the on-board systems.

Table 1: Mission Management and Control Functions

Function	Description
Mission Planning	Decisions of intent for mission, planning of optimal flight path and task scheduling, including ad hoc mission planning to react to changes in the mission
Intelligence Gathering	Fusion of information from sensors and other intelligence sources
Communication Management	Allocation of spectrum resources and encryption methods
Navigation	Generating the flight path to execute the mission plan
Flight Control	Control of avionics to follow the flight path
Self-Defence	On-the-fly modification of the flight plan to avoid threats, execution of self-defence systems (countermeasures) and collision avoidance functions
Target Acquisition	Target search, detection, recognition and identification
Target Engagement	Threat evaluation, weapon allocation, weapon deployment and execution of the engagement
Co-operative tactics	Allocation of missions and activities to UCAVs operating in swarms
Abort decision making	Safety critical functions to abort missions

Long-range, stand-off air-to-ground missiles, such as MBDA's Storm Shadow missile, also autonomously follow long flight paths. Storm Shadow is an air-to-ground cruise missile, which has a large airframe and a range of greater than 250km [25]. The flight is controlled by the tight integration of an Inertial Navigation System, a Global Positioning System and the digital matching of terrain data with sensor data. This allows the missile to correct its position constantly and follow a pre-designated flight path autonomously and with high accuracy.

Similar flight control technologies and algorithms to those used in these two examples could be applicable to the control of a future UCAV platform, reallocating the functions performed by the remote 'pilot' on the ground to control systems.

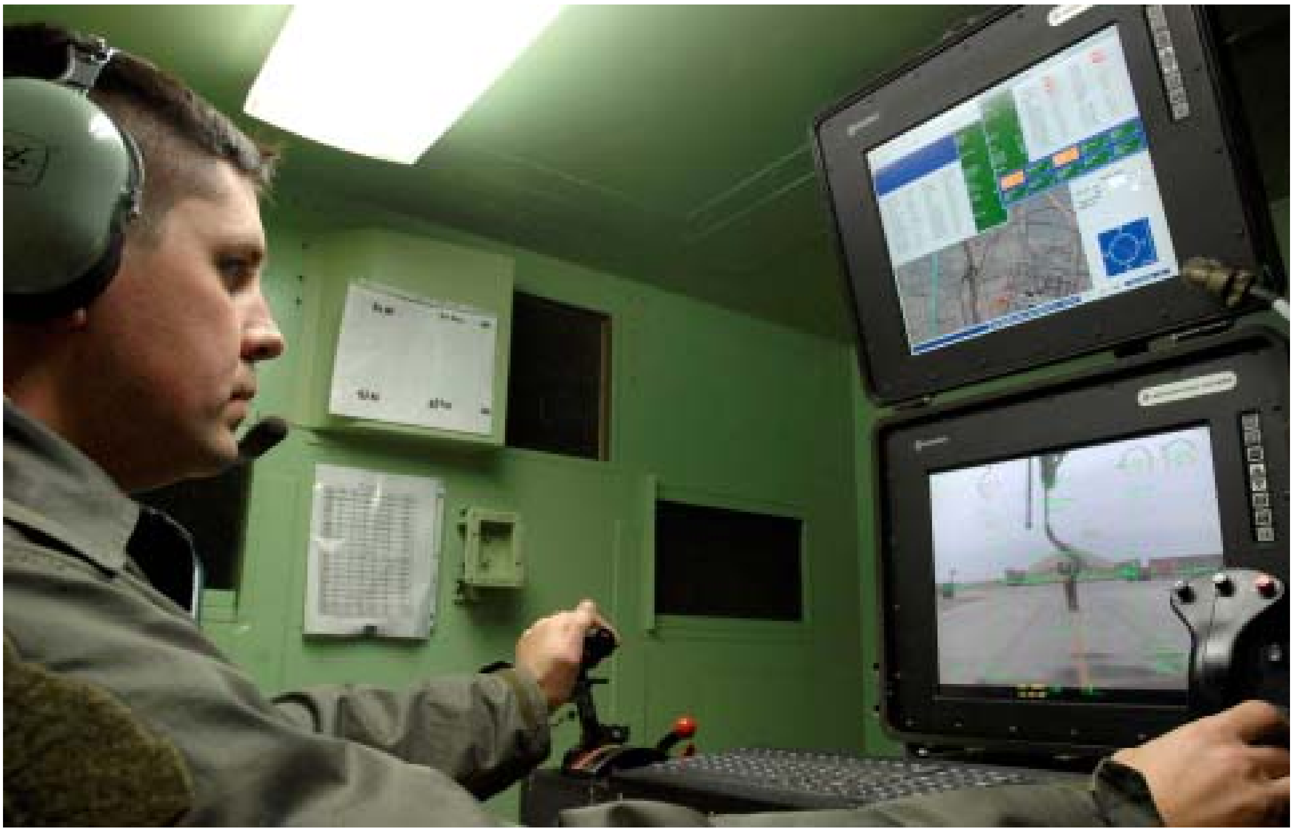
The guided weapons industry also has experience in many of the other mission management and control functions described in Table 1. Many weapons systems require intelligence gathering, communication management and target acquisition functionality. All weapons systems perform target engagement functions such as threat evaluation, weapon allocation, fire control and execution of the engagement. Expertise from designing systems that carry out these mission management and control tasks could be transferred to the development of UCAV systems.

Many weapon systems have sophisticated mission planning and re-planning tools. These facilitate the planning of numerous missions, involving many aircraft and multiple targets. The Storm Shadow Mission Planning Application is an example of tool which is used to plan and deconflict flight paths and schedule multiple engagements. Similar applications would allow the efficient planning of the coordinated use of UCAVs in groups.

The guided weapons industry also has considerable experience in designing human controller interfaces for weapon systems. This expertise could be used to develop the ground controller interface for the UCAV system.

Communications Infrastructure and Data Links

In today's systems, all airborne data captured by the UCAV is relayed to the ground, where is it processed and interpreted. Once the necessary decisions have been made, control demands are then uplinked to the airborne platform. This process places huge demands on data link rates, in particular when air-to-ground video transmission is involved. These problems of bandwidth and spectrum constraints must be addressed as the operation of UCAVs becomes more widespread. The US DoD *Unmanned Aircraft Systems Roadmap 2005-2030* identifies the principal issues associated with UAV communication technologies as 'flexibility, adaptability, and cognitive controllability of the bandwidth frequency and information / data' [12].



Inside the Ground Control Station of an MQ-1 Predator. *Photo courtesy DoD.*

It is worth noting that there is a fundamental trade-off between the degree of on-board autonomy and the demand for data link capacity. As more of the processing is conducted by the on-board systems, only the 'results' will need to be transmitted the ground for authorisation. However, as it is generally accepted that a 'man-in-the-loop' will be retained for target identification, it is likely that the demand for imagery transmission will remain for the foreseeable future. Systems that relay real-time colour video to the ground require many megabytes per second and currently this is achieved using VHF/UHF Radio Frequency (RF) band data links or UHF and K-band SATCOM. RF data links are used for line-of-sight and beyond line-of-sight applications (up to about 100 miles in good weather). Over longer distances satellite relays are used.

The launch and recovery of today's UCAVs are conducted from ground control stations at the airfield in theatre. During this stage, the flight control uplinks and imagery data downlinks are sent in real-time using an RF data link. Once the UCAV flight has been stabilised, control of the aircraft can be transferred to a ground control station further a field using SATCOM (for example US and UK aircraft can be controlled from the Creech Air Force Base, Nevada). The UCAV imagery is also transmitted to the controller using the satellite relay, but is also available to troops in theatre via RF data links.

The guided weapons industry has very little experience in SATCOM technologies, but has considerable expertise in RF data links, as they form a critical component of many weapon systems. In the future, new data link technologies will be required for military applications to address bandwidth and spectrum constraints. At present, compression algorithms provide an imperfect method of reducing bandwidth, but this is unlikely to meet the requirements of advanced sensors. The development of more bandwidth-efficient modulation methods and network-enabled solutions will be required to satisfy demands for greater data rates.

A potential beneficial future technology is lasercom. This technology uses optical data links, and could offer data rates of two to five orders of magnitude greater than the best future RF systems. The laser communication link has a smaller aperture than RF, which leads to a lower signature and greater security. However, some key technological challenges remain, such as accurate pointing, acquisition and tracking methods to establish and maintain the communication link. The ability of optical data links to provide stable communications in bad weather is also limited.

As a result, it is likely that RF communications will continue to dominate low-level ground-air communications in the foreseeable future. Therefore, communication and data link expertise from the guided weapons industry, such as technologies under development for loitering munitions systems and those present in other long-range missile systems, could be transferred to UCAV applications. In fact, the communication infrastructure required for a partially autonomous UCAV system is similar to that of a loitering munitions system, with the main components being:

1. Transmission of live video to a ground controller for target identification;
2. Transmission of ground-to-air messages confirming acquired target and authorising the engagement;
3. Uploading of flight plans and target models to the UCAV if the mission is modified or re-tasking is necessary;
4. Downlink of health and diagnosis data.

Established communication architectures from existing weapons systems may, therefore, be applicable to future partially autonomous UCAV systems. The communication infrastructure must be robust and secure, and this is also an area in which the guided weapons industry has considerable expertise.

Sensor Systems and Image Processing

Before an engagement, the UCAV must search for, acquire and track the target. In future systems these functions may be autonomous and so will require a significant increase in on-board sensor and image processing capabilities. These technologies are very mature in the guided weapons industry, but must be integrated into the launch platform rather than the munition. Long-range, fire-and-forget cruise missiles are required to process sensor data to autonomously acquire, track and intercept the target after launch. Similar image processing and tracking algorithms will be required in UCAV systems, and this is a further area in which the guided weapons industry can contribute to UCAV performance.

Currently, the key requirement for UCAV sensors is to provide imagery for target detection and identification by a ground controller. Where possible, sensor systems should be capable of being used for the entire range of UCAV missions, and provide 24 hour, all-weather performance. Using a suite of sensors, this capability is achievable using existing technology.

Present systems, such as the MQ-1B Predator and the MQ-9 Reaper, provide this comprehensive performance using three types of sensor:

1. A variable-aperture television camera for clear daylight conditions
2. A variable-aperture infrared (IR) camera for use low light or at night
3. A Synthetic Aperture Radar (SAR) for looking through smoke, clouds or haze.

The cameras produce full motion video, which can be viewed as separate real time video streams, while the SAR generally produces still frame radar images. In the case of the MQ-9 Reaper, the television video can also be fused with the IR sensor video. Both aircraft are equipped with a colour television nose camera, which is used by the ground controller to pilot the aircraft.

The guided weapons industry is at the forefront of emerging sensor technologies, in particular sensor applications that require targets to be acquired and tracked. The advent of high definition television video formats for military applications should improve the resolution of video imagery. Advanced electro-optic and infrared sensors currently under development provide high resolution, highly stabilised imagery with wide fields of view that increase the area of coverage. Improving SAR technology will provide more detailed information on a target vehicle or the battlefield than is currently possible. There are also many other emerging technologies, such as Hyperspectral Imagery, that may have UCAV applications.

A further challenge is provided by small, moving targets in complex environments. For these targets, higher resolutions will be required than currently exist on UAVs used in ISR roles. The target will then also need to be tracked and this could be achieved using tracking algorithms that currently exist in weapon systems. The sensor system may also play a role in conducting short-range engagements. In such engagements, it is possible that remote control guidance, such as Command to Line-of-Sight[5], could be used to guide the missile onto the target. This would remove the requirement of the missile to have its own seeker, and so would reduce its cost considerably. These remote control guidance systems are present in numerous existing weapons systems.

As UCAVs become more autonomous (and so are no longer remotely 'piloted') sensors systems may also be used by UCAVs to self-navigate. This method is currently used in guided weapons, such as the long-range Storm Shadow missile which navigates using the TERPROM (Terrain Profile Matching) system. This system matches stored digital terrain data with sensor data to produce a highly accurate Terrain Referenced Navigation method.

Airframe and Stealth Technologies

Although the UCAV airframe is not necessarily an area in which the guided weapons industry has great expertise, there may be some niche technologies that may be applicable to airframe improvement. As operational requirements place demands on UCAVs to be deployed in highly attritional environments, airframes will have to become smaller, stealthier and more agile. For this reason, one could speculate that airframes will evolve to become more like very large guided missiles than fighter aircraft. The requirement for high 'g' manoeuvres, in particular for nose-dives to drop weapons and air defence avoidance manoeuvres, will place demands for avionics and actuator systems similar to those presently on loitering munitions and long-range cruise missiles. To enable high stealth characteristics, low signature propulsion technologies will be required, and so some propulsion expertise developed for large weapon systems may be transferable to UCAV systems.

Defensive Aid Suites

Survivability is a key consideration for UCAVs, especially as it is likely that their missions will involve the suppression and destruction of enemy air defences. Increased survivability is primarily achieved by devising flight plans and attack profiles that reduce risk and by producing an airframe that is stealthy, small and agile. However, UCAV defensive aid suites (DAS) that provide both radar and infrared countermeasures may be applicable to some missions. The guided weapons industry conducts extensive research into countermeasure technologies, such as chaff and flare dispensers. MBDA produces the Saphir family of chaff and flare dispensers, which provide active protection to more than 200 helicopters. UCAVs may be able to employ similar decoy systems to increase their survivability.

Collision avoidance technologies will also contribute to increased UCAV survivability. ASTRAEA is a project that involves a consortium of major aerospace and defence companies addressing the issue of UAV use in non-segregated airspace alongside general air traffic. The project includes developing 'sense and avoid' technologies to prevent mid-air collisions. These technologies can also be applied to UCAVs.

Conclusions

The advantages and capabilities of UCAVs are numerous, and their value has been demonstrated during current operations in Afghanistan and Iraq. The numbers of UCAVs in air inventories are growing and currently there is the large investment in UCAV technologies and demonstrator programmes. For these reasons, it is predicted that UCAVs will become an increasingly important component of the air power of the world's leading nations. Therefore, UCAV development presents significant opportunities to the guided weapons industry.

The primary opportunities are provided by integrating weapons systems onto UCAV platforms. There are also technologies from guided weapons systems that could be applicable to the design and development of UCAV platforms, which provide additional opportunities.

[5] In Command to Line-of-Sight guidance systems, the missile is totally controlled by the launch platform. Both the missile and the target are tracked sensors on the launch platform. The launch platform then sends the missile control orders, with the necessary missile path corrections, to intercept the target.

It is possible to identify the following three types of UCAVs, each providing different capabilities and therefore different opportunities:

1. Armed ISR UAVs
2. Large, advanced, stealthy UCAVs
3. Small, agile, expendable UCAVs.

Identifying these three types of UCAV system provides a framework around which opportunities to the guided weapons industry can be analysed.

UCAV Weapon Technologies

The arming of UCAVs provides the primary opportunities to the guided weapons industry. The applicable weapons technologies depends on the type of UCAV system and the role it will be performing. The current opportunities focus on arming UCAVs with conventional guided missiles and jamming systems. In the future, the employment of micro-munitions, E-bombs and Directed Energy Weapons from UCAVs will provide further opportunities to the guided weapons industry.

Table 2 summaries the short-term, medium-term and long-term opportunities to guided weapons industry associated with arming UCAVs.

UCAV Platform Technologies

The core technologies of UCAV platforms are currently shifting from the airframe to areas in which the guided weapons industry have substantial expertise, such as mission management and control and data link infrastructures. In both of these fields it can be argued that the guided weapons industry is at the forefront of technological advances. In addition, there are sensor, image processing, stealth and defence aid suite technologies that could be translated from guided weapons systems to UCAVs.

The opportunities associated with UCAV platforms focus on technologies that currently exist in guided weapon systems. The guided weapon technologies that could be transferred to UCAV systems can be summarised as follows:

1. Mission management and control technologies from guided weapon systems can improve the capabilities of UCAVs, in particular in the areas of navigation and flight control. Experience from guided weapons systems of other mission management and control functions such as intelligence gathering, communication management, target acquisition and target engagement could also be applied to the development of UCAVs.

2. Established communication architectures from existing weapons systems and emerging communications and data link technologies may be applicable to future UCAV systems.

3. The guided weapons industry is also at the forefront of advanced sensor and image processing technologies, some of which will have UCAV applications.

4. The guided weapons industry may also be able to provide some niche airframe and stealth technologies. For high agility, some high ‘g’ avionics and actuators expertise from guided weapons could be transferred to UCAV airframes. To ensure high stealth, low signature propulsion technologies from guided missiles may be required. ‘Sense and avoid’ technologies will also contribute to increased survivability by preventing mid-air collisions.

5. Defensive aid suites may also be used by UCAV systems. The guided weapons industry conducts extensive research into countermeasure technologies, and chaff and flare dispensers may be able improve the survivability of UCAVs in high-risk environments.

Table 2: Summary of UCAV Weapon Opportunities

Type	Short-Term	Medium-Term	Long-Term
Armed ISR UAVs	Low cost, simple, small, lightweight and short-range air-to-ground conventional missiles Jamming systems	Advanced air-to-ground conventional missiles Micro-munitions Advanced jamming systems E-bombs Self-protection weapons	Directed Energy Weapons
Large, Advanced, Stealthy UCAVs		Longer-range air-to-ground conventional missiles Micro-munitions Advanced jamming systems E-bombs Self-protection weapons	Directed Energy Weapons Air Superiority and Air Supremacy Weapons
Small, Agile, Expendable UCAVs		Very small air-to-ground conventional missiles Micro-munitions Advanced jamming systems E-bombs	Directed Energy Weapons Air Superiority and Air Supremacy Weapons

Appendix A: UCAV Advantages

UCAVs have many advantages and provide significant operational capabilities. It is a common argument that unmanned aircraft are better suited to '4D' tasks: the dull, dirty, dangerous and deep. The dull aspect refers repetitive missions or missions that require persistence, and so are better suited to autonomous systems than humans. 'Dirty' refers to environments in which there are nuclear, biological and chemical threats. 'Dangerous' tasks are those in which there is a high risk to the aircraft and aircrew. 'Deep' tasks are those that are beyond the range of current manned aircraft. In addition to these performance advantages, it can also be argued that UCAVs are more cost-effective than manned aircraft.

UCAV Performance

A principal advantage of this type of UCAV over piloted aircraft is their greater endurance, which enables them to provide an enduring capability in theatre and to perform long range missions. This point was made by General Moseley, Chief of Staff of the US Air Force from 2005 and 2008, who when naming the MQ-9 unmanned aerial vehicle, 'Reaper', stressed that 'the key advantage is not keeping manned aircraft and pilots out of harm's way, but the persistence UAVs can inherently provide' [26]. UCAVs have the potential for greater endurance, as they are not restricted by pilot fatigue; their endurance is only restricted by the availability of resources such as fuel, battery life and lubricants. If in-air refuelling can be developed, UCAVs should be able to provide almost indefinite capabilities.

UCAVs are generally perceived to be more expendable than manned aircraft due to the absence of a pilot and their relative low cost. For this reason, they can operate in environments previously considered too risky for piloted aircraft. It can be argued, therefore, that to exploit this characteristic UCAVs will continue to be relatively low cost platforms, rather than some of the extremely expensive large, advanced, stealthy concepts currently being demonstrated. As the technological sophistication of UCAVs increases, there will be an inherent reluctance to exploit these greater capabilities as the financial cost and political consequences of losing the UCAV to the enemy increases. Advanced, sophisticated UCAVs will be very high value assets, and so will not be expendable. Therefore, this type of UCAVs is likely to stand-off to ensure survivability and will require complex stand-off weaponry.

UCAVs have the potential to be more stealthy and agile than their piloted peers. Improved stealth characteristics are possible because there is no requirement for a cockpit which severely constrains aircraft cross-section and shape. Increased shape optimisation also improves the drag characteristics of the airframe. In addition, UCAVs can be designed to be more manoeuvrable. In piloted aircraft, the manoeuvrability is constrained by pilots' G-tolerance; when exposed to excessive accelerations in the 'headwise' direction (above about +9G), pilots may suffer from G-induced loss of consciousness. However, the cost implications of adding expensive stealth and agility capabilities to the UCAV platform will add value to the asset and may constrain their operational use in very hostile environments.

UCAVs are suitable for operating in complex target environments, such as urban areas, where there is a high risk or collateral damage or fratricide. In these environments, the use of conventional payloads can be problematic and so small and precise effects are required. A UCAV that can approach close-in to targets is an ideal platform for delivering these types of weapons.

Elimination of Risk to Aircrew

One should not underestimate the elimination of risk to aircrew, such as injury, capture and loss of life, provided by UCAVs. Whilst the benefits of preventing injury and loss of life are obvious, there are also some significant political benefits to protecting aircrew. The capture of aircrew by an enemy could constitute a significant triumph, and can be used as part of a propaganda campaign or as a valuable negotiating tool. In addition, conflicts are increasingly influenced by the 'CNN Effect': the huge media interest generated by the loss of aircrew could lead a challenge to the political and military objectives of the campaign. Aircrew injury, capture and loss of life can also have significant negative effects on the morale of military comrades and the civilians of supporting nations.

Autonomy

It can also be argued that in fully autonomous systems, the removal of humans will improve the engagement decision-making process. The judgements of an autonomous system are not influenced by human emotions, such as anger, frustration and existing mindsets. Computers on-board a UCAV will also be able to integrate and process information from many more intelligence sources (such as on-board sensors and intelligence networks) and very much more quickly than a human. These factors permit fully autonomous systems to make more logical and accurate engagement decisions.

If a human element is preserved in the engagement decision through a ground controller, it can be argued that this controller would actually have greater situational awareness than a pilot. It is likely that in a UCAV control room, the controller would have greater access to intelligence and battlefield information than is possible in a cockpit.

Cost Analysis of UCAVs

Unmanned platforms have the potential to be more cost-effective than manned aircraft. To analyse any potential cost benefits, it is necessary to consider the different types of UCAV system described previously in this report, namely: armed ISR UAVs, large, advanced, stealthy UCAVs and small, agile expendable UCAVs. Although no universally accepted data exists in the public domain, it is possible to construct some arguments supporting the cost benefits of the various UCAV systems.

Armed ISR UAVs

There is an ever increasing demand for situational awareness during operations. To achieve this, large numbers of ISR UAVs will form an essential part of air inventories. Arming these platforms provides a combat capability at a small design cost and modest additional operation and support cost. Additional training will be required for the ground controllers as they will now be weaponeers, and the support staff in theatre will now need to be trained armourers. However, procuring this type of UCAVs provides the opportunity to engage fixed and mobile, time-sensitive targets at a small additional cost.

Large, Advanced, Stealthy UCAVs

The cost benefits of large, advanced, stealthy UCAVs, similar to Taranis or J-UCAS, requires more investigation. These aircraft will be used exclusively in deep penetrating strike roles, and so will be a direct replacement to capabilities currently provided by manned fighter aircraft.

A cost comparison between unmanned aircraft and piloted aircraft is required to ascertain the potential cost benefits. The Defense Advanced Research Projects Agency (DARPA), in conjunction with the US Air Force, conducted such a cost comparison as part of the UCAV Advanced Technology Demonstration (ATD) Solicitation [27]. This report concludes that the unit cost of an advanced UCAV would be 'less than one-third that of a Joint Strike Fighter'. The justifications provided for this statement are:

1. Removing the pilot from the vehicle eliminates man-rating requirements, pilot systems, and interfaces
2. New design philosophies can be used to optimise the design for aerodynamics, signature, reduced maintenance and low cost manufacturing processes
3. New design freedoms that can be exploited to produce a smaller, simpler aircraft
4. Advances in small smart munitions will allow these smaller vehicles to attack multiple targets during a single mission and reduce the cost per target killed.

A cost analysis of these advanced UCAVs, and any subsequent comparison with manned fighter aircraft, must not only consider the acquisition cost but also the operation and support costs. The cost of ownership for an unmanned platform will be considerably different for a manned aircraft. The UCAV ATD Solicitation predicts 'cost reductions of 50-80% when compared to a current tactical aircraft squadron' [27]. The report proposes that UCAVs will be required to fly fewer sorties as there will be less of a need to fly training exercises to retain pilot proficiency[6]. There will also be considerable reductions in the operation and support costs of consumables, maintenance and personnel.

Small, Agile, Expendable UCAVs

A similar cost comparison will have to be conducted for small, agile, expendable UCAVs. However, as the principal advantage of this type of UCAV will be their expendability, they will be designed to be low-cost. It is envisaged that the unit costs could be orders of magnitude less than large advanced stealth UCAVs due to lower sophistication level of the technology involved. Lockheed Martin's Minion system was designed for low cost, resulting in an estimated cost that would have been substantially cheaper than the Joint Air-to-Surface Standoff Missile (JASSM) [9].

[6] Typically about 80 percent of the useful life of today's combat aircraft is devoted to pilot training and proficiency flying [28]. UCAV operators will train on simulators with the same equipment that they would use in actual missions. The operator would experience little difference between the simulator and flying an aircraft, and so less UCAV flights would be needed for pilot training.

Appendix B: UCAV Challenges

Currently there are some significant technological issues associated with unmanned air vehicles. Air Chief Marshal Burridge, Commander-in-Chief Strike Command between 2003 and 2006, summaries the main challenges facing unmanned air vehicle development [2]:

1. Interoperability of systems
2. Vulnerability
3. Limited capacity to address a wide area
4. Insatiable demand for bandwidth
5. Inability to deal with ambiguity in the same way as manned aircraft.

In the case of a combat UAV, the added complication of conducting engagements presents further challenges. These issues must be overcome before UCAVs can be regarded as a universal replacement for manned aircraft.

Interoperability of Systems

Interoperability is a key issue associated with UCAVs. At present, UCAVs systems are generally not interoperable and there is limited capability to integrate assets and share information across Joint and Combined operations. However, the NATO Industrial Advisory Group (Sub Group 53) seeks to improve UAV interoperability. It has produced NATO STANAG 4586, which defines standards for key interfaces and communication infrastructures for UAV control systems. There are also demands for networked-enabled weapons systems, which have led to the guided weapons sector gaining expertise in interoperability technologies.

Vulnerability

The nature of UCAV missions means that they will often be operating in environments in which enemy air defence assets are present. Mission planning and flight control methods, stealth, agility and defensive aid suites must all be improved to reduce the vulnerability of UCAVs. Potentially, UCAVs could also use self-protection weapons to destroy or disable any incoming missiles.

Limited capacity to address a wide area

Air Chief Marshal Burridge describes the 'soda straw' effect associated with UAVs [2]. Many optical sensors are unsuitable for wide area surveillance tasks and the low speed of UAVs means that they can only cover small areas. There are also deconfliction issues that restrict the number of unmanned platforms that can be used in a given volume of airspace. These challenges can be overcome by developing sensor technologies, more efficient search methods and tighter flight control techniques. Increasing the range of the weapons launched from UCAVs will also increase their area of influence, provided that long-range targeting can be achieved.

Insatiable demand for bandwidth

Data transfer, especially the transmission of video, between the airborne platform and the ground controller places large demands on bandwidth. Improvements in communications infrastructure and data link technologies are necessary to meet the requirements of increased UAV and UCAV operations.

Inability to deal with ambiguity

The inability of an autonomous system to deal with ambiguity leads to some ethical and legal issues. Retaining a 'man-in-the-loop' for authorising the engagement overcomes some of these problems. As autonomy levels increase, it can be argued that computer systems will provide a greater ability to deal with ambiguity than a human brain, processing more data, quicker and with less bias.

Conducting engagements

UCAVs are required to engage targets as well as perform ISR functions. It is a weapon system, which will identify, track and then engage targets. As a consequence, targeting systems, robust fire control systems and suitable weapons are required.

Appendix C: Ethical and Legal Issues associated with UCAVs

While UCAVs have many operational advantages, there are significant legal and ethical issues associated with their use. The Intermediate-range Nuclear Force (INF) Treaty leads to critics believing that UCAV systems are illegal as they do not conform to agreed limits on range. The Missile Technology and Control Regime (MTCR) restricts the export of UCAV technologies outside the MTCR community. In addition, there are ethical and legal issues associated with the UCAVs as they become more autonomous.

There is a legal issue associated with autonomous combat vehicles arising from the necessity to allocate responsibility for any unlawful actions, under the Nuremberg Principle. The Laws of Armed Conflict require participants to limit collateral damage, through accurate target recognition and identification before engagement. In a manned aircraft, it is ultimately the pilot who is responsible and accountable for the engagement decision. Being present in the operational theatre, the pilot is well placed to make accurate judgements concerning the collateral consequences of his actions and can refuse to carry out any orders that he deems to be illegal. Accountability is less clear-cut in the use of autonomous vehicles: does it lie with the programmers, manufacturers, controllers, commanders or government?

If the UCAV is fully autonomous, legal judgement and accountability is more difficult to achieve. It is for this reason that current concepts still include a degree of human influence, particularly with regard to engagement decisions. A 'man-in-the-loop' is preserved in the form of a ground controller, who is then responsible for any illegal actions of the UCAV. However, the ground controller is often detached from the engagement environment and has no experience of the operational theatre. It may be more difficult for him to make accurate moral and legal decisions, not withstanding the abundance of intelligence and battlefield information that is presented to him in the control room. In some instances, the detachment of the controller from the effects of his actions could promote careless and unnecessary operation.

The role of the human influence in UCAV operations is an interesting one. As weapons systems become highly sophisticated, it is not too difficult to envisage the situation in which the UCAV controllers or commanders are civilian contractors or non-military government officials. In this case, the UCAV controller or commander must be considered a combatant under international law, and so would relinquish all protection that the Laws of Armed Conflict give to non-combatants. As such, the UCAV controller or commander could be targeted on the battlefield.

Appendix D: Challenges to the Development of Directed Energy Weapons

All of the DEW technologies described in this paper present significant challenges. For UCAV applications, the principal challenges are associated with size and weight constraints. Current systems under development, such as the Boeing Advanced Tactical Laser System, require large volumes to generate the power required to destroy targets. Considerable technology advances are required to develop DEW units that are small and lightweight enough for deployment on a UCAV.

A second problem is the high potential for self-kill due to energy spillover. For example, microwave spillover may affect the internal systems of the UCAV, such as the avionics.

There is thirdly the potential for the UCAV to jam its own data links; the UCAV will be using data links in bands that may be subject to interference from the DEW. This self-inflicted jamming would result in the loss of operator control of the aircraft.

Accurate pointing of a DEW is extremely difficult to achieve from an airborne platform and, in order to achieve the desired effects, a DEW beam will have to be focused on a point for a number of seconds. During this time, a pointing control system will have to prevent the beam from moving from the target, whilst coping with significant vibrations and buffeting of the airframe.

Blooming is a further technical consideration associated with the use of laser DEWs. Laser beams begin to cause plasma breakdown in the air and this causes the laser to defocus and lose energy to the atmosphere. A laser beam or particle beam can also be scattered by rain, snow, dust, fog, smoke, sand or other such particles in the air. This reduces the efficiency of these weapons, limiting their use in such conditions.

Appendix E: Discussion of UCAV Autonomy Levels

There are a number of mission management and control tasks currently undertaken by a pilot on a manned aircraft that must be reallocated for a UCAV. These functions can either be assumed by a remote operator or automated (either in on-board systems or the ground equipment). Both of these options rely on autonomy and communication (data link) technology and advancements in these two areas will determine the future autonomous capabilities of UCAVs.

Current technologies provide automation in basic functions, but with very limited autonomy in performing more complex tasks. A fully autonomous capability, in which the UCAV will generate and perform multifaceted missions, is unattainable until a true Artificial Intelligence[7] technology becomes available.

The degree of autonomy of a system is difficult to quantify. Generally, a system can be classified with respect to three broad categories:

1. UCAV is remotely operated, with no or very little autonomous functionality
2. UCAV is partially autonomous. Some of the functionality is performed by its systems, but maintaining a 'man-in-loop', in particular with regard to deciding mission objectives and the engagement decision
3. UCAV is fully autonomous, creating and completing missions without human involvement.

Current systems are mostly partially autonomous, with functions divided between UCAV systems and human operators. Until a true Artificial Intelligence has been developed, UCAVs will continue to operate under human influence. The human will generate missions, in some cases remotely pilot the aircraft, and will be ultimately responsible for authorising any engagements. By retaining this human controller, some of the ethical and legal issues associated with UCAVs are overcome. It should be noted that a high degree of autonomous mission control must always exist in case ground-to-air communications are temporarily lost. In such a situation, the UCAV must be able to continue its stable flight safely.

A more detailed classification of autonomy is provided in the US DoD *Unmanned Aircraft Systems Roadmap 2005-2030* [12], which identifies the following ten Autonomous Control Levels:

- Level 1: Remotely guided
- Level 2: Real-time health / diagnosis
- Level 3: Adapt to failures and flight conditions
- Level 4: On-board route re-plan
- Level 5: Group co-ordination
- Level 6: Group tactical re-plan
- Level 7: Group tactical goals
- Level 8: Distributed control
- Level 9: Group and strategic goals
- Level 10: Fully autonomous swarms

Currently, the MQ-1B Predator UCAV operates at Level 2; it is remotely guided by a ground controller in a control room, whilst reporting real-time health and diagnosis. The ground controller is very much a 'pilot' on the ground, flying the aircraft using a joystick and other controls. The most advanced UAV in terms of autonomy used by the US Air Force in operations is the RQ-4 Global Hawk, produced by Northrop Grumman. The Autonomous Control Level of this high-altitude, long-endurance surveillance aircraft is almost Level 3. The Roadmap predicts that Autonomous Control Level 10 will be reached by 2015.

[7] There is no universally accepted definition of Artificial Intelligence. Autonomous military systems will remain under the command of senior officer and will be constrained by Rules of Engagement. It is proposed, therefore that Artificial Intelligence in a military context refers to the ability of a system (or systems) to decide on the most suitable action to fulfil the senior officers intent for operations and then to perform these actions without human input.

Acronyms and Abbreviations

ADS	Active Denial System
ATD	Advanced Technology Demonstration
CNN	Cable News Network
DEW	Directed Energy Weapon
DoD	Department of Defense
GAM	GPS Aided Munitions
GPS	Global Positioning System
HPM	High Power Microwave
INF	Intermediate-range Nuclear Force
IR	Infrared
ISR	Intelligence, Surveillance and Reconnaissance
JDAM	Joint Direct Attack Munitions
J-UCAS	Joint Unmanned Combat Air Systems
MEMS	Micro Electro Mechanical System
MTCR	Missile Technology and Control Regime
NEMS	Nano Electro Mechanical System
RAF	Royal Air Force
RF	Radio Frequency
SAR	Synthetic aperture Radar
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Air Vehicle
UHF	Ultra High Frequency
VHF	Very High Frequency

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