AVT-357 Technical Evaluator's Report

Technologies for Future Distributed Engine Control Systems (DECS)

Technical Evaluator's report of the proceedings and highlights of the AVT-357 Workshop which took place virtually between 11 and 13 May 2021.

CONTRIBUTING OR SUPPORTING AUTHORS

Technical Evaluator:

Dr. W.D.E. ALLAN
Royal Military College of Canada
Kingston, Ontario
CANADA

billy.allan@rmc.ca

ABSTRACT

This report provides an overview of the proceedings of the AVT-357 Workshop focused on Technologies for future distributed engine control systems (DECS). There were two co-lead nations, Canada and Poland, with 7 participating nations in all. A three-day virtual workshop was held in May of 2021, comprising of six focus sessions each addressing matters pertaining to the introduction of DECS ranging from distributed architecture to smart sensors, chips, software, control systems, to diagnostics and prognostics. The outcomes were broad in scope, but largely addressed by sixteen presentations including a keynote that presented the challenges and advantages of the introduction of consumer-grade, high-power and availability, but low-cost and traceability and reliability multi-core processors. Conclusions accumulated from the presentations are summarized. Recommendations include continued emphasis on standardization methodologies, pursuit of control-by-light, hostile-environment-capable instrumentation, and further exploration of artificial intelligence, whilst not losing sight of the advantages of simplicity in engine control. A record of discussion is included.

Keywords: Gas turbine engine, digital engine control, instrumentation, engine monitoring, engine control, engine test cell, artificial intelligence, network.

LIST OF ACRONYMS, NOMENCLATURE AND/OR GLOSSARY:

AI	Artificial Intelligence
ANN	Artificial Neural Network
AR	Augmented-Reality
AVT	Applied Vehicle Technology
COTS	Commercial-off-the-shelf
DECS	Digital Engine Control System
EHM	Engine Health Monitoring
EMI	Electro-magnetic Interference
EMP	Electro-magnetic pulse
FADEC	Full-Authority Digital Engine Control
ML	Machine-learning

RFID	Radio Frequency Identification
R&D	Research and Development
STO	Science and Technology Organization
TE	Technical Evaluator

FOREWORD:

While the state of the art in aero-engine control remains a centralized, engine-mounted, full-authority digital engine control (FADEC) system, the emergence of technology at a suitable state of readiness and the imminent introduction of hybrid and more electric propulsion have motivated the exploration of distributed engine control systems (DECS). The advantages in control system weight per overall engine weight, combined with the emergence of artificial intelligence (AI) and advanced networking opportunities, have facilitated the exploration that was the general subject of this workshop. The capabilities of engine test cells provide inspiration for sensors and logic that is up to the complex and unforgiving task of high-fidelity engine control. The goals of this workshop were to investigate opportunities demonstrated by engine test cell instrumentation, control, sensors, techniques for their migration to flying platforms. Furthermore, engine models, networks and control schemes' potential to support distributed control were presented and discussed. The breadth of topics was high for a workshop, and in the event of detailed contribution, notwithstanding its quality, the consequent capacity to incorporate it into a cohesive theme was limited due to the breadth of the study.

Considerations for contributing techniques and technologies to DECS include flight safety, robustness and reliability, performance, high-temperature resilience, life-cycle cost, interoperability, and cyber-security, among others. The diverging trends in control strategies: open networking schemes on one hand, with their capacity to reduce costs, introduce novel approaches, and remain supportable while on the other hand, the network security, proven fault-tolerance and robustness of well-designed, well-standardized, proprietary schemes.

At the same time, innovative exploration in networking concepts, instrumentation and monitoring systems, control strategies and machine learning, provided it is done with an eye on DECS applications, fell within the mandate of the workshop. The effort was seen to complement and to build upon recent Science and Technology Organization (STO) investigations, notably AVT-180 (Gas Turbine Engine Test Cell Instrumentation), AVT-229 (Test Cell and Controls Instrumentation and EHM Technologies for Military Air, Land and Sea Turbine Engines) and AVT-306 (Transitioning Gas Turbine Instrumentation from Test Cells to On-Vehicle Applications).

The stated goals of the workshop were firstly to identify and evaluate hardware and software technologies proven in the test cell environment that are needed to enable the transformation of turbine engine control systems from centralized to distributed architecture; Secondly, to provide a definition of what needs to be done at the hardware and system level to increase robustness, temperature resistance, flight safety, and the ability to operate effectively in the engine environment; Finally, recommendations were expected on best practices and standard requirements to facilitate integration of ruggedized components.

ACKNOWLEDGEMENTS:

The enthusiasm of the participants and Co-chair, Hany Mustapha were appreciated since the Technical Evaluator (TE) was assigned in the late stages of activity, due to the sudden unavailability of the original evaluator. It is evident that significant effort was put into the preparation of the papers presented at the workshop. Advice from Mr. Jim MacLeod, the Mentor was greatly appreciated. Leadership from Dr. Radoslaw Przysowa was clear from the very beginning, and the author credits him for his initiative, diligence and thoroughness in steering the activities of the workshop.

Chapter 1 – Technical Review of the Workshop

Dr. W.D.E. Allan
Technical Evaluator (TE)
CANADA

1.1 GENERAL

The programme committee for this Research Workshop spanned 18 months from January 2020 until June 2021 and involved seven nations (BEL, CAN, DEU, GBR, ITA, POL, USA), led by Poland and Canada.

The workshop took place virtually over three days, with papers distributed between six sessions. The programme was opened with a keynote address by Eric Féron, Dutton/Ducoffe Professor of Aerospace Software Engineering at Georgia Institute of Technology. His remarks will be summarized, as will the general themes of the presentations, in the second section of this report. The fourth section will be reserved for the record of questions, answers and discussion points that followed each presentation. While important to account, this section will be left to the end of the report, preceded by the TE observations on the achievements of the workshop in Section 3.

1.1.1 Workshop Topics to be Addressed

The following is a list of contributions envisaged for the AVT-357 Research Workshop. Firstly, at the system level:

- Distributed intelligent control systems;
- Fault tolerance concepts and robust control;
- Flight safety and cybersecurity strategies;
- Modular architectures;
- Certification considerations;
- EMI-tolerant engine control networks, fibre-optic engine control networks, fly-by-light systems;
- High temperature-compatible communication architectures;
- Standardized methodologies for component evaluation, integration and testing; and
- Robust, reliable diagnostic and prognostic systems.

At the component level the following were targeted:

- Standardized smart sensors and actuators;
- Standardized system infrastructure – software, power supplies, chips, communication hardware;
- Use and transition of test cell-proven advanced measurement techniques;
- Fibre-optic sensing; and
- Certifiable components.

At the workshop, this wide range of topics were clustered as follows:

- Engine modelling & power management;
- Sensors and data transfer;

- Neural networks and other control schemes;
- Experiment reporting; and,
- Condition & health and usage monitoring.

1.1.2 Scheduled Activities

Six sessions were scheduled over three days, each with three presentations:

a. Distributed Architectures 1, Chair: Maria Grazia DE GIORGI, Italy

   i. Keynote address: Distributed control architectures: New middleware for smart software and hardware scheduling (Prof. Eric FÉRON, Georgia Institute of Technology, USA)

   ii. The concept of networked future distributed engine control system (Vadym SLYUSAR, CSRI AME AF, Ukraine)

   iii. Using the telemetry system as an element of the engine operation monitoring system of UAS (Teresa BUCZKOWSKA-MURAWSKA, Air Force Institute of Technology (ITWL), Poland)

b. Control Systems, Chair: Michał CZARNECKI, Poland

   i. Advanced Integrated Power Centre with Electric Power Transfer Functionality (Serhiy BOZHKO, University of Nottingham, United Kingdom)

   ii. Neural Nonlinear Autoregressive Model, (Luciano STRAFELLA, University of Salento, Italy)

   iii. A Nonlinear Neural Network Based Model Predictive Control for Industrial Gas Turbine, (Ibrahem M.A. IBRAHEM, École de technologie supérieure, Canada)

c. Chips and Software, Chair: Patrick HENDRICK, Belgium

   i. Efficient coding techniques for propulsion systems, (Michal CZARNECKI, Rzeszów University of Technology, Poland)

   ii. Challenges and Chances of Multi Core processors within future Control and Monitoring FADEC, (Karel STASTNY, Aerospace Embedded Solutions GmbH, Germany)

   iii. Predictive Control and Identification of Multivariable Gas Turbine Dynamics (Kacper GRZĘDZIŃSKI, Cranfield University, United Kingdom)

d. Smart Sensors, Chair: Andrew MILLS, United Kingdom,

   i. Self-Oscillations of the Free Turbine Speed in Testing Turboshaft Engine with Hydraulic Dynamometer (Yevhen MARTSENIUK, JSC FED, Ukraine)

   ii. New sensors for optimized performance, control and monitoring of turbofan lubrication systems, (Patrick HENDRICK, Université libre de Bruxelles, Belgium)

   iii. High-Temperature Magnetic Sensors, (Edward ROKICKI, Air Force Institute of Technology (ITWL), Poland)

e. Diagnostic and Prognostic Systems, Chair: Neil MARTIN, United Kingdom,

   i. Towards explainable artificial intelligence for centrifugal compressor operating conditions classification (Mateusz STAJUDA, University of Edinburgh, United Kingdom)

   ii. Comparative Study of a Powerplant Life Consumption Rate, (Ioannis TEMPLALEXIS, Hellenic Air Force Academy, Greece)

iii. Turbine engines resonance parameters monitoring, (Marcin KLUCZYK, Polish Naval Academy, Poland)

f. Distributed Architectures 2, Chair**:** Hany MOUSTAPHA, Canada,

i. Network of Smart Tip-Timing Sensors in Distributed Blade Health Monitoring System, (Jerzy KOTKOWSKI, The Air Force Institute of Technology (ITWL), Poland)

ii. Architecture of distributed control system for gearbox-free more electric turbofan engine, (Yevhenii KONONYKHYN, National Aerospace University "KhAI", Ukraine)

iii. Technical Evaluator Preliminary Report, (B. Allan, Canada)

2.1 WORKSHOP ACCOUNT

2.1.1 Notes from the Keynote Address

The keynote address by Prof. Féron focused on the emergence of inexpensive, light, powerful and plentiful computing devices and the challenges and opportunities they present to the aircraft designer. At issue, among other matters, is the research and development (R&D) motivation of the alliance and its members: the balance between conservatism demanded by flight safety-critical designs and the rate of advancement of consumer electronics, which essentially threaten the very existence of the infrastructure upon which the aerospace mission relies. For example, standardization and detailed documentation execution and management are inherent to risk-averse and unforgiving aerospace certification and operations. Yet the time demanded for proper performance of these activities is on the scale of that actually consumed for the delivery of multiple generations of a consumer electronic innovation. The three opportunities presented are found in:

a. Architecture: Maybe the perfection demanded by the aerospace mission, achieved from traditional architecture and support methodologies, can be offset by the innovative application of less-than-perfect but attractive new devices. They would be distributed networked, redundant and smartly managed;

b. Processors: Low-cost processors offer a trove of possibilities, including massive cheap computation capacity. Whereas this is not directly needed for engine control, perhaps the multi-path possibilities can make up for imperfection with parallel and simultaneous redundant processes, thereby achieving the level of reliability expected. Expected imperfections can be mitigated by the vast increase in computing capacity and repetition of processing activity.

c. Distributed Control. The topic of the workshop emerged in the final point: achieve the 1:1 billion reliability expectations using optimization modes, innovative connectivity and a reliance on the more-well-documented of the newer, less-tested and less-well-documented, cheaper components from, for example, the automotive industry.

2.1.2 Outcome from the Keynote Address

Themes emerging from the Keynote Address that resonated throughout the workshop included:

a. Standardization and the challenge presented to it by an equally critical cyber-security trend to proprietary systems.

b. The increasing application rate and advantages of consumer-grade electronics, together with their razor-thin cost margins and consequent minimalist approach to overheads such as documentation and convention.

c. The potential for creative networking and algorithm techniques for lighter, more robust instrumentation and process monitoring;

d. The twin-challenges faced with the introduction of AI: when to determine its own limitations demand a reversion to conventional control and whether to allow untraceable neural-network opportunities from a regulatory point of view.

2.2 WORKSHOP CONTRIBUTIONS

2.2.1 DECS characteristic technologies

The following technologies emerged from the presentations and papers, as organized by the targets of the workshop.

2.2.1.1 Network enabled distributed architectures. For a DECS to replace FADEC, the components of the engine control activity must be retained, even if distributed about an airframe or even off-airframe. While the latter may be a reach too far for the moment, one could consider the possibility of maintaining a remote digital twin or secure redundant control algorithm that could replace or reinforce its onboard counterpart in the case of damage or failure. In either case, the architectures would retain a reliance on on-board instrumentation for aircraft condition and engine status, including sensors for mechanical purposes (vibration, speed, tip-gap and fuel flow, for example), gas-path monitoring (temperatures, pressures and even particulate or gas properties, for instance), or environmental conditions (ambient conditions, altitude, airspeed or Mac h, and perhaps humidity among others). How the signals are transmitted is immaterial, but light-weight, electromagnetic interference (EMI)-free, cyber-secure, lightning protected, robust and reliable means could include conventional electrical signals or transmission by light. The role of existing, non-dedicated networks is a logical route, as is a dedicated engine control option.

2.2.1.2 Instrumentation. Engine control, distributed or not, will continue to rely on signals transmitted from sensors on the air vehicle (even a proximate vehicle) or within then engine and its immediate surroundings. Vibration, temperature, pressure, rotation, proximity, opacity, luminescence will continue to need to be sensed and transmitted. Instrumentation will need to be rugged, robust, reliable, light, temperature and vibration resistant, electromagnetically compatible (EMC) with response to environmental conditions predictable and consistent. The term smart sensor emerged regularly in the workshop, and it deserves special mention here. It denotes sensors capable of responding to changing conditions, able to self-monitor and diagnose, perhaps even containing logic capabilities that could part- or fully-process signals on-board, and feed, or provide access to, models of the very systems it is monitoring.

2.2.1.3 Speed. Any DECS will need immediacy in its direct control of an airborne engine. Any attempts to introduce AI, routines, optimization, signal processing will need to be parallel and unobtrusive, simply due to the complex hydro-mechanical system-of-systems that a gas turbine is. Control strategies need to be intelligent to the normal physical and thermal response of the engine, and robust enough to detect and respond to slight deviations from these norms. An Artificial Neural Network (ANN) can offer opportunities to expedite control input and monitoring however their ability to reasonably respond to extraordinary situations, and their consequent certifiability will determine their ultimate role in any future DECS.

2.2.1.4 Fault-tolerance. A successfully deployed DECS will need to match hydro-mechanical, hybrid and FADEC systems in responding to their own faults, or to inconsistencies in signals obtained from the airframe or engine instrumentation. While the former invariably had, often-rudimentary, fail-safe modes of operation, any DECS will be subject to an increased number of potential pathways for failure. Consider, for example, susceptibility to EMI, lightning, thermal or physical damage in an area or areas distant from the engine (historic location of the control system) and perhaps not even aboard the aircraft. A DECS may not simply be a FADEC remote to the engine, but rather a FADEC disintegrated and distributed.

2.2.1.5 Cyber-threat resistant. It is impossible to discuss DECS with its reliance on networks and its distributed architecture without a special mention of the need for resistance to cyber-threats. The scope of the threat is not simply the potential real-time interference with control operations, but meddling or denial of the models, digital twins, look-up tables, algorithms, performance history, support data (such as calibration), and communications protocols and means integral, either built-in or external to the system (the DECS).

2.2.1.6 Standardization. The alliance relies on smooth, integrated response and interoperability of its elements and equipment. At its core, standardization exists to enable this. Thus DECS, whether physically as a system-of-systems, conceptually in terms of protocols, architectures, algorithms or practically (testing, integration, self-assessment, model fidelity) must be subject to agreed-upon standards of performance, response, reliability, precision, documentation and methodology. This was observed to be a point of particular importance when weighing it against emerging cybersecurity strategies.

2.2.2 DECS Elements Emerging from the Workshop

As organized against the workshop targets, DECS characteristics, elements and technologies that emerged from the presentations and papers are summarized in this section. These sections incorporate component-level targets in the overarching system considerations.

2.2.2.1 Distributed Intelligent Control Systems. The introduction of and opportunities offered by multicore processing is likely the most significant advance apparent already in engine control. A move away from dedicated control systems mounted on-board, independently providing robust, simple and reliable engine control is the theme of this DECS workshop. Thus, the role of AI is difficult to ignore, as is the choice of network or networking strategy adopted by future distributed systems. AI systems cannot simply be considered in light of how they learn (structured or unstructured) from the outset, but also as they learn from the outcomes of their activity. AI systems can be based on physical systems or they may rely on data for their learning (data-driven). Constant refinements of engine control will be the expected of any AI-assisted DECS. Engine control would not be the limit either. Machine-learning (ML) will be relied upon to reach into models, including digital-twins and maintenance records, to enable condition-based maintenance, including predictive performance assessments, and feed-forward logistic response. Taken to the next level, A network of AI-assisted activities can build an Augmented-Reality (AR) in which actual engine control is but one function of the overall DECS, which will be simultaneously feeding and drawing upon data banks of performance, engineering, logistic, operational and maintenance/conditions data, enabling control of the asset and by extension its fleet of like-systems parts, components, managers, suppliers and counterparts on the ground and in the air. While the workshop presentations included a range of examples demonstrating various systems in the system-of-systems described here, an example is included here for illustration. Transient performance of a gas turbine engine on a stand was monitored and modelled using in a zero-dimensional, gas-path monitoring scheme. An ANN proved adept at predicting dynamic engine performance and detecting degradation even under these most basic conditions. The concepts are proven, enacting them on a grand scale will be limited only by imagination but also by the conflicting demands of cyber-security, standardization and ruggedization, among other non-physical challenges such as network choice and fail-safe strategies.

2.2.2.2 Fault-tolerance and robust control. Increased and in fact, wholesale reliance on electronic engine control is nothing new. A step to DECS simply enhances the need for robust control and intrinsic tolerance to faults of the various elements of the control system. With distribution, the element number may be increased due to reliance on networks, conduits or wireless means of communication, processors and their models, predictions, data banks and control algorithms, and any number of new participants. Alternatively, existing systems may be leveraged, contributing to a non-scalar increase in element number. Notwithstanding, to maintain aerospace mission operational serviceability expectations, fault-tolerance will demand commensurate increases in component reliability, system monitoring and degraded-mode management. Among the concepts presented in the workshop was the application of predictive engine models that demonstrated the ability to learn from the performance of its control functions, demonstrating great promise for precise dynamic engine control. Clearly a high-fidelity model helps, but with learning capacity, it is not altogether necessary. Instrumentation to feed the control system and to monitor response at a sufficient frequency resolution would be essential, however. If consumer-grade electronics are used, or multi-core processors, the capacity may exist for adequate redundancy, self- and engine-monitoring with space left over for failure accommodation. Note that ruggedization would be necessary, with standardization and other considerations accounted for. However, the work demonstrated the promise and the ability to apply learning, model-based control architecture to distributed powerplants, and to applications where high-fidelity engine models are unavailable. Another technology demonstration from the workshop applied independent telemetry to the health monitoring of an engine. Without interfering with the on-engine control system, a passive monitoring system transmitted engine instrumentation output via telemetry to the monitoring system for furtherance to the engine fleet management centre. Non-intrusive systems such as this open the door to retrofit of DECS to legacy systems. Considerations such as EMC, cyber-security and monitoring system fault tolerance would, of course, need to be accommodated. A final example of potential technologies emerging to support fault-tolerance is the prototype of a dual-generator on a two-shaft turbomachine in support of the more-electric aircraft concept. The integration of the two rotation-to-generation interfaces was novel, clearly contributing to a robust power generation scheme. Such concepts and their control and integration are the stuff of any move to decentralizing control of gas turbines.

2.2.2.3 Flight safety and cybersecurity strategies; Flight safety was an underlying theme in the workshop, but without singular focus. Consideration of reliability, fault-tolerance, robustness in control and health and condition monitoring have, at their cores, the safety of the air vehicle and the primacy of operational readiness and effectiveness. Cybersecurity on the other hand, was treated more directly and is, in and of itself, a direct influence on flight safety. There is a critical reliance of DECS on network-enabled architecture, telemetry, and the following remote activities: control, monitoring, life-tracking, data-base and look-up table access, concurrently running models, logistics, maintenance and operational interfaces and more. It was clear from analysis and from recent real-world events that cybersecurity will be as important a consideration in defining engine control strategies as more traditional considerations, such as the high-temperature, highly-dynamic environment of the gas turbine engine, for example. One of the presentations explored the renewed need for ruggedized chips and other components for instance. An increased interest in consumer-grade electronics for their power, size, weight and multi-core capacity cannot outrun traditional constraints on engine control system design such as EMC, susceptibility to Electro-magnetic pulses (EMP), lightning protection on increasingly more-composite air vehicles, vibration, low ambient temperature and pressure, and high engine temperatures and pressure. The challenges of and opportunities presented by multi-core processors was discussed, highlighting the need to understand fully the potentials of channel-interference and to obtain a deeper grasp of the design of the interaction between cores, the extent of validation and verification activities needed for certification, the testing and documentation available or perhaps not available from commercial-off-the-shelf (COTS), and a full understanding of data communication and the share of sources amongst and with other cores). On the other hand, the advantages of adopting multi-processors include the opportunity for fast and engaged engine diagnostics, prognostics, big-data treatment and adaptive control capacity for mission specific applications, the option of self-protection from and monitoring for cyber-attack, and an expected reduction in weight and volume. And by contrast, a pitch was made for simplicity. Perhaps the key to cybersecurity is complete avoidance of multi-core processors due to the opacity of consumer-quality chip design, the presence of remote kill-switches in some cases, background reconfiguration and communications, incomplete or absent traceability, and frankly an absence of need for high frequency processing for the propulsion systems. For EMP alone, or for physical, thermal electrical shielding for that matter, there is an argument for smart, robust, reliable hydromechanical control systems even today, that does not influence the potential of DECS. It simply demands creativity to adopt one.

2.2.2.4 Modular architectures; The focus of the workshop was DECS, and as such, distribution of functionality and components is implied. A modularity in design might be more complicated than simply deconstructing traditional engine control modules: it may take advantage of existing systems such as passive monitoring or broader systems health and condition monitoring, recording and tracking functionality.

Furthermore, the potential modules which contribute to engine control may exist on other platforms, air- or space-borne, and/or terrestrial. Initially modular designs were introduced for logistic and maintainability reasons; the concept can be taken to another level when these historic modules, such as a FADEC module, is itself modularized and distributed. What is lost is the simplicity sought by the logisticians and maintainers, justifying, in part, the development of FADEC in the first place. However, the power offered by current digital systems: such as parts tracking using Radio Frequency Identification (RFID) for example, higher power and multi-core processing and big data management have already demonstrated their abilities to mitigate the complexity introduced by further modularization of engine control and monitoring. Considering the de-modularization of the powerplant that is part and parcel of the introduction of hybrid and all-electric propulsion, a high reliance on instrumentation, data management, coincident modelling, network enabled powerplant control and monitoring and perhaps sophisticated control strategies involving AI and ML render a certain inevitability of modular architecture in engine and engine control design. And to get there from mere, passive parallel systems, leverage of existing systems and enhanced data capture, information generation, on and off-aircraft, real-time modelling and simulation will all be important contributors.

2.2.2.5. Certification considerations. The certification of DECS was addressed from many angles during the AVT-357 workshop, but perhaps the most significant outcomes pertained to squaring the adoption of powerful, cheap, light, widely available, multi-core, consumer-class computer processors with their relatively low reliability, traceability, repeatability, transparency, security, and physical, electrical, thermal, chemical and electrostatic/magnetic durability. The importance of certification and standardization to NATO partners cannot be compromised, yet the attraction of the advantages demand exploration, determination and adoption of new certification strategies, new testing methods and protocols, new expectations for design information and traceability from manufacturers and a reconsideration of design to accommodate redundancy to make up for reliability, and the use of readily available processing power and clever control and monitoring routines and methodologies to self-diagnose, monitor, model, record and report, thereby mitigating matters traditionally addressed by rigorous certification processes. In the interim, thorough understanding of architectures and designs, matched with non-traditional testing methods, depths and scopes, is essential if COTS computer processors are adopted for DECS. A second consideration for airborne platform certification is the degree to which engine control is affected by off-aircraft components such as a ground-based model or logistics/maintenance function. Certification of any distributed control system module would be required not simply for purposes of certification of the control function, but due to the essential and ready access to networks and other data transfer routes, any of which could make a critical powerplant susceptible to hostile interference.

2.2.2.6. EMI-tolerant engine control networks, fibre-optic engine control networks, fly-by-light systems. While there were passing mentions, the workshop did not directly address fibre-optics and fly-by-light. Nor was EMI-tolerance directly treated, however one presentation stood in odds to multiple others that had promoted the cost, flexibility, power, availability and other tremendous advantages of COTS multi-core processors. In that work the simplicity of low-power computing was highlighted as also having the advantages of resistance to cyber-attack, ease of redundant design and robust performance. Efficient coding is seen as a logical target for research with its commensurate contributions to standardization and certification. There are no black-box style algorithms nor look-up tables for example, contributing to the relief from increasing concerns on equipment certification. A second important observation from the workshop is the emergence of non-metallic structures as primary in modern aircraft. While weight advantages are overwhelming, a downside is the reduced lighting protection and reduced resistance to EMI generated by more-electric aircraft, or those with a DECS, with higher network density, conduits carrying higher currents and increased susceptibility emerging from increased instrumentation and control infrastructure.

2.2.2.7. High temperature-compatible communication architectures. So long as gas turbines perform a role in aerospace propulsion, their monitoring and control will rely upon instrumentation and support auxiliary equipment capable of operating predictably and for extended periods under extreme conditions of temperature, among other physical conditions. Hydro-electro-mechanical devices will interface with computing components for the physical measurements, processing, transmission and control functions. This was however, subject of just one of the papers, without a great deal of complementary contribution from other presentations. That paper treated over-tip sensors which are emerging as a powerful contributor to life usage, tip clearance with its implications on mechanical vibration, thermal efficiency and timing of events. To return to communications architectures and their design for high-temperature environments, whether connected by fibre-optic or electrical connections, or even by wireless telemetry, there will be at least one end of the system in or near the engine. Persistent exploration of new concepts must continue, with emphasis on weight, durability, reliability, compatibility and sustainability. Only cursory mention was made of fly-by-light and other fibre-optic applications, but this is one of the simplest means to reduce EMI and lightning susceptibility and overall weight.

2.2.2.8. Standardized methodologies for component evaluation, integration and testing. Standardization in general was a feature of the workshop, and particularly as it pertains to the challenge faced by designers seeking to build in cyber-security features by avoiding COTS and commercial coding. Proprietary systems were superior from that standpoint, in diametric opposition to the demands of standardization. The openness of the forum was in itself a method for broad application of component evaluation, integration and testing strategies, but only in an indirect fashion. Future systems incorporating DECS, to reach the impact that their potential suggests, must be implemented widely. To do that under the current approaches endorsed by the alliance, rigorous standardization, documentation, and commonality will be needed. In the meantime, wide dissemination of techniques and methodology for evaluation, integration and testing must suffice.

2.2.2.9. Robust, reliable diagnostic and prognostic systems. The emergent processing power offered by multi-core COTS computing equipment meets long-standing demands of innovators of diagnostic and prognostic techniques, equipment and strategies. Robust fault-tolerance achieved through multi-path networks and the capacity to incorporated real-time equipment modelling and simulation both support implementation efforts. The workshop featured presentations on a range of diagnostic, prognostic and life management system: Debris, wear, fatigue and vibration monitoring and innovative routines to predict control needs, some relying on ANNs. Even high-speed equipment such as centrifugal compressors and transient engine performance were the subject of demonstrations of the ability of AI to assess dynamic instabilities. DECS will benefit from these approaches and not simply in the control function, but also in life-monitoring, performance tracking and the introduction of digital-twins.

2.2.3 Gaps to widespread adoption of DECS

Workshop participants contributed the following to a list, assembled by the TE, of gaps impeding the wide-spread introduction of DECS.

a. There does not appear to be an overall plan for standardization to support interoperability including interfaces, software component composition and controller modularity. The plan must recognize the distributed systems envisaged and take the form of a system of standards;

b. The understanding of dynamic systems must be sufficient to allow recognition of imminent hazards brought about by coupling of mechanical, sensing and/or control systems. Modelling will continue to be integral to aero-engine control if the full-spectrum of capabilities is to be met, including life, usage, condition, health and performance monitoring as well as logistics support from such innovations as digital twins;

c. The full potential of telemetry needs to be explored for its contributions to the leveraging of related functionality, promoting non-interference in complex or proprietary control systems, simplifying designs or reducing weight;

d. Increased electrification of powerplants will demand different approaches to control strategies, enhanced by the need to monitor power generation, which could include dual-purpose gas-turbines (power and thrust generation);

e. Physics- and data-based neural networks will play increasing roles in control of sophisticated equipment, including DECS. Emphasis on their applications to aero-engine and related systems like monitoring of transient performance or debris accumulation and type should continue, with an eye on general application of results and not simply specific design application;

f. Fly-by-light and fibre-optic developments must advance to counter the tendency of weight to increase as smart-systems are added to engines and aircraft. Their support of electromagnetic, damage and lightning compatibility efforts are equally attractive.

g. The full implication of COTS, consumer grade multi-core processors on engine control must be explored further. For example, the quality, documentation, hidden features, and potential of these components is not sufficient to meet standardization and cyber-attack resistance expectations of the modern airforce.

2.2.4 Recommended specific targets for future study

To advance the pace of adoption of DECS, the following (as assembled by the TE) are recommended for future study by workshop participants and their partners.

a. AI and when, how to let it transfer authority, and then, transfer it to what?

b. Sophisticated models must be rigorously tested against, not simply their experimental rigs, but they must also be incorporated in the system-of-systems architecture that is the present-day reality of propulsion systems;

c. Physical systems and their instrumentation need to be involved in the development of learning models/AI-driven prediction strategies;

d. Non-traditional components should be tested by a range of partners in order to assess reliability independently and to promote the development of methodologies for performance and quality evaluation;

e. A scheme should be developed that encourages any new development or innovation to include a quantitative or relative (normalized) assessment on its impact on aircraft weight. It could go as far as to assess potential impact on life-cycle cost of the powerplant.

2.3 TECHNICAL EVALUATION CONTENT CONCLUSION

This evaluation of the content of AVT-357 was prefaced on the assumption that DECS will rely on the following features:

a. Network enabled distributed architectures,

b. Instrumentation,

c. Speed,

d. Fault-tolerance,

e. Cyber-threat resistance, and,

f. Standardization.

In this context, the workshop presentations were assessed against the anticipated outcomes of the effort. Some themes emerged as well, that may not have been expected at the outset. For example, the ability to build DECS into legacy systems might benefit from non-intrusive, telemetry-able systems, capable of leveraging existing systems and instrumentation to conduct other tasks, including distributed control. While the focus of most presentations tended to presume the trend to adopting or needing the computing power and economy of COTS multi-core processors, the simplicity of DECS achieved through efficient programming was illuminated, with complementary advantages of simpler cyber-security demands, significantly reduced cost, and ease of certification, validation, verification, and configuration management. The actual control the powerplant is not a high-intensity processing function in fact; what are high-demand are the additional tasks being assigned to the control system, as well as the leveraging of engine instrumentation for other monitoring and control functions. On the other hand, the tendency to higher power is attractive. Difficulties presented by this approach to traceability, documentation, standardization, cyber-security, and certification must be the subject of significant consideration as DECS is advanced. An issue that emerged in more than one presentation was the potential distribution of control to related and currently independent systems that would need to be considered in the certification of any DECS-supported power-plant. The advantages are attractive however, considering the potential contributions of modelling and simulation, digital twins, health, condition, performance, usage and life monitoring, all fed from the same instrumentation, delivered on perhaps the same or parallel networks, feeding not simply the maintenance, logistics and fleet management functions, but perhaps even operations. DECS potential can be achieved however, only with sustained emphasis on establishing broadly accepted methodologies for standardization of systems-of-systems, and the same for test, evaluation, documentation and certification of these sophisticated and diverse systems and an increased understanding of commercial computing components and system architectures. Other considerations include the emergence of the more-composite aircraft, with their generally increased electrical resistance to grounding (earthing), challenging engineers seeking EMC, as well as EMP-, lightning- and cyber-attack-resistance. This is furthermore occurring as the densities of conductors, critical networks and multi-role instrumentation are on the increase. There will only be greater reliance on creative generation of power, high-temperature-capable instrumentation and communication and control by light (fibre-optics). Overall contribution to aircraft weight needs to be borne in mind as DECS is employed, since it will inevitably incorporate more features than simple engine control. With the emergence of the more-electric aircraft, hybrid propulsion and distributed power generation, there is a physical de-modularization of the traditional powerplant. Assuming gas turbines to remain key components, the concurrent introduction of DECS is inevitable.

This concludes the TE report. The final section of this work is the TE's record of post-presentation discussions.

3.1 RECORD OF WORKSHOP POST-PRESENTATION DISCUSSIONS

3.1.1 Session 1, Keynote Presentation, Distributed control architectures: New middleware for smart software and hardware scheduling, Prof. E. Féron.

3.1.1.1 Question 1: Are there any frequency bands certified for data transmission in the engine? Response: Presume that this means wireless data transmission. In the present context, no wireless safety-critical data transmission is envisaged; only wired-communications are relied upon. However, they have used wireless systems in the laboratory for reasons you mention: one can reduce the number of wires needed for the embedded architectures.

3.1.1.2 Question 2: Ten years ago, Tesla revolutionized control systems in the automotive industry, also a very conservative industry like aviation. How do you predict when aviation and especially commercial aviation will move in this direction? We are working on it in our labs. DECS are planned and discussed for the last 15 years, and we are still struggling. What are your thoughts on that? Response: My answer will be heavily influenced by my commercial aviation experience. IN a car a cat can travel a billion miles and he would only lose 7 of them traveling a billion miles. In an aircraft, the cat would not lose a single life over a billion miles because we might lose 0.02 lives. The level of reliability we are seeking and have achieved over time, is baffling. It represents a certificate of excellence and a very heavy legacy. Once you are perfect from the safety viewpoint, and given how sensitive anyone is to the news of the loss of any flying machine, you become extremely hesitant to embrace innovation. So, the automotive industry is far more tolerant to innovation and more able to introduce it that aviation is. However, it is a great scout for the technologies that we are adopting. For that reason, many of us are happy to see Elon Musk for example, show a dual-redundant autonomous driving computer car, even though they preferred triple redundancy. That said, Tesla is never far away from SpaceX, and there is little doubt that Space X is drawing heavily on Tesla.

3.1.1.3 Question 3: How do you address the problem of certifying systems in which optimization algorithms are present. Response: This has been a topic of interest for me for 15 years. There are two ways: by means of analysis and show that an optimization algorithm will find an answer within a given amount of time, and that is compatible with other systems. The second is safety-by-design procedures, whereby if we design these algorithms in such way that they work slightly harder than they otherwise would, so they build the backup solutions that we need to execute in case the algorithm fails. We have done this in uncertified environments, but with safety in our mind. They used this approach in 2003 demonstrating an unmanned loyal-wingman.

3.1.2 Session 1, Paper 2, The concept of networked future distributed engine control system, V. Slyusar.

3.1.2.1 Question 1: Can you comment on future directions for these techniques and which will be the driving technology trends? Response: Dr. Slyusar concurred with the observations from the Keynote speaker, Dr. Féron: challenges in standardization will dominate. Under NATO umbrella however, standards can be forced/adopted to enhance multinational standardization efforts. He noted the importance of a 2014 STO report on disruptive technologies as an example.

3.1.2.2 Question 2: Is there state of operation when system decides that isn't reliable anymore and gives full control to operator performing only basic function? Response: In such cases, only the pilot’s opinion can be taken. AI might revert to recommendation-only status. This could be the final role for AI in aerospace (safety critical) systems.

3.1.3 Session 1, Paper 3, Using the telemetry system as an element of the engine operation monitoring system of UAS, T. Buczkowska-Murawska & M. Zokowski.

3.1.3.1 Question 1: Can you describe the advantages and disadvantages of this technology in comparison to other options? Response: It is anticipated that the development will occur in the next few years but the future will see it used in other applications including civilian and military one.

3.1.3.2 Question 2: Did JETI use RS232 Protocol? Response: No, it did not – the 9-bit protocol caused problems so an in-house protocol was written and used.

3.1.3.3 Question 3: What were the three engine output parameters referred to as S1, S2 and S3 on your slides). Response: (there were some communications problems.) The Workshop Chair pointed out Table 1 of the article, where engine parameters were listed. This satisfied the question.

3.1.4 Session 2, Paper 1, Advanced Integrated Power Centre with Electric Power Transfer Functionality, S. Bozhko & P. Wheeler.

3.1.4.1 Question 1: Could you estimate weight savings? Response: Experiments were not intended to simulate actual device architecture, so it was scaled to prove the concept. Another possible solution is to introduce the electrical components directly into the engine shafts – this was demonstrated some years ago.

This team presumed they were working with more traditional engine shafts, and sought to add power and electronic devices and exploit available systems. Suggested they can save 0.5% on fuel use.

3.1.4.2 Question 2: Once the concept has been proven what are the achievable size and mass targets for given power outputs and are there any relationships in existence for size and mass that could be used in future concepts assessment activities? Response: Has not explored beyond existing solutions, so does not envisage great increases.

3.1.4.2 Question 3: Is there an overspeed safety option? (Follow-up) What about overages in current? Response: I do not think it is a concern they need to address, since the engine needs to be more concerned than associated electrical systems. (Follow-up) Current is controlled by the rectifiers.

3.1.5 Session 3, Paper 2, Neural Nonlinear Autoregressive Model, M.G. De Giorgi, L. Strafella, & A. Ficarella.

3.1.5.1 There was no follow-up discussion nor any questions.

3.1.6 Session 2, Paper 3, (Ultimately delivered in Session 4) A Nonlinear Neural Network Based Model Predictive Control for Industrial Gas Turbine, I.M.A. Ibrahem, O. Akhrif, H. Moustapha, & M. Stanlszewski.

3.1.6.1 Question 1: What do you think this controller would bring to the state of the art. Response: Limited capacity to answer due to his lack of familiarity with it.

3.1.6.2 Question 2: So many of the components are interrelated in gas turbines. How can you assign sub-models in the ensemble with so many dependent parameters? Response: They are still fed with updated parameters.

3.1.7 Session 3, Paper 1, Efficient coding techniques for propulsion systems, M. Czarnecki.

3.1.7.1 Question 1: Your model applies to single-spool engines. Is it transportable to multi-spool engines? Response: Yes – the method focuses only on the map, and does not need to know.

3.1.7.2 Question 2: Where is the nozzle accounted for? And what of variable nozzle geometry? Response: Works with the nozzle design only. With the performance map of the nozzle, it can be introduced. Has not done this however.

3.1.7.3 Question 3: Your work has been on micro-turbines. Maybe it is a means to scale to larger gas turbines. Have you succeeded to scale up your methods to larger machines? The opportunity to capitalize on the potential for control technology Response: It is impossible to scale from the small to large, since he did not have access to the control systems of larger systems. But a common system for one example was tested by a colleague.

3.1.7.4 Question 4: Is it worth applying your methods to larger machines?

A4: It is worth it, but scaling compressor needs to be verified experimentally.

3.1.7.5 Question 5: Have you attempted these methods on transients? So you do not have the lines on the compressor map available. Response: The controller is limited and the transient would need to be modeled. No, there are no lines available on the map.

3.1.8 Session 3, Paper 2, Challenges and Chances of Multi-Core processors within future Control and Monitoring FADEC, K. Stastny, M. Wichmann & L. Rietschel.

3.1.8.1 Question 1: Can you comment on the supervisory, dual-network and others, I am not sure you need multi-core due to the multi-level controlling. Response: Agree – you do not need it now. But in the future, with anticipated increases in demands on FADEC, it is likely that multi-core processors will be needed. Data communication will be the new demand that will take up dedicated cores. Distributed processing of flight controllers is an example.

3.1.8.2 Question 2: What about using different cores in an multi-core processors for different tasks? Response: This is envisaged, but we do not seek to split a FADEC across different engines for emergency reasons. Do not want to adopt a hyper-visor approach. Want independent FADEC to allow function transfer from one to another in the case of a FADEC failure.

3.1.8.3 Question 3: Is FADEC electronic-warfare-safe? What do you do if the FADEC determines on-board sensors are untrustworthy. Response: This is not a big difference from today. If we identify unreliable sensors, redundancy will be adopted for safety-critical systems.

3.1.8.4 Question 4: What about the cooling of the distributed FADEC. Follow-up: Do heat-pipes suffer from aircraft attitude? Response: Already a concern and this will continue. Heat pipes are needed and being employed already. (Follow-up) Aircraft attitude is not a factor since conduction is the transfer mechanism, not convection.

3.1.8.5 Question 5: Is it possible to use Intel processors? Response: It is possible, but with these processors, we are not achieving demands of aerospace quality standards. Intel is not seeking to change their product development approach towards consumer and automotive applications. NXP and Texas Instruments are seeking to achieve aerospace standards. We are seeking to select for entry into service in the next 5 or 6 years, and most designed for consumer applications will be obsolete by that time. We must select a micro-controller for long-life. There are some from NXP (10-15 years of product life), Intel is not doing this. Texas does have military applications, so they maybe a reliable supplier for long-life designs.

3.1.8.6 Question 6: Are you using Cast 32 limitations on dynamic reallocation of different cores in hyperthreading or do you foresee them being used. Response: If you wish to use Case 32 of dynamic reallocation during normal operations, you need to apply to authorities. Our approach is that if you wish to use these features in dynamic reallocation you need to define them at the beginning of the mission. You cannot make every function dynamic application. You need a dedicated functionality that is activated at the beginning of a mission. Multi-core processors have this capacity with spare cores for different functionalities. We are not anticipating dynamic reallocation upgrading real-time but rather a dedicated trigger to be activated. It would have had to be certified at the beginning with functions previously validated and verified up-front.

3.1.8.7 Question 7: Is it Electronic warfare-safe (and EMP)? Response: We do not expect any great changes from today's technology levels. Chips themselves are not hardened as it is. Dedicated shields will be needed, as they are now. Reminded us that the increased use of carbon-fibre is driving the demand to protection to the chip itself, regardless. From DECS, buses needed to be protected and made redundant and emerging, fibre-optic data transmission is a way-ahead. We can only establish point-to-point

3.1.8.8 Question 8: Have you done any work on high-temperature components and/or smart nodes? (follow-up and Silicon on insulator (SOI)? Response: No, up to now, silicone-carbide has been used. No SOI has not been used.

3.1.8.9 Question 9: Any new data buses being developed? Response: The ones you know, but we only have proprietary buses being developed to support distributed systems. For security reasons, it is anticipated that proprietary buses are the best protection option for now. There is the TTTK from Europe, but you are aware of that. Small air-mobility aircraft are developing their own systems. Cybersecurity was discussed, with reference to a recent B747 incident in Europe. And Cyber-security favours proprietary system architecture. Discussion highlighted an emerging protectionism between the USA and Europe for example, or some European nations. Cybersecurity, sustainability, hydrogen and climate are where the money is now.

3.1.8.9 Question 10: Where will the money be on cybersecurity? FADEC or other systems. Response: Suggest that every module has to have its own encryption, decryption. And this is the focus of much work – How to access one system yet prevent undesired access. There will not be a centralized device. Tesla is seeking to centralize controlling – this is not the case in aerospace for the security point of view.

3.1.9 Session 3, Paper 3, Predictive Control and Identification of Multivariable Gas Turbine Dynamics, K. Grzędziński.

3.1.9.1 Question 1: What guarantees exist that a stable control system will result? Can a large mis-match exist? Response: If the original constraints were appropriate, the excitation signal is still bound. Main problem with the method is that updates would not be made on-line, which is a safer approach.

3.1.9.2 Question 2: Have you considered the costs of injecting an excitation signal? Would that drive new sensor requirements (more sensitive). Response: You can programme into the excitation, weighting one signal over another, or suppressing rate of change.

3.1.9.3 Question 3: Your bounded signal is bounded by question marks and some do not seem to be bound. (Notwithstanding paragraph 3.1.8.1 discussion.) Response: You need to decide how much you wish to bound your signals. A filter is not really necessary since it is being driven by a model that accounts for constraints.

3.1.9.4 Question 4: Your test was on a low-inertia machine. What effect might a large inertia have? Response: Results completely transferable to high-inertia cases. The dynamics matrix would change and account for the inertial parameters.

3.1.8.5 Question 5: (difficult to hear) You appear to be on the edge of stability. Presume you want to use this for (inaudible). Response: If you do not want to use the algorithm, that is your choice. But if you are comfortable with setting your constraints with some factor of safety to remain below the margins of (inaudible) stability you will theoretically be able to maintain stability. Obviously, the current work needs more experimental validation.

3.1.10 Session 4, Paper 1, Self-Oscillations of the Free Turbine Speed in Testing Turboshaft Engine with Hydraulic Dynamometer, O. Lytviak, V. Loginov, S. Komar & Y. Martseniuk (speaker was not able to attend).

3.1.11 Session 4, Paper 2, New sensors for optimized performance, control and monitoring of turbofan lubrication systems, P. Hendrick

3.1.11.1 Question 1: Our experience is that the time taken for the GTL system to detect particles does not prevent excessive bearing wear. We use a different sensor. Could you try it on your rig (rho-C-k) which is more sensitive? Response: Yes, we would be very interested to collaborate.

3.1.11.2 Question 2: What do you think of rate-of-change of particle arrival as key trigger. Response: It has a high probability, but it is hard to measure. But this is very promising.

3.1.11.3 Question 3: Perhaps there are ways to accelerate the test? (Comment from Dr. Martin We have done something like this by deliberately damaging, and accelerating the wear test.) Response: You also need to have the right shape. It is important to get the right particles of the right size and shape to adequately model the phenomenon. (Comment: Dr. R. Przysowa – noted that their tribology lab is also a potential participant in any collaboration.)

3.1.11.4 Question 4: Is it possible that someone looking at these data and particularly the ferrous vs. non-ferrous particulate capability, might think that the difference does not warrant the investment, what do you think? Response: The error margin on the QDM is certainly not zero. Referred us back to the sources of error. The difference between the two devices may actually be smaller when one considers uncertainty.

3.1.12 Session 4, Paper 3, High-Temperature Magnetic Sensors, E. Rokicki, R. Przysowa, J. Kotkowski & P. Majewski

3.1.12.1 Question 1: How did your results compare to the piwg.org statistical parameters presented? Response: These results were simply signal amplitude, so not all parameters were translated into the PIWG parameters. Results are promising but there is room to improve the sophistication of the results. The main advance is in the sensor design innovation over traditional methods, and specifically improvements in high temperature performance. Acknowledging that for modern gas turbines, even the improvements are insufficient.

3.1.12.2 Question 2: Are you combining two different frequencies here in the results slide (slide 15)? Response: No, there are two test conditions: idle and take-off.

3.1.13 Session 5, Paper 1, Towards explainable artificial intelligence for centrifugal compressor operating conditions classification, P. Kucharski, B. Kowalewski, M. Stajuda, G. Liśkiewicz.

3.1.13.1 Question 1: How do you determine if you have light surge rather than typical rotor-stator pressure interaction. Response: This is the challenge of my career. The key thing is to be able to differentiate a random pressure change and a real threat. Our methods detect most, but not all. This is why AI has promise to detect the signals from the noise in these very dynamic and non-linear features. Initial results are promising and they believe the AI top-up on more traditional methods will be useful.

3.1.13.2 Question 2: Why is the input data size greater than the output vector? Response: (unintelligible)

3.1.13.3 Question 3: One of the biggest issues about AI and natural learning systems is not the mathematics but the quality or correctness of the result. How reliant can and should we be on the outputs in EMS and what form should this output evidence be to support certification as being safe. Response: Not able to provide a definitive answer to the question but this hypothesis: for safely, this can be increased through interoperability and clarity (explainable) if the traced features are not abstract but connected with physics. Then the possibility of having wrong prediction decreases to some extent. (Response part II) Mateusz: The input on the left are signals from 5 primary and two secondary sensors. On the output there are classes into which the space was divided, so actually the network gives information where the particular signal falls within the condition space (TOA available)

3.1.13.4 Question 4: We all know that the surge margin imposed in ECS can reduce efficiency, by as much as 10-15%. In comparison to current surge protection techniques how much do you think that these techniques could reduce the size of the surge margin and what percentage efficient increase could this provide and still operate safely. Response: Surge margin: Will depend on the machine, in theory with a very quick system you could operate on the verge of surge line. IN practice I don't think it is feasible and no one would risk it. Value-wise, working up to the point reducing efficiency by 5% but this is just a hypothesis. In general, data driven, especially connected with explainable AI could be used to decrease surge margin.

3.1.14 Session 5, Paper 2, Comparative Study of a Powerplant Life Consumption Rate, I. Templalexis, N. Christou, I. Lionis.

3.1.14.1 Question 1: With respect to the instrumentation and methods used in engine testing and operations: Do you think a mission-based method like yours could be sufficient to convince OEMs that safety and cost of dynamic control costs could show health and life monitoring systems are worth the effort. Response: There is no doubt that the advantages are well understood. But there will always be a blend of time versus condition-based maintenance. The trust is simply not there yet. (Follow on comment) OEMs are naturally conservative, and efforts will still be needed to convince them of the residual life of expensive and critical components.

3.1.15 Session 5, Paper 3, Turbine engines resonance parameters monitoring as a technical condition predicting tool, M. Kluczyk, A. Grządziela, Ł. Muślewski, M. Pająk.

3.1.15.1 Question 1: Have you used piezo-electric sensors at extended operating temperatures? Can you comment on measuring vibration in the hot section? Response: temperature of sensors was carefully considered to avoid overheat of piezoelectric sensors. Future sensors show promise up to 250 ºC. (Comment from B. Zaghari) There is a Kistler accelerometer capable up to 800 ºC. 250 ºC is the maximum one can get from off-the-shelf systems, with the caveat that Gallium nitride might get you as high as 500 ºC. Amplifiers' issues include a need for different circuit models. Dr. A. Behbahani noted that he has these at USAFRL, and the instruments work, it is the packaging that is the problem.

3.1.15.2 Question 2: What of distributed electronic treatment. Response: this is promising and an essential step for distributed engine monitoring.

3.1.15.3 Question 3: Where are the shock absorbers located, do you have any intention to test non-linear stiffness régimes. Response: The absorbers were installed on a special frame between two engine sub-frames.

3.1.15.4 Question 4: What would be an actionable condition indicator on your device (such as an increase in resonant response). Response: Yes exactly, a critical level needs to be determined, higher than linear conditions indicate – by maybe 10%. But much research needs to be done to be certain.

3.1.16 Session 6, Paper 1, Network of Smart Tip-Timing Sensors in Distributed Blade Health Monitoring System, J. Kotkowski, E. Rokicki, R. Przysowa, P. Filipkowski N. Christou.

3.1.16.1 Question period. (There were no questions nor discussion for this paper.)

3.1.17 Session 6, Paper 2, Architecture of distributed control system for gearbox-free more electric turbofan engine, V. Popov, S. Yepifanov, Y. Kononykhyn, A. Tsaglov.

3.1.17.1 Question 1: Regarding surge-reluctance machine and starter-generator testing: was the power shown the power generated? Response: Yes, that is correct. It is a 2-stage process. The first is constant torque, then power is limited to prevent over-load.

3.1.17.2 Question 2: You have options between SRM and permanent magnet machines. Was the selection based on specific speed? Response: In this machine, the generators are joined to the rotor, so they are designed to operate at the rotor's speed, regardless of operating point: start-up or normal operating speed.

3.1.17.3 Question 3: Do you envisage a fully electrified engine? Response: We are advancing step-by-step, in conjunction with the sponsoring company who are collaborating with the motor and switch company.

Began with the starter since it is the most complex, then the electrically driven accessories (like fuel pumps). The partner has 20 years of experience, but only recently they are designing electrical machines. The designs of these accessories were developed as the project was conducted.

3.1.17.4 Question 4: Please clarify – is this a propeller gearbox? Response: No, it was an accessory gear-box drive.

3.1.18 Technical Evaluator's Preliminary Report. A preliminary technical evaluation was provided at this stage, the contents of which have been elaborated upon in this report.