INSIGHT

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INTRODUCTION

This paper has been compiled to provide a "Technology Watch" on developing technologies, which are not necessarily integral to the Aerospace Technology Institute (ATI) technology strategy (as published in the 2016 document *Raising Ambition*), but may impact the future delivery of the technology strategy.

The topics covered are a selection of technologies which illustrate some of the diverse areas covered by aircraft systems but are not intended to be an exhaustive list of technologies. The paper identifies some key trends and areas of focus which will be important in the aerospace sector to meet forecast market opportunities and deliver economic impact in the UK.

03 EMERGING TECHNOLOGIES IN COMMERCIAL AIRCRAFT SYSTEMS

EXECUTIVE SUMMARY

- More electric technologies are progressing within current and planned R&T projects although the overall roadmap for more electric aerospace technology in the UK still needs to be articulated and communicated. A follow up paper, specifically focussing on this field will be issued by the ATI during 2017.
- Energy storage will continue to be increasingly important as hybrid systems deliver whole aircraft level benefits which rely on dependable and high capacity energy storage solutions. Activities in this field should continue to be followed to assess opportunities for improving aircraft system architectures through integration of these developing capabilities.
- Intelligent systems deploying System-on-Chip, multi-core processors or safety critical software will be critical for securing and growing UK systems capability in aerospace. In addition, these technologies are applicable across other sectors and a collaborative UK centre of excellence to harness and exploit these technologies should be considered by government, industry and academia to establish how the UK can assert leadership in these topics.
- Cyber security strategies for aerospace need to be clearly harnessed to ensure that disruptive technologies such as artificial intelligence can begin to be safely deployed in relevant applications. ATI is convening a group of industry experts to assemble a roadmap for cyber security in aerospace which will result in a specific ATI publication on cyber security during 2017.
- Thermal technologies are increasingly important in aerospace architectures as new concepts create increasingly demanding thermal loads with reducing opportunities for conventional heat dissipation approaches.

SYSTEMS FOR SMART, CONNECTED AND MORE ELECTRIC AIRCRAFT

Smart, Connected and More Electric Aircraft technologies are characterised by:

- Enabling introduction of more electric systems
- Developing secure digital systems and communications
- Securing capabilities in fuel, landing gear and energy management systems

The following sections in the document describe some examples of technologies which could emerge in “Smart, Connected and More Electric Aircraft” and can be viewed against the relevant ATI Whole Aircraft Attributes. The technologies were selected by the ATI Systems Specialist Advisory Groups. The figure below shows how these technologies align with the most relevant whole aircraft attribute, although many of these technologies could contribute, either directly or indirectly, to multiple attributes.

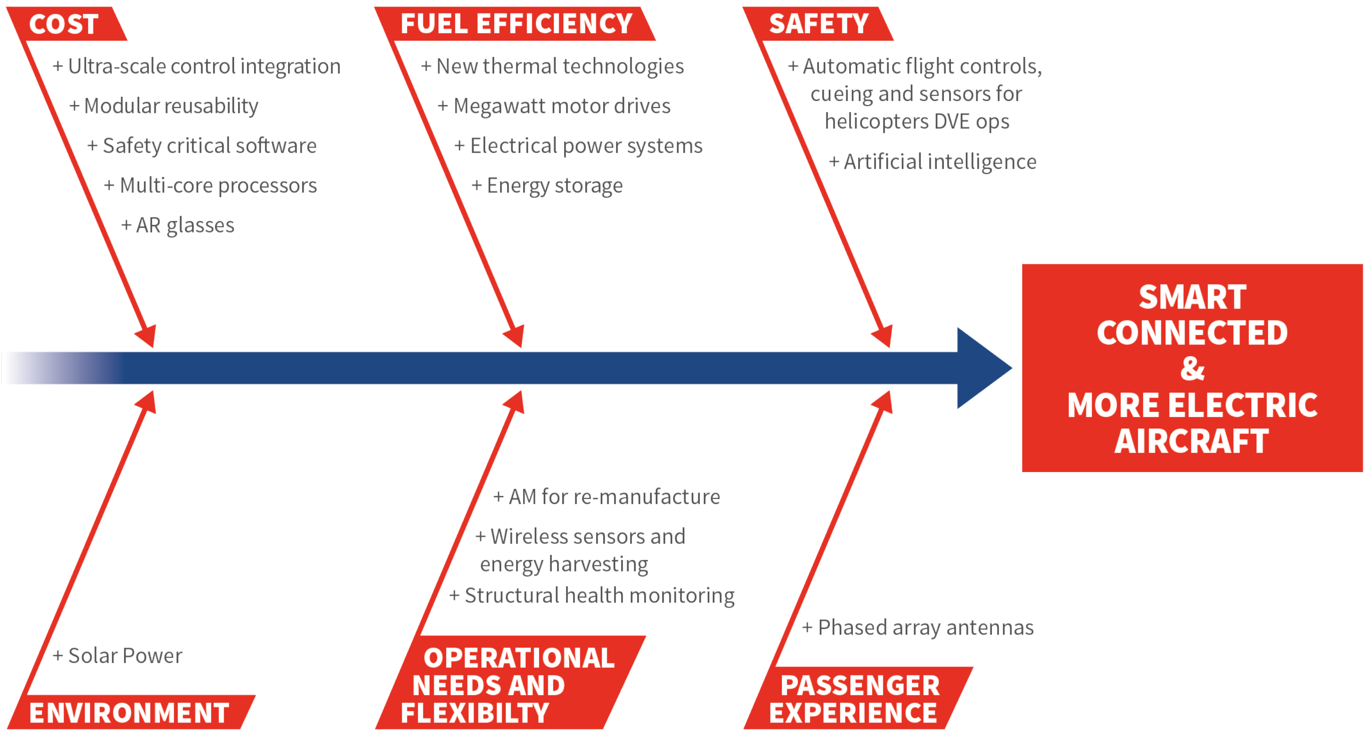


Figure 1: Emerging technologies for Smart, Connected and More Electric Aircraft

More electric systems

Whole Aircraft Electrical Power System

The trend towards aircraft electrical power systems for propulsion is driven by fuel costs and environmental pressures. Another benefit of electrical power systems is the potential to simplify maintenance through system health monitoring and self-diagnostic systems.

Key technologies to enable advances in power systems include solid state silicon carbide (SiC) or gallium nitride (GaN) power electronics devices, surge protection systems, bidirectional power systems, advanced cooling methods, self-diagnostic systems and distributed systems architectures. Electrical power systems can be developed through multi-fidelity modelling tools to provide evidence for ‘virtual certification’, although will ultimately require hardware integration and demonstration infrastructure. Some key considerations for these systems are fault tolerance, cabling considerations and harsh environment capability. There are several future technologies which will drive the adoption of whole aircraft electrical power systems. These include energy storage and recovery systems, high voltage battery systems, fuel cells, self-reconfiguration (healing) concepts, emergency power systems, cyber preventative system tools, advanced EMI/EMC filter systems as well as wireless and embedded sensing. Some of these topics are further discussed later in this paper.

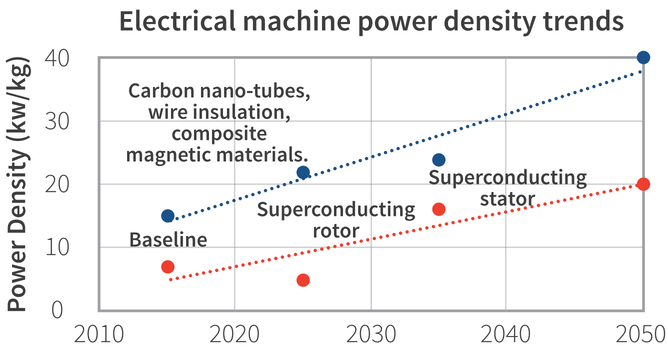
Megawatt motor drives

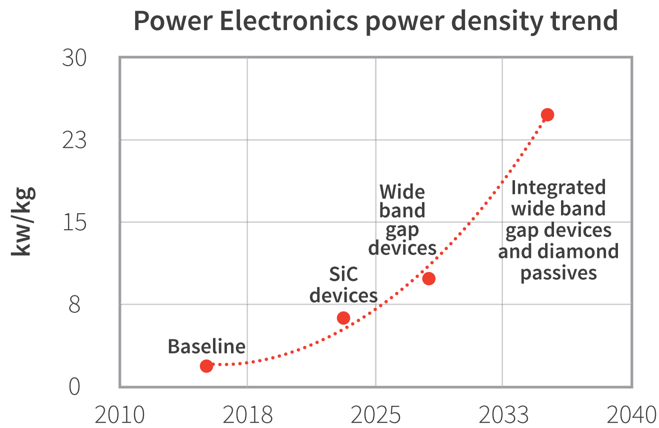
There are some clear potential advantages to meet future emissions targets and increasing fuel costs using electric propulsion. Electric propulsion enables the aircraft to be operated with reduced (or no) dependence on kerosene and instead delivers propulsive force through electrical energy powering electricallydriven propulsors. As a consequence the emissions generated through conventional propulsion (i.e. NO_x, CO, soot and unburned hydrocabons) are reduced or eliminated. Fuel costs also change as the dependency on keresone is reduced. As a consequence, technologies required for hybrid and all-electric aircraft propulsion need to be developed and demonstrated. Depending on the application, environment and thermal management constraints, electrical motors today typically have a maximum power density of less than 20kW/kg. For aerospace applications, the requirement to increase power density will drive electrical machine technologies in thermal management, magnetics and ultimately the realisation of superconducting machines and systems. There are a variety of machine topologies that could yield improvements, although more research is needed confirm which ones offer the best route. Ultimately, higher risk superconducting technology should deliver the highest power densities but again there is much work to do to understand how it can be applied in the aerospace environment.

The need for higher efficiency, higher power density power converters are equally required. Power converters with conventional air cooling are typically limited to 20kW/litre but a reasonable future target for aerospace would be 50kW/litre to align with the motor drive applications. Continued research and development is necessary for a range of technologies and in the application of new materials, innovative designs, power converter topologies, manufacturing techniques and semiconductor devices/ packaging. The combined impact of these underpinning technologies on the design and construction of electrical machines and power converters will be significant.

For example, silicon carbide (SiC) power semiconductor devices and their packaging will be a significant factor in future designs as when combined with emerging power converter topologies, they enable far higher machine speeds without a corresponding reduction in power quality. Many relevant issues such as sensorless speed control and micro-processor implementation of modulation and control are already well understood, although they need developing for the higher power (MW) levels. Care must also be taken not to assume that changing any one variable on machine design will enable the complete desired targets to be made.

For example, increasing rotational speed eventually leads to a larger, rather than smaller, motor due to mechanical integrity constraints. It is therefore recommended that technology development and deployment for electrical machines and power converters takes a system optimisation approach and considers all technology options, probably across several different projects. Any demonstrators built must be designed and constructed with the knowledge that the final application will be many megawatts.





Secure digital systems and communication

Ultra-scale integration for control technology

A System-on-Chip (SoC) is an integrated circuit that integrates all components of an electronic system into a single chip. It may contain digital, analog, mixed-signal, and often radio-frequency functions on a single chip substrate. New ultra-scale SoC integration technologies offer performance increases for avionics systems through elimination of multi-chip, chip-to-chip bandwidth bottlenecks and optimised hardware/software partitioning.

This approach offers the opportunity for rapid change and customisation for avionics systems. Significant avionics cost reduction is envisaged by integrating hardware and software processing solutions in a single device, eliminating board-level high-speed interfaces, reducing component count and power supplies, and simplifying the PCB design. In the electronics market, there is an increasingly rapid obsolescence of stand-alone microprocessor chips. In parallel, PCB design complexity is increasing to layout and track complex hardware devices. As a result there is a shift in computing from legacy technology to modern processor solutions (e.g. ARM) which is potentially bypassing legacy equipment suppliers who had previously enjoyed market security through previously perceived 'barrier to entry'.

This new technology, enabling SoC scale integration, creates the opportunity for chip level integration for control solutions (and other aircraft functions). Ambitious and disruptive advanced control system solutions may be achievable with these solutions, enabling better aircraft level performance optimisation.

In the UK there is an opportunity for aerospace to leverage the massive investment in technology and tools for SoC integration in the telecoms and automotive sectors through well established and leading UK players in this technology. Complex COTS FPGA solutions with hard-core ARM processing are widely available and cost competitive. Robustness of the parts to aerospace environmental effects (e.g. Single Event Upsets) needs to be addressed and mitigated for aerospace applications. Semi and full-custom SoC processes are in wide-scale use and can be applied to build application specific solutions.

This does deliver a very robust solution but currently non-recurring costs for each SoC is high for the first (new) design. These solutions are the latest generation of ASICs (Application Specific Integrated Circuits) and allow for previously un-imagined complex hardware component integration (e.g. Apple SoC devices for iPhone). The design process is enabled by very advanced ECAD (Electronic Computer Aided Design) and simulation tools.

Leading UK companies are providing these enabling technologies (e.g. ARM, e2v) and UK cross-sector applications exist. New architectures are also emerging to support safety critical embedded systems (e.g. ARM Cortex-R52). New products are beginning to appear in the market and are offering step-change capability with new technology (e.g. control integration, advanced signal and image processing). In aerospace in the UK, systems and equipment suppliers need to take advantage of these technologies to remain competitive.

The ATI will convene the UK aerospace sector to scope and prioritise a cross-sector initiative for safety-critical ultra-scale functional integration. The initiative could form links to other sector bodies working in this area, as well as identifying research programmes to address SEU mitigation strategies for FPGA solutions and architectures for aerospace environment, integrity, availability and certification. A UK solution for low-volume high-mix SoC designs for avionics offering competitive advantage for UK aerospace could be a disruptive output, enabling scalable solutions for control system integration and optimisation.

Multi-core processors

Microprocessor technology is driven by mass market consumer electronics applications which means that technology progresses rapidly and becomes obsolete in short timescales (as little as 4 years). For aerospace applications where aircraft remain in service for 30 years or more, processor obsolescence is a key element of the product strategy. The latest multi-core processors which have been developed for consumer applications enable superior computational capability. Porting software into a single core of a commercial multi-core processor offers limited improvement in computational performance but is inherently lowest risk to certify. Allocating process across the cores offers greater performance capability but increases emergent behaviour, particularly if processes are split in parallel across multiple cores.

Due to the inherent risks associated with the low-level functionality built into the multi-core devices by the manufacturers, the certification effort for aerospace applications is significantly greater than older, less capable single or dual core devices. Thus, the cost of certification for multi-core processors is prohibitive and this tends to be a barrier to introducing increased functionality within aircraft systems. In exceptional cases, companies have resorted to developing their own microprocessor to exert control over the functionality, mitigate obsolescence and aid certification.

However, this is not the standard approach taken by most of the aerospace sector. The Certification Authorities Software Team (CAST) have recently released a position paper update CAST-32A Multi-core processors (November 2016) which provides guidance and considerations for using multi-core processors. It is intended to be for guidance purposes only and actual projects will still need to engage in specific discussion with the appropriate certification authority.

The small number of programmes being executed with multi-core processors means that UK systems organisations are not developing avionic solutions at the same rate as commercial processor technology progresses and hence the capability gap for delivering aerospace safety critical software in state of the art microprocessors is increasing. There is an opportunity for the ATI to convene the UK aerospace systems organisations to collaborate and share best practice approaches to developing affordable solutions for adoption of multi-core processor devices.

Software – enabler or hindrance

(Feller & Co, 2013) reported that "the aircraft industry struggles with exponential growth in complexity and cost". This problem is forecast to worsen due to increased functionality that software is anticipated to provide in the future. The ATI have targeted investment in a highly collaborative industry led programme called SECT-AIR to address some of the concerns around software costs and timescales. It is focussed on techniques that support preciseness (reducing error and rework) and automation (removing human overhead). There is a broad range of standards, methodologies and tooling available for the development and deployment of safety-critical software. The trend over the last decade has been towards using model-based systems engineering to support preciseness and automation.

This has not had the expected return on investment due to immaturity of modelling languages and standards, immaturity of modelling tools, tool vendor lock-in, lack of interoperability of solutions, difficulty of implementing change with an industry that has heavily invested in legacy products and the cost and challenge of certification of development tools.

The major challenge with all current software development processes, model-based or otherwise, is their reliance on conventional testing practices. However, testing alone does not guarantee the necessary software quality and contributes to escalating development costs as errors are often found late in the development cycle, or worse after product deployment. Formal verification technologies offer opportunities for reducing cost as they enable errors to be found early in the development cycle. They can also prove correctness of software designs before implementation. However, such solutions are typically developed in academia and are still immature in their industrial tool development. They also face the difficulty of scaling to address the systems currently being deployed and providing the appropriate focus on safety. There are further challenges in certification, including dealing cost-effectively with change, handling data-intensive systems, dealing with autonomy, tool certification, etc.

The escalation of software complexity and cost requires a paradigm shift in the way software is developed and innovation in technology to support it. This is supported through the ATI strategy by bringing the necessary software, systems and safety expertise together through collaborative projects (such as the ATI SECT-AIR project) and continuing to exploit the technologies. The aerospace sector has established a 'centre of excellence' in this field through the ATI SECT-AIR programme. This includes engaging with and learning from other sectors that face similar challenges (e.g. automotive).

Continued research is required to improve the quality of models, together with formal verification, code generation, testing/simulation frameworks, and code analysis tools for managing legacy systems. The integration of such technologies within existing model based systems engineering practices will have a radical impact on reducing the cost of software.

Artificial Intelligence

The development of Artificial Intelligence (AI) in computers has historically been limited by the availability of high performance computing, but the step change improvement in processing power offered by cloud computing offers much greater potential. There are three areas of artificial intelligence to consider for aviation. These are expert systems, autonomous systems and security.

The aerospace industry has used expert systems since the 1980s to aid the design of products and aid optimisation of specific parameters. Legacy expert systems were typically single, integrated software packages from a specific vendor. Today, an internet search engine can 'read' several thousand books per second and in the future, it is anticipated that expert systems will develop autonomous learning capability. If this is then coupled with the ability to automatically iterate designs, traditional aerospace hardware design processes could disappear.

A logical development is for aircraft systems components to be optimised automatically. Whilst expert systems offer a significant opportunity to the UK aerospace sector, the UK needs to protect and leverage IP to remain leaders in aerospace systems design using expert systems within a high value design environment.

Autonomous vehicles have been developed and well publicised by Google, Tesla and others. However, in many ways, aerospace leads the way with autonomous systems, with obvious examples like auto-pilot and Full Authority Digital Engine Control as two technologies that have directly replaced personnel in the flight deck. As connectivity improves between aircraft, ground and between ground systems, there will be further opportunities to optimise aircraft operation. These could include aircraft loading, route planning, maintenance planning and ultimately full autonomy.

It is noted that there are already examples of autonomous systems in service – the F-16 fighter contains an automatic ground collision avoidance system that takes over control from the pilot and this has reportedly already saved a pilot's life. Autonomy is a recognised cross cutting capability in the ATI *Raising Ambition* document and the ATI will continue to work with industry to develop and prioritise the cross-cutting strategy.

Opportunities in artificial intelligence will ultimately succeed or fail based on the security systems that surround them. The current state of aerospace security is appropriate for current systems. However, the increasing pervasiveness of smart devices with 'Internet of Things' (IoT) connectivity is already targeting hitherto everyday household items. For example, the security provisions included for a smart kettle were commensurate with the criticality of a kettle, but the unexpected weakness became clear when they were collectively hacked and used to target another system by over-loading it with spurious messages. Security is an area where sole reliance on the approach taken by wider industry is insufficient for aerospace.

The aerospace sector needs to build systems that provide a security system suitable for our industry. The ATI have already identified this as priority element of the Digital cross cutting theme published in Raising Ambition. The ATI will lead the aerospace sector to define and prioritise technology and capability.

Wireless sensors and energy harvesting

Wireless sensor networks offer many potential advantages for aerospace, particularly for applications including structural health monitoring and prognostics and test data collection. Wireless sensor networks enable replacement of heavy and bulky sensor wiring harnesses with a wireless link which is of obvious benefit for monitoring rotating and fixed structural components, as well as engines and landing gear systems. Wireless technology can also enable easier retrofit of monitoring systems both for system upgrades and temporary data acquisition. Energy harvesting provides a means to "harvest" small quantities of otherwise wasted energy from the environment to provide power to wireless devices, thus avoiding the need for a wired power supply or batteries. Sources of energy typically include mechanical movement or vibration, temperature difference or light.

Robust, long-life wireless monitoring and control systems are now reliably deployed in other sectors (e.g. automotive tyre pressure monitoring, industrial process control and building automation). Wireless and energy harvesting technology is also a key enabler of the Internet of Things (IoT). In the UK there are well established academic research programmes on wireless sensors and energy harvesting in aircraft applications.

For aircraft health monitoring and prognostics applications, collaborative R&T projects with industry have successfully moved the state-of-the-art forward with small-scale demonstrations. Several technology challenges which remain to be addressed include: power consumption, robustness of electronics, alignment of energy harvesting capability with electronics, scalability to large networks, development of current and emerging suppliers (who are typically focussed on IoT and consumer applications), choice of wireless protocols, on-aircraft data transmission range, aircraft EMC requirements, security and data integrity, integration with data processing and maintenance systems, and the approach to qualification and certification.

In addition to these challenges, a significant limiting factor reported by many projects is the difficulty in accessing representative demonstration facilities on a ground test aircraft system test facility or a major sub-system scale to allow testing and validation of large scale wireless sensor networks and energy harvesting systems in relevant environments. In the UK there is an opportunity through the ATI to align these types of technology validation needs with existing and developing UK technology infrastructure.

Automatic flight controls, sensors and cueing for helicopter Degraded Visual Environment (DVE) operations

Helicopters crashes are statistically 35% more likely than fixed wing aircraft (ref: NIAG 167) and most helicopter accidents occur at low height and low speed. Degraded visual environment (DVE) is a factor in most helicopter accidents (ref: EASA research project 2011.02) and the solution to safe operation in DVE lies in a combination of automatic flight control systems (AFCS), 2D and 3D sensors and effective cueing (ref: NIAG 167 and 193).

The AFCS (Automatic Flight Control System) provides stability and improves the handling qualities by controlling the motion of the aircraft while in flight. Some examples of DVE modified AFCS control laws are: transition modes (up and down (multi-stage)), basic hold modes (hover height, attitude hold and position), basic command modes (translational rate command, attitude, sensor driven guidance, collective channel only (basic fly up command), collective and cyclic (fly up / around), and auto land (GPS and/or optical). AFCS DVE modes appear to be the key aspect of reducing workload and increasing safety.

Several 3D sensors have been developed and key examples are Millimetre wave (MMW) radar, Lidar and FLIRs. MMW radar can penetrate all dust, but further development of signal processing and displays is required. Light detection and radar (Lidar) can detect wires and poles, and is useful in confined areas, but loses capability in heavy dust. Forward looking infrared sensors (FLIRs) are good for night pilotage. Database controlled flight into terrain (CFIT) avoidance systems are also available and useful for flight in known environments (without new obstacles).

For the flight deck, head-up cuing is commonly regarded as the primary means of pilot interaction with a DVE system, but a combination of head-down and head-up cueing appears to add value, and this may result in a need for two pilots. Overlay of primary flight display information is simple, mature and widely used, but significant effort is required in providing a useful fused sensor picture of the terrain and obstacles. DVE role symbology exists but is immature, and improvements to head-up DVE display symbology would be preferable. Head-down symbology is appropriate in combination with an enhanced auto pilot. Audio cues are also essential. Delivery of these solutions through improved flight deck technology is costly due to safety criticality. Technologies to reduce the development time and cost for the systems should continue to be progressed through industry and academic collaborative research.

Phased Array Antennas

A phased array antenna is composed of a spatial distribution of radiating elements, each typically with a phase shifter. Beams are formed by shifting the phase of the signal emitted from or received by each radiating elements, to provide constructive/destructive interference to electronically steer the beams in the desired direction. An active phased array antenna has many digitally controlled radio frequency elements integrated with the radiating elements and these enable a high gain directive beam from a low-profile enclosure.

Phased array antennas typically require separate transmit and receive apertures, although in some cases, dependent on the technology and specification, a combined transmit-receive device is possible using a single shared aperture. This is increasingly seen as a key technology for both future satcom and air-to-ground connectivity, within the commercial air transport and business jet markets, to support the growing demand for high-bandwidth passenger services, support the growing demand for high-bandwidth passenger services, as well as air traffic control, aircraft operation and information service applications. Phased array antennas are the most advanced form of antenna used on aircraft, although the technology is not mature at the higher frequency bands (>2GHz). These higher frequency bands are planned to be exploited by communication service providers to provide continuous connectivity solutions.

Phased array antennas also enable aircraft to use future planned low earth orbit satellite constellations as these require frequent satellite handover between the many small satellites and hence multi-beam capability. Phased array antennas also enable low profile and conformal radomes which reduces aircraft drag and weight. Phased array antennas have the potential to support the ever-increasing number of frequency bands and communications links needed on future aircraft, as well as coping with increasing interference, without increasing antenna sites, using smart multi-band beam-forming techniques.

The technology offers potential spin-off applications in defence, unmanned aerial vehicles as well as land and maritime applications. Further development of this technology will target improvements in performance, cost, environmental capability and thermal management. Further consideration of this technology and its alignment with the overall ATI technology strategy for aircraft communication is provided in the ATI publication *Raising Ambition*.

Structural health monitoring

Health monitoring systems are successfully deployed on a range of products such as aircraft engines and helicopter gearboxes and the systems have had a major impact on how products are designed and supported in service. The data collated can be used to better understand the in-service environment, thus driving product optimisation and can be used to more accurately predict maintenance intervals and reliability, ultimately leading to a safer product. The state of the art for structural health monitoring depends heavily on the type of structure being monitored and the certification and regulatory environment surrounding it.

Example applications are rotorcraft components, damage tolerant components, and safe life components. Monitoring of rotorcraft components is predominantly performed through frequency domain analysis of vibration signals (as almost all critical components of the rotorcraft are rotating). This provides an effective means of health monitoring and a natural extension of the engine, gearbox, and shaft monitoring systems which have been in service for several years. Rotorcraft can also benefit from damage tolerance structural health monitoring techniques which are in existence for fixed wing aircraft.

In the damage tolerance regime, the state of the art systems look to replace regular inspections with bespoke monitoring equipment installed in-situ.

A variety of systems exist, leveraging off-wing techniques such as ultrasonics and eddy current techniques but installing them directly on-aircraft. In the safe-life regime, the existence of cracks is not permitted, so monitoring systems aimed at detecting cracks are not suitable. In this regime, the state of the art is focused on direct load measurement (through traditional means as well as fibre optic sensors) and indirect load and response measurement (through monitoring of the aircraft behaviour followed by an analytical treatment to determine the structure's response).

A potential application which has not yet been developed is the aircraft landing gear system. There are number of key technical challenges that need to be overcome for this system to be implemented on landing gear products with a high level of confidence. These include: sensor integration, light weight solutions, data management and processing of big data. Some of the critical technology enablers are wireless autonomous sensors, reliable robust and accurate sensors, high memory capacity and processing tools.

Additive re-manufacturing

Recent improvements in additive manufacturing technologies have already enabled production and repair of metal parts for the aerospace industry. Electron beam melting, selective laser melting and other metal deposition processes, such as wire and arc additive manufacturing, are regarded as the best candidates to achieve this challenge. For this purpose, it is crucial that these technologies are well characterised and modelled to predict the resultant microstructure and mechanical properties of the part.

While these processes present many advantages to the aerospace industry in comparison with traditional manufacturing processes, airworthiness and air transport safety must be guaranteed. The impact of this regulatory framework on the implementation of additive manufacturing for repair and production of parts for the aerospace industry is significant.

This is a long-term concept with significant hurdles still to be overcome. These challenges include materials characterisation and component certification. If successful, this concept will significantly impact business models and the supply chain. The current focus should be on developing additive manufacturing processes to produce aerospace components with well characterised material properties. This topic is recognised as a cross cutting capability in the ATI *Raising Ambition* publication. Further information on this topic can be found in the ATI White Paper on Additive Manufacturing.

Augmented reality glasses

Augmented reality offers multiple benefits throughout the whole product lifecycle. One specific instance is the use of augmented reality glasses. Smart glasses are not new but despite several decades of technology development they have yet to be adopted at scale by the aerospace sector for product design, manufacturing, operation or maintenance.

This slow adoption may be linked to the need for long pilot programmes to demonstrate return on investment before larger scale deployment. Smart glasses have the potential to improve productivity by connecting the workforce directly with the smart systems and automation in the aerospace design and manufacturing environment. There are many potential applications in the design & development phase (e.g. design visualisation, overlay of data on physical prototypes, design mock-ups, test monitoring, etc.), with more applications in manufacturing and MRO (e.g. replace paper with digital data, assembly overlays, fault diagnosis, real-time inspection, build record validation and configuration control) as well as a range of other applications such as training or sales & marketing.

Some of the challenges which have slowed the uptake of smart glasses in aerospace include: tracking issues (including shop floor environment issues), human factors (weight, comfort, nausea), response times and latency, cost of hardware, software and content, workforce acceptance and obsolescence (in a fast-moving technology).

Emerging thermal technologies

Thermal management systems are widely deployed across the aircraft and in many cases, are independent systems meaning that whole aircraft level thermal management is not optimum. For future aircraft, there is a need to integrate and optimise through platform level thermal management as well as taking advantage of thermal technologies being developed in adjacent sectors. Fundamental material based technologies may unlock heat management system solutions which can then enable greater optimisation at whole aircraft level. These technologies range from new materials to new system architectures.

Engineered meta-material thermocrystals consisting of nano-structured semiconductor (Si90Ge10) crystals. These concepts use anisotropic thermally conductive material as heat waveguides, which transfer heat along one direction, or as thermal diodes that allow the heat to flow one way only. Such materials could significantly improve the efficiency of thermoelectric devices (or for defence application, achieve thermal cloaking).

A second example is the application of high-efficiency thermoelectric devices. These devices could improve the business case for waste heat energy recovery from thermal engines and increase their overall efficiency. Researchers have demonstrated tin selenide (SnSe) single crystals, which increases the thermoelectric efficiency above 20%. This is twice the efficiency of PbTe. The performance enhancement is attributed to the intrinsically ultralow lattice thermal conductivity in SnSe.

A third example is the use of oscillating heat pipes which operate like fluidly-pumped devices where the thermal energy from a heat source is converted into kinetic energy, and the working fluid inside oscillates between hot and cold channel areas. Potentially this could enable future aerospace engine architectures, including core mounted accessories and controls.

A final example is high conductivity carbon nanotube (graphene oxide) membrane as a flexible, low-cost, bulk production paper-like material. Fabrication techniques are being developed for cost effective manufacturing of these materials which are known as buckypapers. These high-performance materials are highly conductive – both electrically and thermally (well known as the highest thermally conductive material). These papers could be used to make heat sinks by dispersing heat more efficiently, or using the membrane's efficient reflection of heat, could also be used to improve the fire resistance of components. Films of the membrane could also be used to protect electric circuits from electromagnetic interference or as protection from lightning strikes on aircraft, replacing the conventional copper mesh and hence reducing weight.

Thermal technologies are increasingly important in aerospace architectures as new concepts create increasingly demanding thermal loads with reducing part of the UK aerospace system design. There is an opportunity for the ATI to lead the aerospace sector to increase the exploitation of thermal management technologies.

Energy storage

There are a variety of energy storage mechanisms but in this paper the discussion focusses around battery technology. The chart compares different energy storage options and shows the dominance of kerosene in terms of both mass and volume specific energy. Alternative energy storage technologies include fuel cells, liquid air, compressed H2 or liquid H2, ultra-capacitors, or mechanical flywheels. Although some of these sources match or exceed the specific energy of batteries, the implementation in a vehicle also relies on the specific power (kW/kg) of the "engine." For many of these alternative energy sources there is a need for heavy containment systems or thermal management features which means that the specific power of these alternative energy storage systems is unviable for aviation.

However, battery technology has progressed significantly since conventional battery capability was established in the 1870s. Batteries already power small ultra-light aircraft and are now being considered for larger aircraft in hybrid arrangements combined with other power generation systems. Batteries can respond quickly to changing power demands and hence are well suited to support critical transient load requirements. Whilst batteries provide electrical power without production of carbon, the overall environmental impact through indirect emissions from the power source used to charge the battery also need to be considered.

The challenge for aerospace is to achieve specific energy density (Wh/kg) and specific power (kW/kg) for the conversion of the stored energy which are comparable with hydrocarbon based power systems. Hydrocarbon fuels used on almost all types of vehicle possess high energy density and enable the weight of the fuel to be combined with a significant weight of atmospheric oxygen, thus lowering the weight that needs to be carried by the vehicle. The weight of the battery itself does not reduce during the mission as is the case when kerosene is consumed and hence this also needs to be considered in the overall aircraft concept.

The power density (kW/kg) of the vehicle engine itself is complementary to the battery energy density and determines the viability of any vehicle or mission. Whilst aircraft propulsion systems based on batteries and electrical motors are two to three times more efficient than functionally equivalent conventional propulsion systems with combustion engines (such as gas turbines) and geared transmissions, the energy storage density of hydrocarbon fuels means that conventional technology is far superior at a whole system level in terms of propulsion system plus stored energy weight and volume. Conventional aero engine and hydrocarbon fuels are therefore superior to electrical energy storage for high payload and range requirements. Aircraft with radical configurations and mission profiles and/or hybrid electric architectures are likely to be the first to fully utilise breakthroughs in battery systems. Battery systems with specific energy greater than 800 Wh/kg are anticipated to be required for parallel hybrid propulsion systems on regional and single-aisle aircraft. All-electric regional and single aisle aircraft are anticipated to need a battery specific energy of 1800 Wh/kg. The current trajectory for battery research anticipates a battery specific energy of 500 Wh/kg by 2030.

High specific energy battery systems will require major breakthroughs to overcome the weight impacts of key components such as current collectors, electrolytes, separators, battery cases and terminals. For aviation, the battery technology challenges will need to demonstrate appropriate safety as well as consideration of the infrastructure requirements to deploy battery solutions in the air transport system. Further discussion of battery technology will be included in the forthcoming ATI publication on More Electric Aircraft due to be published later in 2017.

Solar Power

Solar power is potentially attractive as a renewable power source with solar cell efficiencies now approaching 50% compared to 25% in 1990. In addition, cost of the cells is continuing to reduce through mass production. In aviation, solar panels are already deployed for lightweight, high endurance aircraft. These ultra-light aircraft can store enough power to stay aloft through the hours of darkness. However, with cell weights of ~1 g/W of energy and power density of <200 W/m2 the ability to provide significant amounts of power for large commercial transport aircraft is limited.

Technology	Theoretical energy density (Wh/kg)	Target energy density (Wh/kg)	Timeframe
Nickel batteries	–	180	2015
Graphite/Ni/Mn/Fe Anodes	400	220	2018
High voltage cathodes	560	250	2021
Silicon/metal alloy anodes	880	300	2024
Lithium metal polymer/ solid state battery	990	>300	2026
Lithium air/lithium sulphur	3000	>>300	2030

Disregarding additional losses and inefficiencies such as actual versus ideal wavelength conversion and incidence losses, solar cells deployed across the wings and fuselage of a conventional single aisle commercial aircraft would only deliver tens of kilowatts of power for an aircraft overall power scheme of tens of megawatts. Integration of solar power in large commercial hybrid aircraft is therefore seen to be unlikely. However, increasingly effective solar energy capture performance through large scale ground based solar farms could be considered as a renewable energy source to charge hybrid aircraft electrical systems at airports.

TRENDS AND INSIGHTS IN COMMERCIAL AIRCRAFT SYSTEMS EMERGING TECHNOLOGIES

For the selected topics covered in this paper the following summary shows likely market penetration in aerospace and UK positioning.

Topic	Estimated maturity timeframe	Aerospace sector approach	Current maturity	UK competitors	UK positioning to develop	UK positioning to exploit	Key attributes impacted
Whole Aircraft electrical power systems	Exploit	Drive	Medium	USA, Germany	Strong	Strong	*1, 2, 3, 4*
Megawatt motor drives	Exploit	Drive	Low	Germany	Strong	Strong	*1, 2, 3, 4*
Ultra-scale control integration	Exploit	Adopt	Low	USA, Taiwan	Weak	Weak	*1, 5, 6*
Multi-core processors	Secure	Adopt	Medium	USA	Moderate	Weak	*1*
Safety critical software	Secure	Drive	High	India	Strong	Strong	*1, 6*
Artificial intelligence	Position	Watch	Low	USA	Moderate	Moderate	*1, 4, 5*
Wireless sensors & energy harvesting	Exploit	Adopt	Low	USA	Moderate	Weak	*1, 4*
Rotorcraft flight deck systems	Exploit	Drive	Medium	USA, Italy, France	Strong	Strong	*4, 6*
Phased array antennas	Exploit	Drive	Low	USA	Strong	Moderate	*4, 5*
Structural health monitoring	Exploit	Drive	Medium	USA, Germany	Moderate	Moderate	*1, 4*
Additive re-manufacturing	Position	Adopt	Low	USA	Moderate	Moderate	*1, 4*
Augmented reality glasses	Position	Drive	Low	USA, Japan, Italy	Weak	Weak	*1*
New thermal technologies	Position	Watch	Low	USA, Germany	Moderate	Weak	*2, 3*
Energy storage	Exploit	Adopt	Medium	Japan, Korea, China	Strong	Strong	*2, 3, 4*
Solar energy	Position	Watch	Low	USA	Weak	Weak	*2, 3*

Key

Estimated maturity timeframe:
+ **SECURE** (next five years)
+ **EXPLOIT** (next 10 years)
+ **POSITION** (next 15+ years)

Key Attributes: **1** - Cost, **2** - Environment, **3** - Fuel efficiency, **4** - Operational, **5** - Passenger experience, **6** - Safety

Several of these topics have complementary activity in other industries and sectors as well as aerospace. There is an opportunity in the UK to convene systems capability to focus activity to deliver timely solutions to meet multiple industry and sector needs.

In some cases, this is already underway but there are some gaps to consider:

- In safety-critical software, the ATI have already brought together a broad industry and academic consortium (in the SECT-AIR project) to progress more affordable approaches. This consortium should consider consulting and engaging with other sectors as appropriate.
- For multi-core processors, system-on-chip technologies and artificial intelligence (including security considerations), there is benefit from the aerospace sector convening a dedicated working group to characterise and deploy best practise in the UK.
- Further development of electrical system technologies to support future aircraft needs to be coordinated with technology developments in other sectors, aligning with automotive developments which are progressing at pace.
- Artificial intelligence and especially cyber security issues have some shared learning opportunities with other sectors although safety criticality in aerospace will continue to drive adoption of improved protection strategies and associated processes.

NEXT STEPS FOR THE ATI

1. More electric technologies are progressing within current and planned R&T projects although the overall roadmap for more electric aerospace technology in the UK still needs to be articulated and delivered. A follow up paper, specifically focussing on this field will be issued by the ATI later in 2017.
2. Intelligent systems deploying System-on-Chip, multi-core processors or safety critical software will be critical for securing and growing UK systems capability in aerospace. In addition, these technologies are applicable across other sectors and a collaborative UK centre of excellence to harness and exploit these technologies should be considered by government, industry and academia to establish how the UK can assert leadership in these topics.
3. Cyber security strategies for aerospace need to be clearly harnessed to ensure that disruptive technologies such as artificial intelligence can begin to be safely deployed in relevant applications. ATI is convening a group of industry experts to assemble a roadmap for cyber security in aerospace which will result in specific ATI publication on cyber security during 2017.
4. Thermal technologies are increasingly important in aerospace architectures as new concepts create increasingly demanding thermal loads with reducing part of the UK aerospace system design. There is an opportunity for the ATI to provide technology leadership and increase exploitation of UK thermal management technologies across the aerospace sector.
5. Energy storage will continue to be increasingly important as hybrid systems deliver whole aircraft level benefits which rely on dependable and high capacity energy storage solutions. Activities in this field should continue to be watched to gauge appropriate opportunities for integrating these developing capabilities in new architectures.

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Contact us

For further information on emerging technologies in the aerospace sector please contact **info@ati.org.uk**