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NEED FOR ROBUST SENSORS FOR INHERENTLY FAIL-SAFE GAS TURBINE ENGINE CONTROLS, MONITORING, AND PROGNOSTICS (POSTPRINT)

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ABSTRACT

Sensor reliability is critical to turbine engine control. Today's aircraft engines demand more sophisticated sensors in the control systems, requiring advanced engine testing for component performance demonstration. Expertise in the gas turbine instrumentation community is located across the gas turbine industry itself, within several specialized university departments serving to supplement the more general research programs in gas turbine research. Sensor technology has advanced in many fields; however, implementation has been slower in aerospace applications. Today's push for engine health management through adaptive control systems demands more robust instrumentation with inherently fail safe sensors.
The future needs of the USAF require innovative reliable control architectures. These needs require new ideas for turbine engine controls, employing the next generation computing, communication hardware and advanced sensors. Turbine engine control research includes: implementation, control theory, algorithms, sensors and transducers. Separate feedback loops are used to control the fuel, compressor, and nozzle to provide the desired engine thrust. State-of-the-art controls act on sensed engine parameters which provide measurements at a fixed time interval The controller outputs adjust valves, and actuators to maintain stable engine operation. Current digital controls are based on synchronous, clock-based systems that take digitized analog sensor inputs at an approximate rate of 30Hz.

In current engine control methodology, all signals travel on dedicated lines. All sensors or signal loss requires substitution with an equivalent (redundant) signal from other sensors or virtual values. Loss of a parameter (total signal loss) may lead to control failure and potential engine shutdown. Control algorithms use look up tables with embedded program values. Present control algorithms do not incorporate health management decisions as part of their function. All sensor signals have a specific bandwidth and travel by wire (or wireless in the future) to the control (FADEC) to complete the control process. All faults in the control system must be resolved in real-time All transient faults, captured may be evaluated at a later time when the aircraft completes its mission. All critical sensors are redundant. However, there needs to be a more robust sensor fault detection technology to be incorporated with the turbine engine to achieve more robust control and reduce both NRE and support cost

INTRODUCTION

The capability and requirements for sensors, control, and condition monitoring for effective control and EHM depends on the design and integration of the system as well as the sensors, signal conditioning systems, analysis techniques, and the controls algorithm used. SOA Control, sensors can detect and manage a limited number of faults to ensure engine safety. This is due to the fact that there are several layers of safety net exits in the turbine engine control system. This redundancy is especially true for safety critical component. However to successfully address consequential damages, reduction of unscheduled maintenance and under extreme circumstances, the unavailability of sensor signal, and an alternative strategy is necessary to explore. This is especially true for modern controls which have a real- time operating system, and failure of any sensor data is can not be tolerated. False alarm and missed alarm rate should also be minimized. What is needed to optimization of the control systems by making the sensor more robust and reliable?

In the future, sensor and actuator communication can be handled differently if in-situ evaluation of the data would be done either locally or at the FADEC. This concept minimizes the effects of failures. Instead of employing a direct feedback loop, the system operates like an "open" loop system. Digital Sensors, multi-sensors, and several layers of safety could be used to minimize the effects of loss of all sensors needed to complete the mission. Therefore, the loss of a sensor does not necessary affect the engine performance. As a result, identification of the fault is much easier to accomplish, enabling higher levels of fault detection safety. The engine control systems employ a real-time operating system in a distributed, asynchronous, local-based environment. The system may include smart digital sensors and multi-sensors communicating through networks operating wirelessly or by wires. With this networked architecture, the failure of all sensors will not jeopardize the mission of the aircraft. The control system of the future will have sophisticated system software that interacts with the engine physical system in a highly integrated way. Feedback is achieved through correction of actions based on sensing the current states. Figure 1 shows modern model-based system.

In traditional control techniques, all sensors are hard wired to a central controller. A new concept to control the aircraft engine uses a collection of heterogeneous sensor data to collect damage and performance information to potentially achieve significant maintenance and safety improvements. Using, Ethernet communication, and in-situ sensor systems containing physics-based data and health information, we can achieve improved efficiency, productivity, and reliability. Additional benefits of the new control system are engine health management is now an integral part of its function.

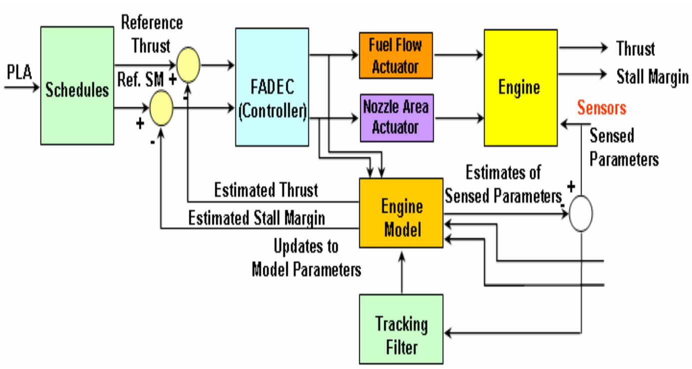

Figure 1: Model-Based Closed Loop Control of Thrust and/or Stall Margin

This paper is not meant to discuss in detail all technologies related areas. This paper discusses in some aspect of issues related to sensors used in controls and prognostics health Management for advanced turbine engine technologies

SENSOR NEEDS

Simon, et al have reviewed in details the sensor needs for control and health management of intelligent aircraft engines [1]. These needs were discussed in categories of active control, advanced health management, and distributed control. It has been noted that significant enhancements are necessary to develop advanced sensors for engine productions. For example, Pressure measurements are required in environments which are becoming ever harsher. The sensors are exposed to Corrosion, Oxidation, High Vibration, and High Temperatures. Transducers must be protected from the environmental effects Requirements must be an integral to the design philosophy.
Figure 2 shows the sensing technologies for engine controls and health management. The selection of the sensor type and location(s) are critical factors in determining the effectiveness and requirements for an engine e surge and stall control system.

Processing of the data from sensors is used to move the actuators and other actions required by FADEC.
Typical sensors used in Turbine Engines:

- PURPOSE
  - PROVIDE INFORMATION TO THE CONTROL AND MONITORING SYSTEMS AND PILOT
- COMPONENTS
  - PRESSURE SENSORS: P2, P3
  - TEMPERATURE SENSORS: T2, T2.5, T4, T5.6
  - SPEED SENSORS: FAN (N1), CORE (N2)
  - POSITION SENSORS: (MMV, NOZZLE, VANES)
  - OTHER SENSORS: A/B LITE-OFF, LUBE AND VIBES
  - CONTROL SYSTEM
  - MONITORING SYSTEM
- OPERATION
  - MOSTLY ANALOG OR MECHANICAL ACTION (SOME DIGITAL)
  - HARD WIRED OR MECHANICAL CONNECTION
  - CONSTANT INFORMATION STREAM

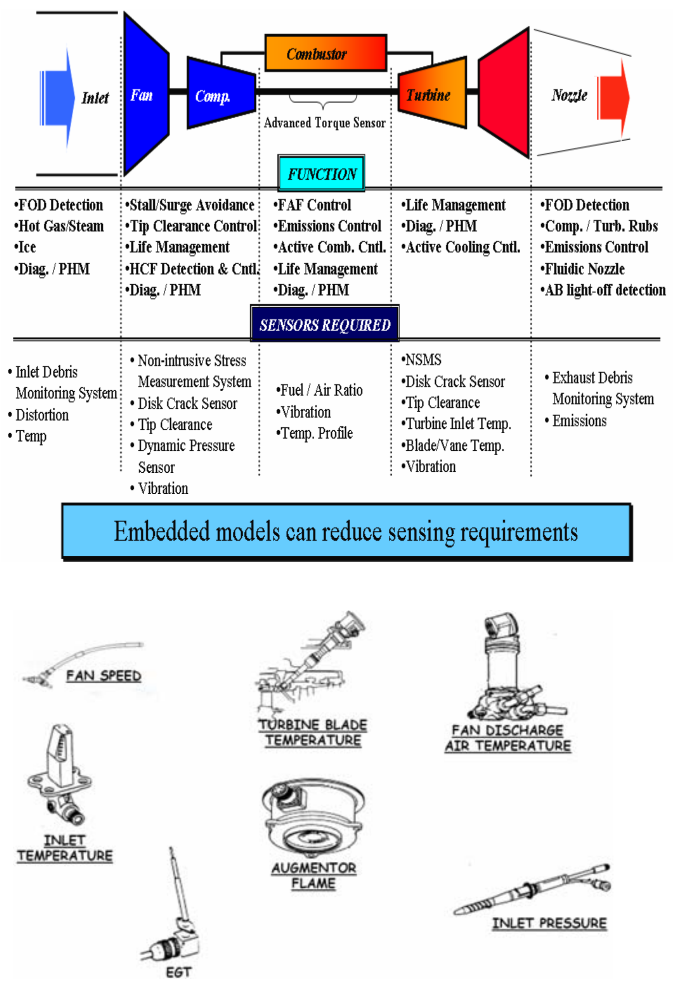

Figure 2: Potential Sensing Needs and Engine Locations

Figure 3 compares current and future of a typical temperature sensor. This paper does not confine itself to issues related to the choice and design of the sensors. However, the ways the sensors need to be redesigned are discussed.

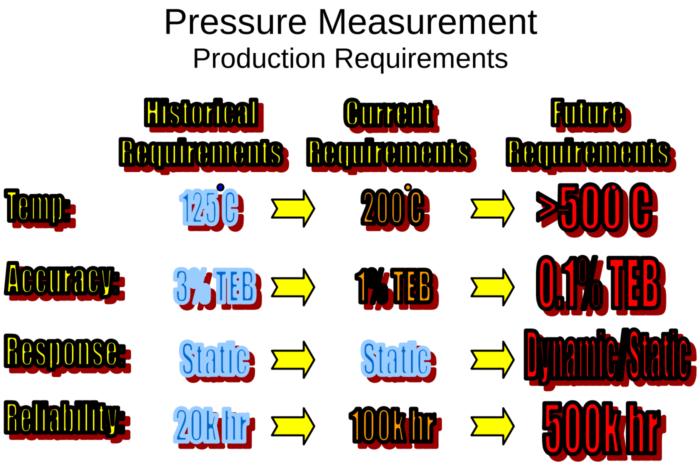

Figure 3: Comparison of Production Requirement for a Pressure Sensor

ACTIVE CONTROL TECHNOLOGIES AND SENSOR NEEDS

For active engine control, the system requires a robust sensor and failure or degradation should not effect the operation, and safety mechanism of the engine and the vehicle. Sensors should be able to monitor the engine for control and monitoring purposes. Modern gas turbine engines today use a Full Authority Digital Engine Control system (FADEC) to achieve optimum performance of turbine engine today. Many modern turbo-machines, such as multistage axial flow compressors rely on complex scheduling of stator vanes and bleed valves and monitoring of temperatures, pressures and flows to achieve stable operation with margin reduction. The ability of a FADEC to process and analyze many sensors inputs from the engine at many locations, to apply sophisticated control laws, manage engine efficiently, safely, enables many modern gas turbines to function economically and reliably. The key successes in modern gas turbines control system today are reliable sensors. Today, the goal is to improve reliability and reduce cost by improving sensors, actuators, and control systems. The use of a variety of sensors and mechanical installations needs improvement to achieve these goals. Failure of the sensors will result in unreliable uneconomical engine. In the active control, the engine relies on sensor data, the operator, the vehicles data, the data stored in the FADEC which also relies on past operation of the engine.

SENSOR TECHNOLOGIES AND ISSUES

Sensor, Transducers, Detectors [2, 3]

Sensors, transducers and detectors are not the same. According to Peter Stein of Phoenix, Arizona, a 49-year veteran of the industry, "In order to make definitions, you must first have a global, totally interdisciplinary view of the measurement world which is applicable to all transducers/sensors/detectors--past, present, and future--in all disciplines." Mr. Stein is incensed by the International Office of Legal Metrology's definition of thermal zero for strain gauge-based transducers as "the output from a transducer due only to temperature changes in its environment." The problem with this definition, he writes, is its dependence on "whether the transducer is fed from DC or AC signal conditioning." He goes on to postulate that "no transducer has any properties until its three boundaries with the rest of the world have been defined and specified." And this requires "a completely new conceptual and mathematical model of a transducer as a six-terminal, three-port device."

Every piece of the hardware associated with temperature detection, for example (thermocouple, connector, signal amplifier, and all leads), "is a transducer or sensor or detector," Stein says. "These words are interchangeable and are NOT separate concepts." His reasoning is that every transducer processes both information and energy, whether such operations constitute signal conversion or simple transmission of information.

Transducer: 1. A device that is intended to transform an electrical signal into acoustic, biological, chemical, electrical, magnetic, mechanical, optical, radiational, or thermal stimuli for the purpose of transmitting information. 2. A device that is intended to transform energy in one form into energy in another form for the purpose of transmitting power.

Sensor: A device that is intended to transform acoustic, biological, chemical, electrical, magnetic, mechanical, optical, radiational, or thermal stimuli into an electrical signal for the purpose of transmitting information.

In short, a transducer has an electrical input; a sensor has an electrical output.

Sensor Integration

Sensors and sensing techniques are diverse among manufacturers. They all need to be integrated into the FADEC and /or Engine Health Management box or flight control. This requires the addition of signal conditioners and software addition to the control algorithms. Signal conditioning of the signal may involve amplification, filtering, and may contain some processing (this case may be called smart sensors) All the sensors needs to be interfaced with the hardware through analog signal multiplexer and analog-to-digital converters. For distributed systems, this can be accomplished by either additional multiplexer card or built in I/Os which accept certain inputs. All FADECs have multi-channels inputs with implement multiple communications channels using common interfaces such as RS-232, RS-488, MIL-I-1553, CAN bus, ARINC Bus, Ethernet (both hard-wired and optical). For digital signals, data are sampled at different rates for different sensors.

Deterioration Due to Sensor and Turbine Aging [4]

Sensors, controllers, and turbofan engine performance change due to aging, deterioration caused by usage, or merely variation due to manufacturing tolerance. Usually, the controller and sensors are designed to operate within acceptable limitations for many flight cycles, until the engine has reached to its limits to be overhauled. These limits are sometimes operability constraints, performance constraints, other limits built into the control logics. If sensor has reached its useful life, these constraints may not be realized. It is absolutely essential to know when we have reached to sensor failure. A fail safe sensor is very important to determine degradation that requires the engine to be overhauled as limits are reached. For the engine to operate the same level of thrust as a new engine, it must operate hotter or faster to account for this deterioration. The shift from nominal operation increases with use and will eventually reaches the performance and safety limits. Any sensor degradation can not be tolerated, since it will be compounded with engine degradation, including electronic components. Adaptive control has been suggested, but more work still needs to done to evaluate the robustness of the scheme for degradation. However, it is always assumed that the sensor is always operates normally.

Fail-Safe Sensors by Design

A sensor package is designed to be "Fail Safe" if it is guarantees that the system will remain safe in spite of failures. Fail-safe reduces consequences when the event occurs (likely to happen). Safety critical sensors (sensors in which occurrence of fault can result in loss of human lives, mission failure, loss of aircraft or loss of engines) demand special attention, where any types of failures, how insignificant, are never tolerated. These types of sensors are desired to have fail-safe properties. In a typical sensor design, any sensor failure is an indication of guaranteed leads the sensor to an interruption (safe state). This “safe state” is identified by FADEC or a warning light or built-in- test (BIT) to perform functional checks upon system startup. The BIT will be capable of isolating failed or faulty components down to a major subassembly level and requires repair of the fault before the sensor is allowed to return to its initial normal state. Sensors are usually tolerant towards a few numbers of faults before they fail. Exploitation of this property of the sensor by making it both self-stabilizing (as long as the sensor tolerate the faults and don’t fail) and fail-safe (when the sensor cannot allow one more fault to occur to avoid failure). By "Fail Safe", we mean that if you utilize this sensor in the turbine engine environment, and for any reason fails to provide output signal or perhaps you forget to reconnect the sensor to the electronics after service, the panel light will come on indicating a failure, which does not prevent the system to continue normal operation. Sometime a virtual sensor or secondary measurement by other sensor can provide the missing sensor data. This scenario also holds true if you lose electrical connection to the sensor. The need for developing highly reliable sensor systems to ensure reliable operation even in adverse conditions in the turbine engine, has led to the development of fault tolerant sensors [5, 6]. In this paper we will summarize some the work done by researchers. Fault tolerant sensors are referred as fail-safe sensors. Any fault detection that leads the sensor to a possible failure can be categorized as fail-safe, if appropriate remedial measures can be taken. Implementation for Fail-Safe sensors where safe-stabilization and fail-safe properties can be merged has been reviewed by researchers. Other fail-safe models have been proposed in a situation where safety cannot be guaranteed after the occurrence of a failure. Methodologies for Fail-safe sensors must be designed in the very early functional design stage by means of functional models and function-based failure and risk assessment. The methodologies for fail-safe designs by means of multi objective multi-level optimization, takes into consideration mission lifecycle (design, maintenance, operations). The fail-safe design and implementation of the sensor can guarantee that in a fail safe sensor a fault won’t result in making the sensor weak giving way to further faults within a short period of time. The efficiency and reliability issues sensor faults have been investigated by researchers.

The implementation of a fail-safe sensor for turbine engine applications has not been adapted by sensor manufacturers. In Fail-Safe sensors, even in the presence of failures, safety of the sensor in ensured though safety may not be guaranteed. Thus, when there is a failure, the sensor may not behave normal, as safety is compromised. When safety is not compromised, we have Masking Tolerance. E.g. a common fail safe sensor is the pilot-light sensor in most gas furnaces. If the pilot light is cold, a mechanical arrangement disengages the gas valve, so that the house cannot fill with unburned gas. If safety is preserved the fault-tolerant model becomes masking fault-tolerant model. But, the significance of the model lies in the fact that nothing ‘disastrous’ will happen ever. Implementation cost for this model is cheaper than the Masking model (as safety is not ensured), but, like the above two models, when faults occur frequently, the Fail-safe property is difficult to guarantee. Thus, all of the above models are effective only over a certain time period, depending on the number of faults the can be tolerated.

Faulty Sensor

The function of the sensor is to detect the occurrence of fault in the turbine engine. The sensitivity and efficiency of a sensor depends on, how fast and how reliably a sensor can detect a fault after it has occurred. To improve response time of the sensor it is thus desired to minimize the time between the occurrence (time constant) and detection of the fault. The reliability of the sensor depends on fault tolerant and accuracy. We have to ensure sensor vulnerability, and the health of detection mechanism. Sensor response should be repeatable. Throughout the discussion here, it is emphasized that the sensor is not a separate device, the function of the sensor is keeping track of the entire system, and the results, analysis, and final decision by the FADEC or operator is based on the global collected information. Sensors are basically comprised of some guards and actions performed by all or some of the processes in the turbine engine dynamics, which collectively or independently detects a fault in the system. It is obvious that if we can manage to obtain the information of all process states at a particular instance, it becomes a trivial job for a detector to compare and check all the system states to detect a fault. But taking a global snapshot is not a trivial job. It has considerable overhead in terms of time and space. Hence, the dead time between the occurrence and detection of fault is increased significantly. Specifically, if the system network is significantly large or sparse, the time to take the snapshot increases considerably. Also, in this time some transient fault may appear and disappear without getting detected at all! This is especially true if we have simultaneous faults (remember, in any feedback system one fault will be effecting other components, and this is different). As such, we can never detect the sensor inherent fault, if the faults are superimposed. This is highly undesirable. This is because, if the sensor remains unsafe (faulty) for a longer period of time, faulty computation can result in more faults with highly undesirable effects. To lessen this unsafe period, we need to quicken the detection process. This implies, the sooner we can resolve the faulty sensor, the sooner we can resolve the issues. This quick action may result in a safe or unsafe outcome.

Figure 4, Safety Margin Regions

Figure 4, depicts the set of safety margin. In the figure, the yellow circle denoted by SM (Safety Margin), is the set of all possible sensor states representing the normal safety properties being satisfied functioning of the sensor in presence or absence of failure. The green circle S contains a subset of states in SM. This set denotes those states of the sensor when there is no fault, and a faulty action will retain the system in the safe configuration. Thus, the set of states in the set (SM-S) represent the sensor state where occurrence of a single sensor failure will result in system failure.

Faulty Sensor Detection

Jet engines are complex systems and required to be reliable. Any fault observed by the pilot may require corrective action. If the pilot presented with incorrect information, diagnosing a fault quickly enough for any corrective action may not be possible. Sometime no action may be more appropriate. There are many control algorithm embedded in FADEC to deal with these issues. These algorithms specifically tailored for single as well as multiple sensor failures. The key point is realization of specific sensor failure and quick corrective action, if any.

Sensor Location

The idea of fail-safe does not mean that under any circumstances the sensor will be able to survive. Selecting the most optimal location is desirable accuracy and also to minimize degradation or permanent damage. To minimize the replacement cost of a sensor, they need to be protected. Several studies have been made for optimal sensor placement for accurate detection and location in turbine engine. The time-varying sensor data are measured using different types of sensors. An effective and accurate detection should be established to determine the best location of sensor. In selecting the optimum location, one must analyze the best location with the least exposure to harsh environment. A genetic algorithm is used to determine the optimum sensor positions for a diagnostic system. Several studies are required to study fail-safe distributions, i.e. those whose sub-distributions also have a low probability of detection error. The results of some of theses studies shows that genetic algorithms combined with neural networks can be effectively used to find near-optimal sensor distributions for damage detection. The methods presented are generic and can be used in similar sensor position problems. The selection of sensor location(s) is a critical factor in determining the effectiveness and practicality of an engine surge and stall control of an engine. Selections of the control algorithms as well as actuator type used to process sensors data are also important. Figure 5 depicts typical locations of sensors for a typical engine controller.

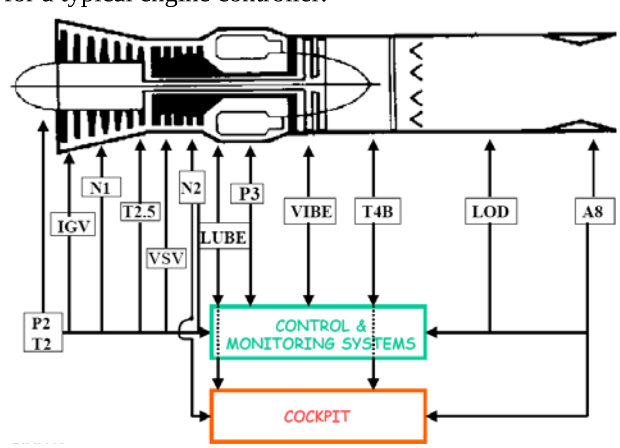

Figure 5: Location of Typical Sensor Suites for a Turbine Engine Controller

Synchronous VS Asynchronous Sensor Communication

Currently, the control system for turbine engine and most controllers is based on synchronous system (clock-based) in which the control system (FADEC) operates with a delay and response time and with a communication network which interacts with the sensor, actuator, and other signals from other computers or human operator. All sensor dedicated lines which operates on the synchronous communicates are the basis for control today. This type of communication is prone to communication delays due to sensor malfunction or loss of sensor. By definition, Synchronous and Asynchronous communication depends on weather or not there is coordination prior to communication. Synchronous communication is when the FADEC is looking on a specific channel for handshaking with a particular sensor. This is for digital sensor outputs. This communication will be with a system of 1's and 0's. The negative voltage is given the "1" value while the positive voltage is given the "0" voltage. This combination of voltages is given as a single bit. These bits in sequences determine what is communicated. Many properties are determined how long the sensor should hold the voltage for a single bit. Some limitations of this may be the data rate maximums, as well as the properties of the wire. Here, the Asynchronous sensor communication is preferred since failed sensor data does not stop the process. The sensor and control system in the future will operate (some operate today) in a distributed, asynchronous. Packet based environment.

For analog sensor signal, FADEC will read each sensor over hard wire. On a periodic basis, FADEC will read all sensors, verify for accuracy, if any data is not valid, continue the process, and using stored sensor data, or use calculated data from the valid sensors. This process of substitution of data will enable the process to continue, even under fail conditions. Multi-sensor data is another option to assure data continuity even if several sensors are not functional.

Modulation is a way of sending a sensor signal for the bits being transmitted. To connect a digital sensor to a FADEC with the capacity to send and transmit data, the modulator of sensor must be linked to the demodulator of the FADEC, and vice versa. The typical connection between the two can be performed through communication channel which contains both a MOdulator and a DE-Modulator, (hence the word "modem") which allows simultaneous transmitting and receiving data. A ground connection is used to allow the completion of a full electrical circuit. This is done with amplitude modulation (AM), Frequency Modulation (FM) or Phase Shift Modulation (PSM). Multiplexing is a way of communicating with many channels over a single connection rather than a single connection from all channels to all channels. It is done by putting many inputs from channels into a multiplexer with one output that is fed to a de-multiplexer. This de-multiplexer then sends the transmission to the appropriate channel being fed off of that de-multiplexer. It is a similar analogy with a telephone system communication. Typical telephone system uses two pairs of wires, and hence, the signals are multiplexed for use over two wires, called full duplex transmission. In a sensor system a multiplexed wires can be used as shown in figure 6.

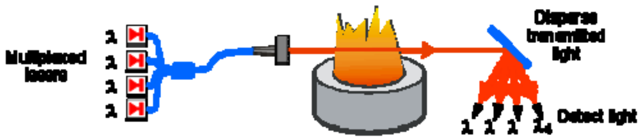

Figure 6: Multiplexed Sensor System [7]

Sensor Technologies

Several attempts have been made to minimize the impact of sensor failures. Existing technologies have been utilized to Fabricate Multiple Detection Sensors. Multiple Sensors in Single Probe/Installation have been suggested. Others have explored the Potential Use of Single Harness for Multiple Sensors. MEMS Technology and High Temperature Optics have all been researched. However, serious uses in turbine engine control have not been realized. What is needed is to Develop, Validate and Implement Multi-Sensor Capability. There are certain applications that have developed Develop Self Calibrating and Self Diagnosing Sensors. The benefits of these are listed below:

- Increased Reliability and Safety with Minimal Cost Impact
- Enabling Technology for Prognostics and Active Control
- Reduction in Engine Control/PHM Sensors
- Reconfigurable Capability – Reduced Design Time
- Reduced Control System Weight and Wiring Complexity
- Reduced Engine Maintenance – Advanced PHM Sensor
- Reduced Unrecoverable, Transient, and Calibration Errors

Sensor Validation

All sensors data used in the engine health management and control must be evaluated for the integrity of the measured data before use. Sensor's signals are often embedded with noise. Typical data integrity is caused by ground loop, drift, electrical noise, vibration, secondary detection, and therefore may affect the signal output. Isolation, grounding, shielding, filtering are routinely performed to validate and diagnose sensor signals. There are more advanced techniques such as fuzzy logics analysis, neural networks, and advanced filtering techniques have been performed to realize the true sensor output and integrities. In addition, statistical signal analysis has been performed to do the same. Validation analysis can be categorized as two fundamentally different techniques: Signal Processing-based analysis, and Physics-Based analysis, which is more advanced. There are overlaps between the two techniques. The detail of these specific techniques is not the scope of this paper. More details can be found in many texts.

Sensors' signal composed of two components: steady-state response and transient response (see Figure 7). The sensor value needs to be evaluated in either component needs to be analyzed for accuracy and error. The error can be as result of feedback system (since they are error actuated system) or the sensor error itself. This paper deals with sensor error itself. Here, we want to make sure the sensors are operating normally. The sensor must be checked for response time and its response must be faster than system response.

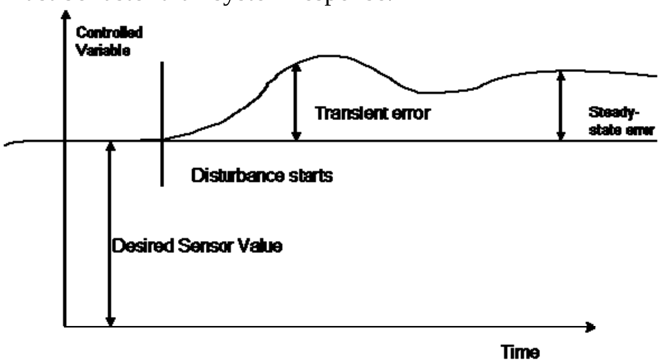

Figure 7: Transient Vs Steady-State Error

The sensor values are first analyzed to determine if they are valid, i.e., within expected operating ranges. If any sensor is determined to be faulty, a modeled value is substituted for the observed value. Artificial neural networks and a set of rules are used to model the sensor values and support sensor validation. Following the sensor validation, the sensor data are processed by diagnostic modules. Check to see if one or a few sensor values exceed thresholds or fail to follow thermodynamic relationships. The sensor validation process always needs to be implemented for critical components. Collaborative techniques including neural networks, fuzzy-logic, and a signal correlation analysis can be used to thoroughly examine the sensors' outputs. The neural network operates by comparing the physical relationships between signals as determined from either a baseline empirical model or computer model of the turbine's performance parameters. The fuzzy logic based sensor validation continuously checks the "normal" bands associated with each sensor signal at a specific operating condition. When a signal goes outside these limits, while others remain within, an anomaly is detected associated with those specific sensors. Finally, signal correlation, cross correlation and special digital filters are used to determine if even small levels of noise are present on a particular signal. These parallel algorithms are combined in a probabilistic data fusion process that determines the final confidence levels that a particular sensor has either failed or has suspect operation. Sensor recovery for failed sensors is also being implemented by incorporating the same data that is used to train the sensor validation neural network but now the network will continuously predict the failed sensor value based on the remaining sensed parameters that have a distinct relationship to the failed sensor. A polynomial neural network is used for this task. Directly related to the sensor recovery networks is the ability to predict other useful information "virtually" by determining conditions at a location that is not or cannot be sensed. Sensor prediction is very useful in "virtually" determining conditions at a location that is not or cannot be sensed such as turbine inlet temperature. Here, the trained neural network once again allows us to predict the conditions at any given point in the flow path utilizing other sensed conditions with a direct relationship to it.

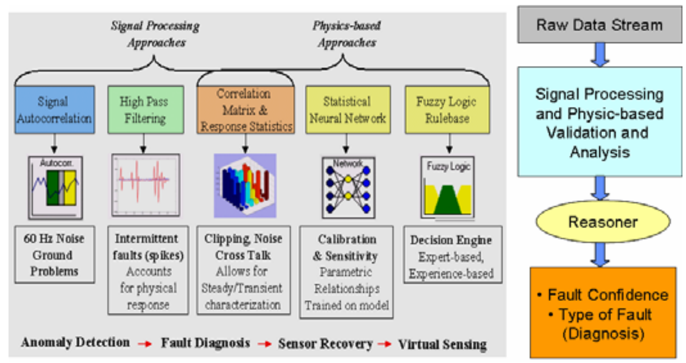

Figure 8: Sensor Validation Technologies

Prediction of faults and degraded performance is accomplished by trending results from the FADEC control logics. Both short-term and long-term trends are computed using linear regression on diagnostic values. The system attempts to predict the time until components fail or until engine components will fail to meet specifications. This concept is illustrated in figure 9. More sophisticated statistical techniques have also been investigated [8, 9].

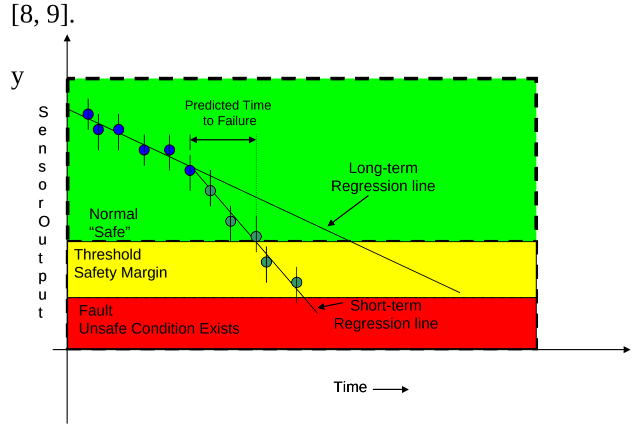

Figure 9: Predicting Time until a Failure

It is Accomplished Using Both Long-Term and Short-Term Trending. The blue Circles Indicate Past Data. The green circles Represent Data Obtained in the Current Run.

Present Controls Sensors

Engine FADEC systems employ three types of sensors, control, feedback, and diagnostic sensors. Critical to maintaining stable engine operation are temperatures, pressures, and speed measurement. Feedback sensors are primarily position sensors for measurement and control of actuator position. Diagnostic sensors may include all control sensor types and additionally, vibration, strain, Infrared, and gas measurement. Over 20 Control loops are required to maintain safe and stable engine operation. Each is routed to a central Controller (FADEC). Today's architectures employ dedicated wiring for each measurement and actuation location. Figure 10 depicts typical sensors suits used in a typical turbine engine control.

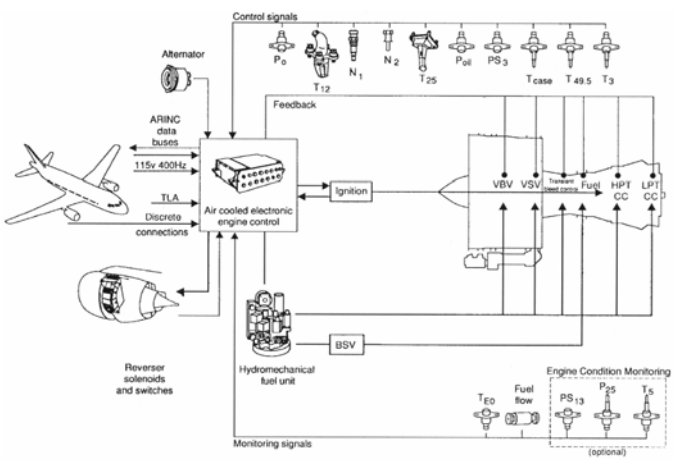

Figure 10: Typical Sensor Suites for a Turbine Engine Controller

Multi-Sensors Array

Multi-sensor Array technology Developed at the John F. Kennedy Space Center, Florida, offers a way to make sensor fail-safe, therefore, offers an improved reliability. This array reduces the need for and costs of sensor calibration and periodic maintenance while significantly extending the life of the transducer when compared to a single-sensor system. The technology utilizes a unique algorithm to determine the health of a transducer employing several nearly identical sensing elements in a cluster. Common sense seems to suggest that multiple sensors are better than one and, if so, how much better? Several projects were conducted to design and implement a test to answer this question and to help quantify the relationship between the number of sensors and the associated improvement in sensor life and reliability. Multiple sensors can be implemented in numerous ways, the most direct of which is to simply increase the number of sensors of a particular type at the measurement site. Another method, which takes advantage of the reduced size of microelectronic sensors, is to pack several sensors onto a single circuit board. Going one level smaller, multiple integrated circuit (IC) sensors composed of single die (small rectangles of silicon containing the transducer circuitry) can be crammed into a single IC package. Finally, multiple sensors can be fabricated directly onto a single die using advanced technologies such as Microelectromechanical systems (MEMS), whatever the technique used to implement a multi-sensor array (MSA). For aerospace applications specially for fail safe applications, when reliability is the goal, MSA offer an advantage tat a single sensor does not. Potential uses are in many applications. The Multi-sensor Array technology is particularly suited to MEMS applications where accuracy, reliability, and low transducer failure rates are essential. They can be used for Monitoring of semiconductor processes, Mass-flow sensors, Optical cross-connect, switches, Pressure and temperature sensors. The benefits can generally be applied to any sensor array or cluster reduces calibration and periodic maintenance costs. Allows higher confidence in sensor measurements based on statistical average of multiple sensors. Extends life of the array compared to a single-sensor system (for a user-defined confidence level). Codes easily and simply onto a microprocessor, improves fault tolerance, lowers failure rates, and has low measurement drift. The MSA has been designed to help reduce the costs and time associated with removal, calibration, and reinstallation of numerous transducers on Space Shuttle launch pads. The sensor array is composed of several identical sensor elements arranged in close physical proximity, all exposed to the same physical phenomena. An algorithm compares measurements of all elements in the sensor cluster, determines which are reliable (based on both current and past reliability), and delivers one output value that is an average of all the elements, each weighted by its reliability. MEMS sensors are particularly suited to this application, as potentially hundreds of them could be placed in a very small area, thereby providing numerous measurements at essentially one point. Using existing technology to fabricate multiple detection sensors:

- Multiple Sensors in Single Probe/Installation
- Potential Use of Single Harness for Multiple Sensors
- MEMS Technology and High Temperature Optics
- Sensors for Mass Flow and Multiphase Flow

Advantages of using multiple sensors are listed below:

- Increased Reliability and Safety with Minimal Cost Impact
- Enabling Technology for Prognostics and Active Control
- Reduction in Engine Control/PHM Sensors/actuators
- Reconfigurable Capability – Reduced Design Time
- Reduced Control System Weight and Wiring Complexity
- Reduced Engine Maintenance – Advanced PHM Sensing
- Reduced Unrecoverable, Transient, and Calibration Errors

Air Force plans to pursue the Multi-Sensor Command and Control Aircraft program. A multi-sensor based planning and control scheme has also been used for robotic manufacturing. Multi-sensors have been individually for critical control sensor (i.e.: EGT). There is a trend toward using multi-sensors on the same hardware to account for failures. This may be an option Figure 11) to use for certain applications that the sensor failure may result in unavailability of the sensor for control application.

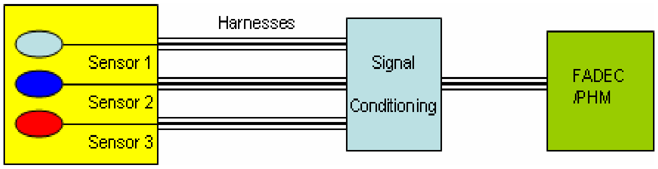

Figure 11: Proposed Multi-Sensor Array For Turbine Engines

Sensors Dual Sensitivity

Sensors or transducers are usually designed to measure a single quantity, such as pressure; however, they usually exhibit some sensitivity to one or more other quantities, such as acceleration or temperature. The error resulted from dual sensitivity of the sensor is not desired. It should be noted here that dual sensitivity of other systems exhibits the same phenomena. The dual sensitivity of other elements become important if the sensor data is measured over long period of time.

Remote Sensors

There have been several programs funded by Joint Strike Fighter (JSF), Defense Advanced Research Agency (DARPA), and office of Naval Research (ONR), and US Air Force to develop smart sensors for prognostic health management. These sensors incorporate self-calibration, and testing functions. These sensors are designed to be wireless, networkable, and integratable for engine and aircraft health management. Testing and evaluation of these sensors in a hostile environment has been performed and its compatibility with avionics has been proven. Testing has been proven and coordinated with activities of the Bluetooth Government Working Group. Prototyping and evaluation of these smart sensors has proven to be an attractive alternative to traditional centralized wired sensors used in the engine and other mechanical systems for aircraft applications. The open-architecture nature of these sensors can be integrated into any architecture for product upgrade. However, application program approach to cooperatively in military aircraft at this point is not desirable especially after Sep 11, 2001. Due to certification requirements and relatively low market share in military applications the life cycle cost of these sensors are relatively high as well [10].

Kulite has designed, fabricated and evaluated the latest generation of leadless dynamic pressure sensors. The key feature of these sensors which are patented are elimination of the gold ball bonding and gold lead wires and the harmonic sealing of the pressure capsule and the transducer assembly which will enable these transducers to operate reliably in most hostile engine environments. It is hoped that these sensor will be used in the future turbine engines.

Future Strategy for Sensor needs

Sensor needs for aerospace applications depends on progress of sensors in other applications. In aerospace applications sensors are exposed to extreme environments such as shock, vibration, high temperature, cosmic radiations, moisture, and others. As the progress is made towards sensor advancement, the controls and instrumentation engineers should devote to designing fail safe and robust sensor using advanced materials that withstand harsh environmental condition. New generations of smart electronics, photonics products with fail-safe & radiation hardening capability will evolve toward a "solid state" appearance with higher reliability, maintainability, and lower cost. Integrating control, engine health management, flight will require advanced sensors for intelligent engines. Integration will eliminate the need for separate control and enclosures, reduce wiring, minimize sensors, and minimize electronic disturbances from long cables, and lower control and measurement cost. Advances in computer performance, human-centered systems, sensor technologies, advanced control systems, electronics, networking and communication are vital to intelligent propulsion technologies. Sophisticated sensor technologies are essential for better understanding of future capability and performance issues related to turbine engines, while minimizing the life cycle costs. Reducing life cycle cost requires development of component life prediction which in turn requires imbedded and smart sensors, micro-actuators, and sophisticated information processing and intelligent software that monitors the intelligent engine. The intelligent engines should exhibit intelligence by reasoning using artificial intelligence techniques. Kulite has designed a pressure sensor that can withstand temperatures exceeding 500 ºC (Figure 12).

Figure 12: Future Sensor Needs for Extreme Environment

Common Standards for sensors for Universal FADEC

The future Universal FADEC will incorporate for both intelligent engines and engine health management will require incorporating common standard sensors specifically designed for harsh environments. Engine sensors needs to be robust, small, reliable, low cost, self-calibrating, low weight, fast response, accessible, radiation harden, and may need to have local processing capability. To improve reliability and reduce cost, common standards for sensors are envisioned. This will also minimizes the obsolescence issues associated with sensors. The common design standards will also help to improve sensors and use best engineering practice amongst all OEMs and FADEC manufacturers.

Revolution in Air Force Logistics

The US Air Force (USAF) has over 24,000 aircrafts which include over 47,000 turbine engines. The aircraft systems are expensive and must be routinely modernized or upgraded to keep pace with threats, missions, and advancing technology. Each modern turbine engine consists of controls and accessories. Sensors are important components of engine control and engine health management. The USAF employs manual diagnostic procedure to diagnose field related problems. Any sensor failures will delays mission availability. To bring about the vision of the USAF of the future, new technologies will need to developed and exploited to enhance operational readiness and to support logistics needs. The logistics community will have to use emerging technologies to makeup for shortfall in specialized personnel and limited resources. The traditional stovepipes of maintenance, supply, transportation must be reinvented and integrated into holistic solutions. This is specially important for mission critical sensors and in hostile enemy sites where specialized personnel are in demand.

CONCLUSION

In this paper, we gave a general view and importance of sensors for turbine engine controls. Implementation of the proposed fail-safe sensor by design is discussed in details in several papers. We have also discussed the need of distributed and multiple fault detectors to ensure fast and reliable fault detection. Apart from proposing a formal model, we have tried to deal with issues to implement the proposed model as well. Further we have argued that in all sensors we can't always ensure safety in presence of failure. In such cases, we have proposed a solution weaker but cheaper (less implementation cost) than Non-Masking tolerance, containing the essence of the proposed fail-safe fault tolerant model. Since, implementation of the models vary with different systems and the degree of fault tolerance, we will be constructing different algorithms for different systems. In the process we will try to make the implementations more efficient. Idea of replication may be employed to make the fault detection more efficient. In formalizing the model, concept of reachability can be introduced, to prove the outcomes more constructively. To improve the reliability of the turbine engine and reduce their life cycle cost further improvement in sensors, transducers, and control systems need to be made. The control algorithm needs to be more robust and corrective action, even when sensors fail. Reliability and design of the sensors needs to be improved further. In many other areas, new sensor technologies are creating new opportunities for turbine engine control. Online sensors are becoming more robust and less expensive and are appearing in more manufacturing processes. To achieve a true integrated control and engine health management, a real operating system with an online sensors are necessary to improve the reliability and performance of gas turbine engines. Online sensors are being used by process control systems, but more sophisticated signal processing and control techniques that use artificial intelligence are needed to more effectively use the real-time information provided by these sensors. Sensor designers and control engineers can also contribute to the design of even better sensors that can withstand a harsh environment, which are still needed. As elsewhere, the challenge is making use of the large amount of data provided by these new sensors in an effective manner. In addition, a new modern control approach to modeling the essential physics of underlying process control is required to achieve fundamental limits of the internal states through these sensor data.

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Instrumentation - Aerospace Applications

Intelligent Turbine Engine Controls and Sensors Session 4B

NEED FOR ROBUST SENSORS FOR INHERENTLY FAIL-SAFE GAS TURBINE ENGINE CONTROLS, MONITORING, AND PROGNOSTICS

52nd International Instrumentation Symposium – Cleveland, OH

Alireza R. Behbahani, Ph.D.
Turbine Engine Division / PRTS
U.S. Air Force Research Laboratory
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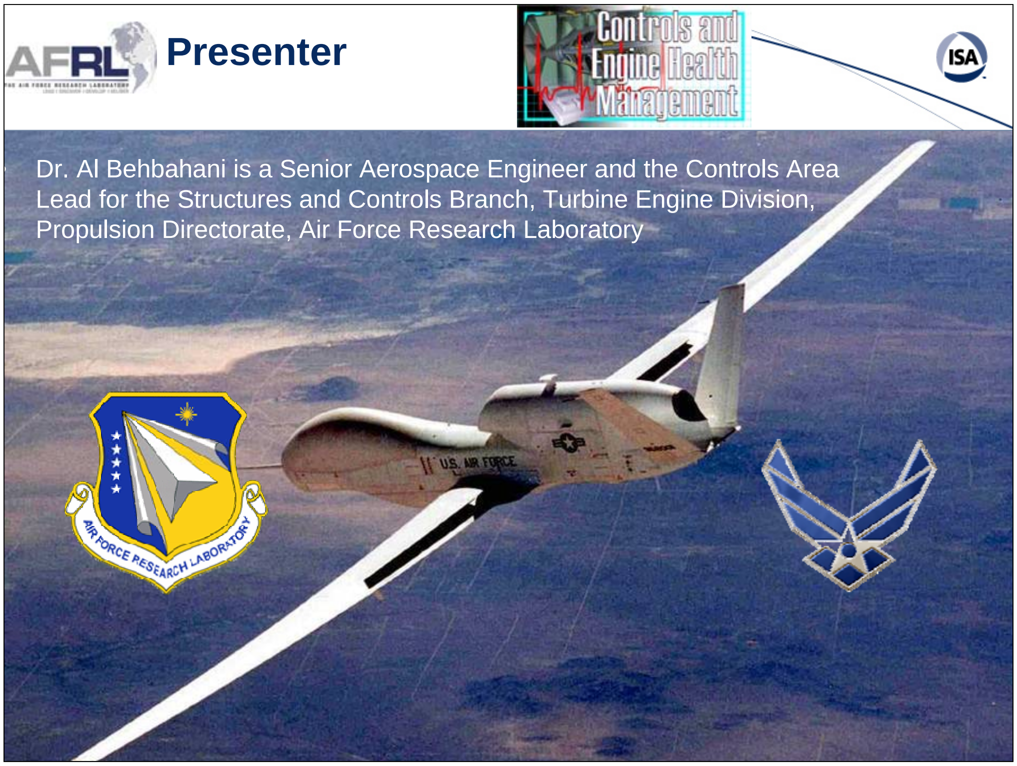
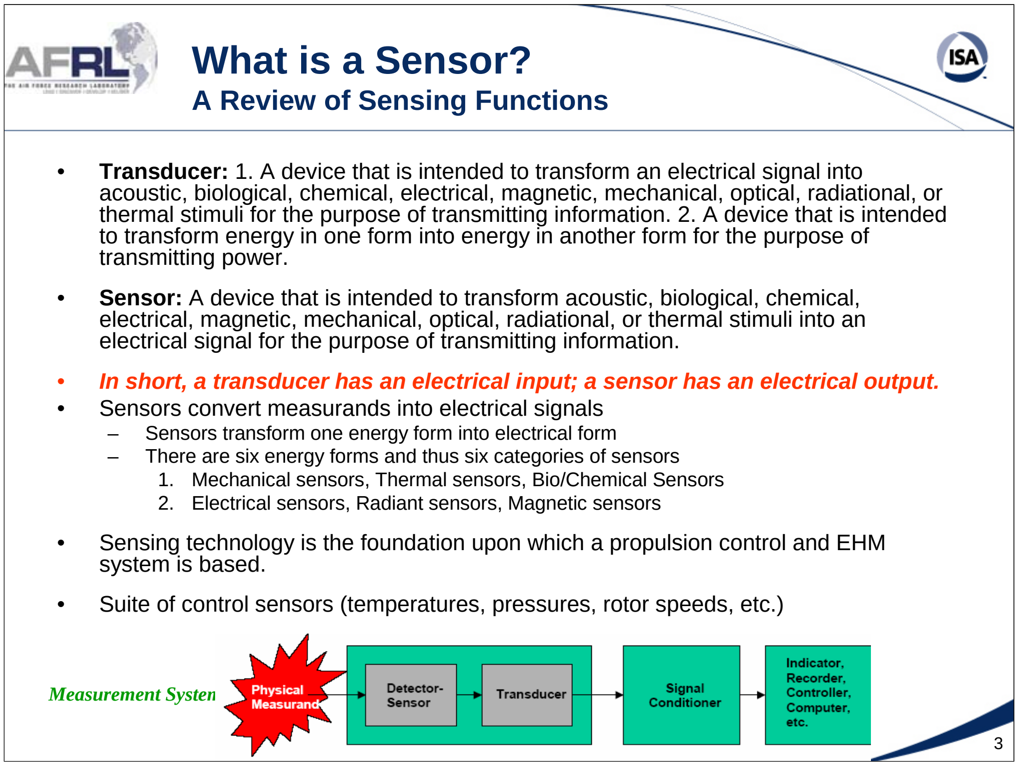


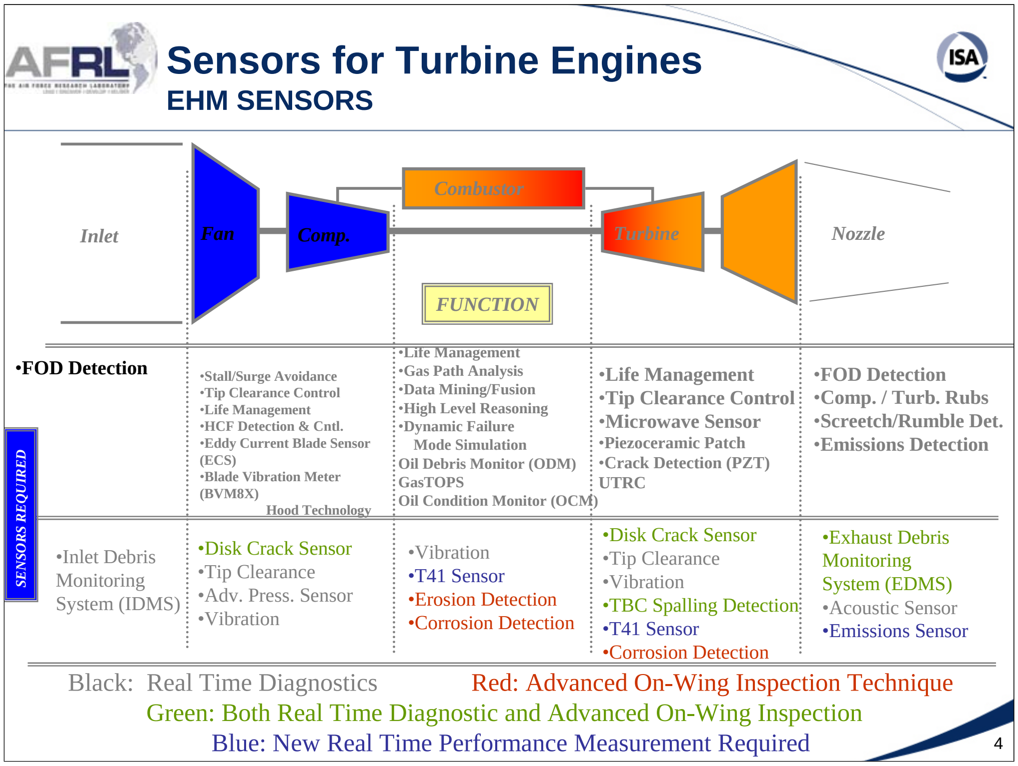
<u>Acronym Primer</u>

MEC: MAIN ENGINE CONTROL (GE)
GGC: GAS GENERATOR CONTROL (PW)
AFTC: AUGMENTOR FAN TEMPERATURE CONTROL (GE)
DEC: DIGITAL ENGINE CONTROL (GE)
DEEC: DIGITAL ELECTRONIC ENGINE CONTROL (PW)
FADEC: FULL AUTHORITY DIGITAL ENGINE CONTROL
PLA: POWER LEVER ANGLE (THROTTLE)
PRI: PRIMARY CONTROL MODE
SEC: SECONDARY CONTROL MODE
CENC: CONVERGENT EXHAUST NOZZLE CONTROL (PW)
UFC: UNIFIED FUEL CONTROL (PW)
ECU: ELECTRICAL/ENGINE CONTROL UNIT (PW)
SFC: SPECIFIC FUEL CONSUMPTION
BIT: BUILT IN TEST
EHSV: ELECTRO-HYDRAULIC SERVO VALVE
ACCEL/DECEL: ACCELERATION/DECELERATION (SCHEDULE)
L&S: LUBE AND SCAVENGE
HYD: HYDRAULIC
DI / AI: DE-ICE / ANTI-ICE
RVDT/LVDT: ROTORY/LINEAR VARIABLE DIFFERENTIAL TRANSFORMER



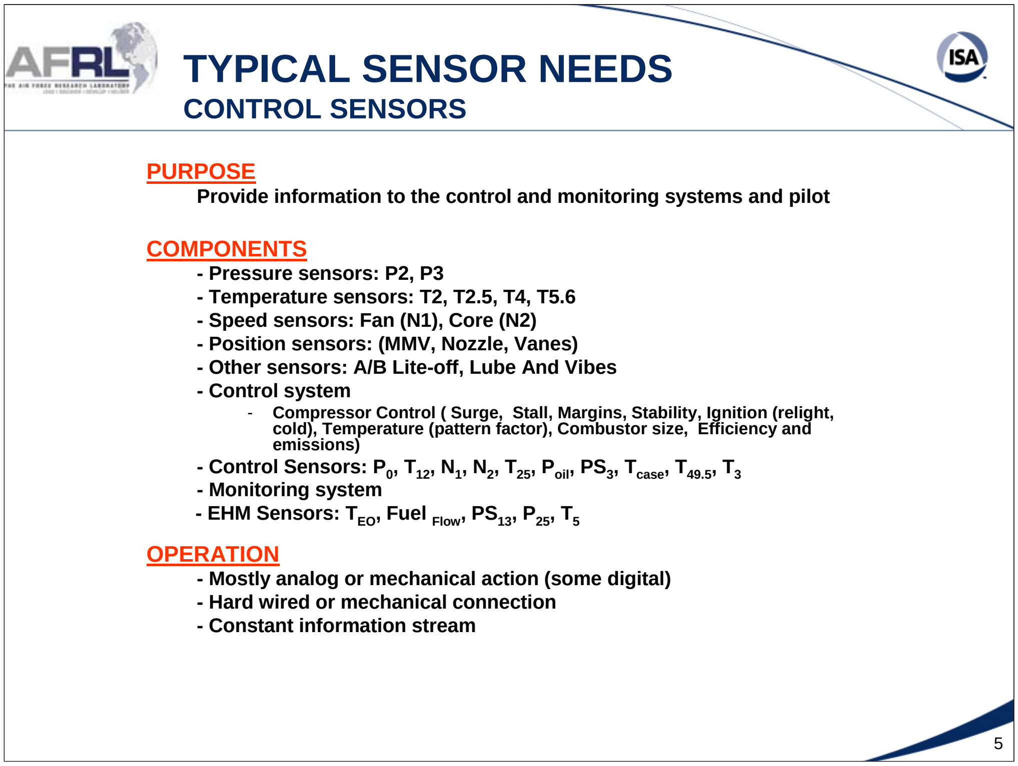
We start with a review of sensing functions. What is the difference between sensor, detector and a transducer? We Define **Transducer** as a device which converts information from one domain to another, usually chemical or physical to electrical (also converts measurand to an analog more easily measured (force-displacement-resistance-voltage). A **Detector** identifies changes in a variable, and a **Sensor** is a device which monitors a specific chemical species in general. ***In short, a transducer has an electrical input; a sensor has an electrical output*** However, in aerospace applications, we refer to only sensor as a device which detects and responds to measurand.   Normally there are Signal Conditioning to amplify, filter, integrate, differentiate, convert freq. to voltage, etc. The signal then is fed through a FADEC or a computer to analyze.

Sensing technology is the foundation to control and manage the engine operation. There are large suits of sensors in the turbine engine control.



There are a number of sensors with specific functions used throughout the engine to control the engine. Each sensor has a specific function and requirement. On-line (real time) control systems for gas turbine engines require specific sensors at many specific locations. Some sensors are for control, others are for information and engine health management. The sensors are color coded here. The variety of input sensors measure parameters including TOT, torque, compressor and turbine rpm, rotor rpm, OAT, and battery voltage. These sensors also may measure air condition, such as airspeed, altitude and barometric pressure. Pilots and control systems monitor these sensors constantly.

The sensors are fed through a Full Authority Digital Electronic Control (FADEC) concept. A FADEC system controls all the functions required of the engine and allows for a number of operational improvements, such as: (i) the possibility of implementing sophisticated techniques from modern control theory, techniques that can both increase the performance and the reliability, (ii) a reduction in weight owing to the limited use of hydro mechanics, and (iii) the possibility of implementing built-in support for maintenance, which lowers the cost of maintenance and improves the reliability of the system. As these examples indicate, FADECs support endeavours toward increasing performance and reliability and reductions in overall cost. The FADEC monitors and logs selected information from the sensors, including start counts, events, surges, engine run time, and malfunctions. It also monitors exceedences, such as overtorques, over-temps and hot starts . Magnetic Speed Sensors (Engine RPM),Resistance Temperature Detectors (Temperature monitoring of critical aircraft components and subsystems), **Total Air Temperature Sensors(TAT)** measurements on airframes and at engine inlets



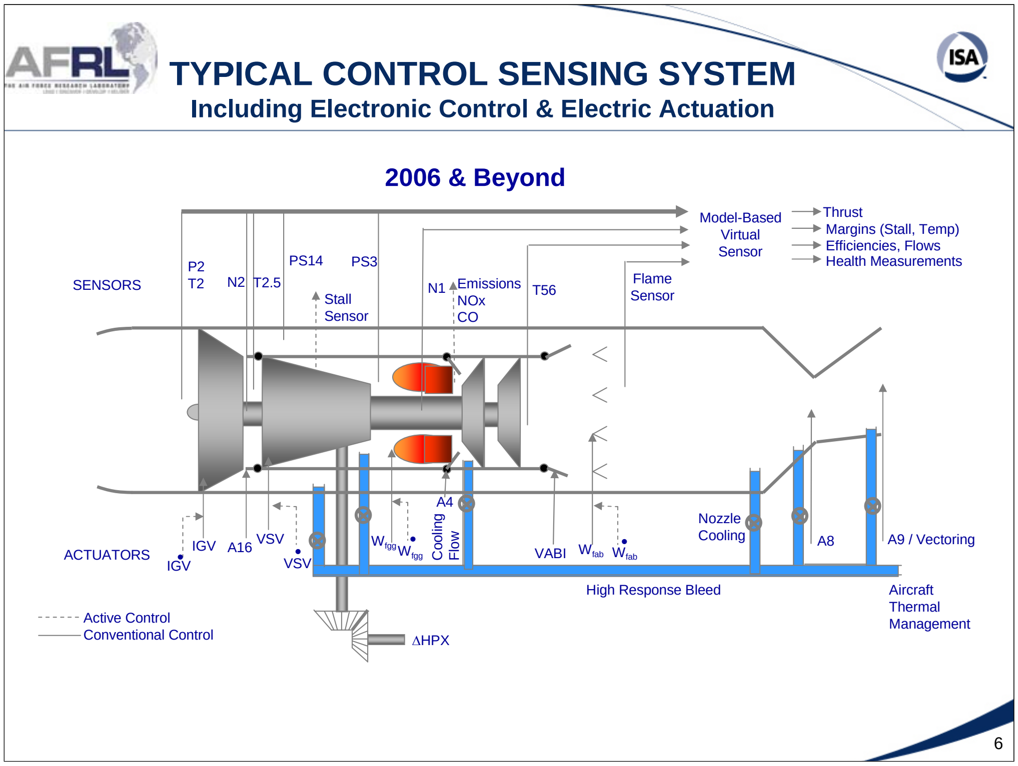
The number of sensors varies with each turbine engine. This depends on the complexity, capability and manufacturing/industry preference. For controls and engine health monitoring and capturing the complex process dynamics, here are listed a number of typical sensors used for turbine engine engines. The purpose is to provide information to the control and monitoring systems and pilot. What is shown here is a typical sensors:

Pressure, temperature, speeds for control

Pressure, temperature for engine condition / health monitoring

To understand why we need sensors for control and EHM, we need to know how a turbine engine control operates. A simple engine control system computes the amount of fuel needed for the engine to produce a desired power (or thrust), based on pilot's power request through a throttle (or a power lever); then it meters the right amount of fuel to the engine's combustion chamber(s); and it maintains the engine power at the desired level in the presence of air flow disturbance and changes in flight conditions. Good indicators of thrust, that have been used successfully, are engine shaft rotational speed (N) or engine pressure ratio (EPR). An aircraft engine is designed to operate in a wide operating envelope in terms of altitude and speed variations. To a control engineer, these challenges needs to be examined. Such as fuel flow (Wf) versus engine shaft speed (N) graphs or a fuel ratio unit (Wf/P3, where P3 is the compressor exit static pressure) versus speed

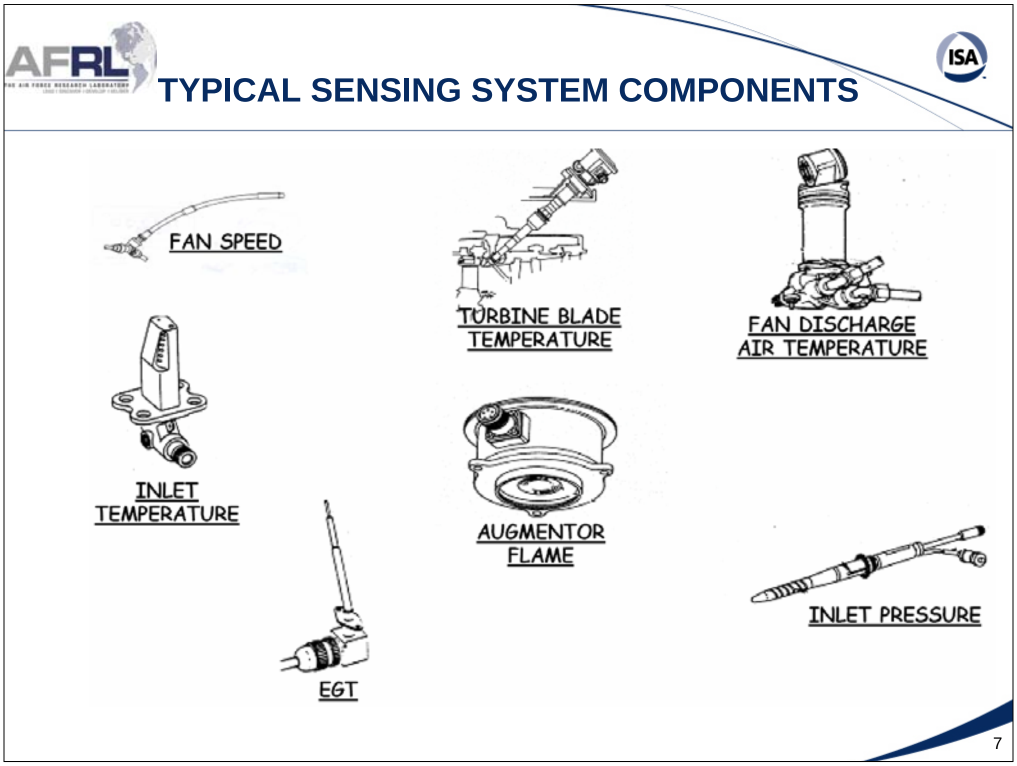
monostable multivibrator (MMV)



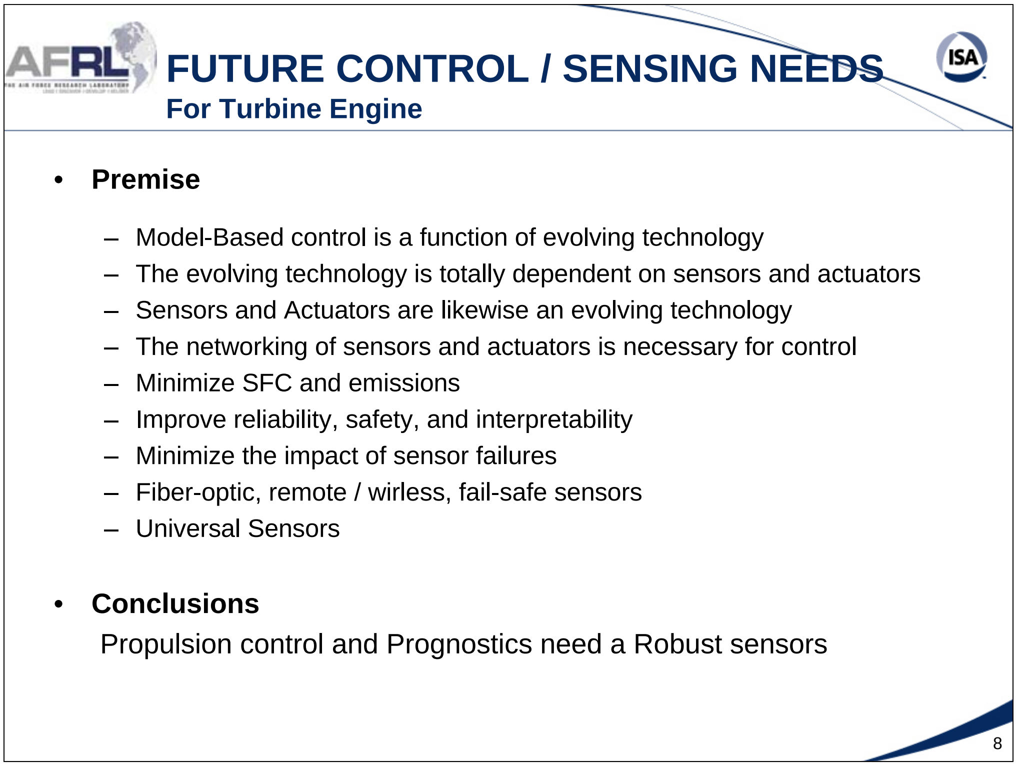
The location of typical sensors are shown here for both control and monitoring purposes.

Sensors may be used to provide engine protection by quickly detecting adverse operating conditions which may indicate a fault or malfunction to reduce or eliminate any permanent engine damage. The FADEC monitors the sensor inputs to detect conditions which may trigger a diagnostic code or fault which may be used by service and maintenance personnel to troubleshoot and repair the engine.

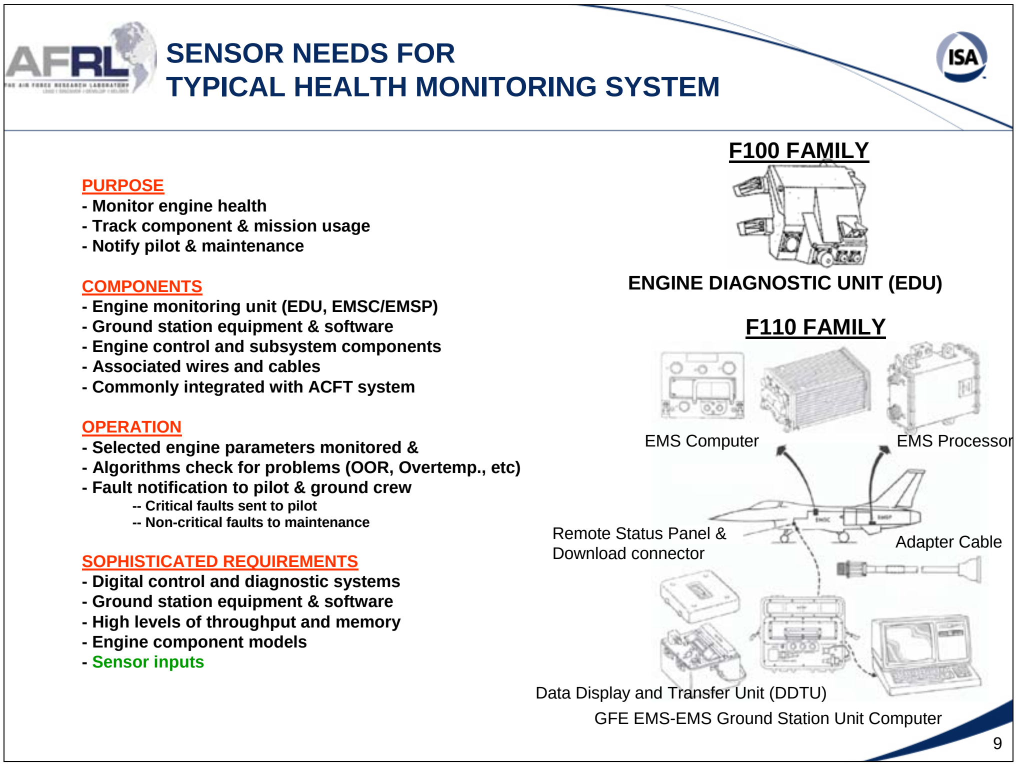
In addition to monitoring sensor inputs to detect potential engine problems, the FADEC typically includes logic to detect whether the sensor itself is functioning properly. However, depending upon the particular sensor, it is often difficult to determine whether the sensor is malfunctioning or whether the sensor is accurately detecting an actual engine condition.



Here I have shown these typical sensors used to control the turbine engine. As shown, the sensors are enclosed in special casing. Each one is designed for special installation

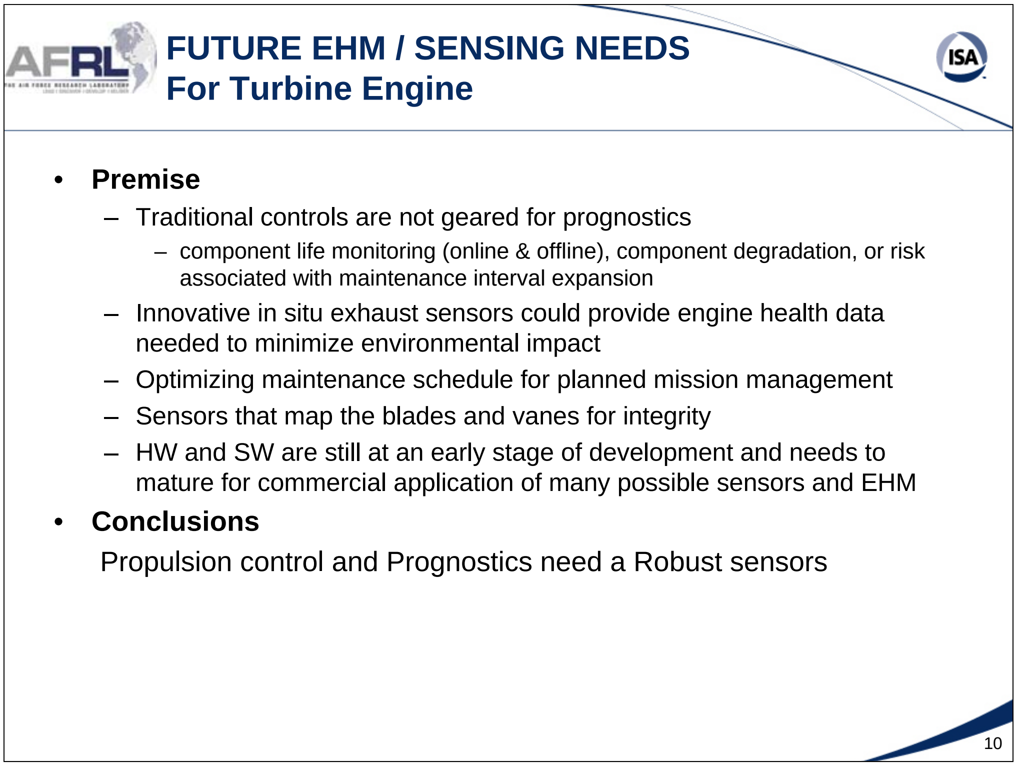


Present sensors fall short in several categories for control. First, model-based control will require new robust sensors for harsh environments. Second, it is difficult to apply existing sensors and actuators for control. The actuators need to have a high response, and the sensors need to be smart and fail-safe. Third, universal / standardized sensors for multiple applications needs to be explored to minimize cost, SFC, and emission; and improve reliability, safety, and interpretability. Finally, the hardware and software are still at an early stage of development and the commercial application of many possible sensors for sensor networking and possible use of neural networks needs to be developed further.



OOR: Ordered Overall range: is a related to data reduction method

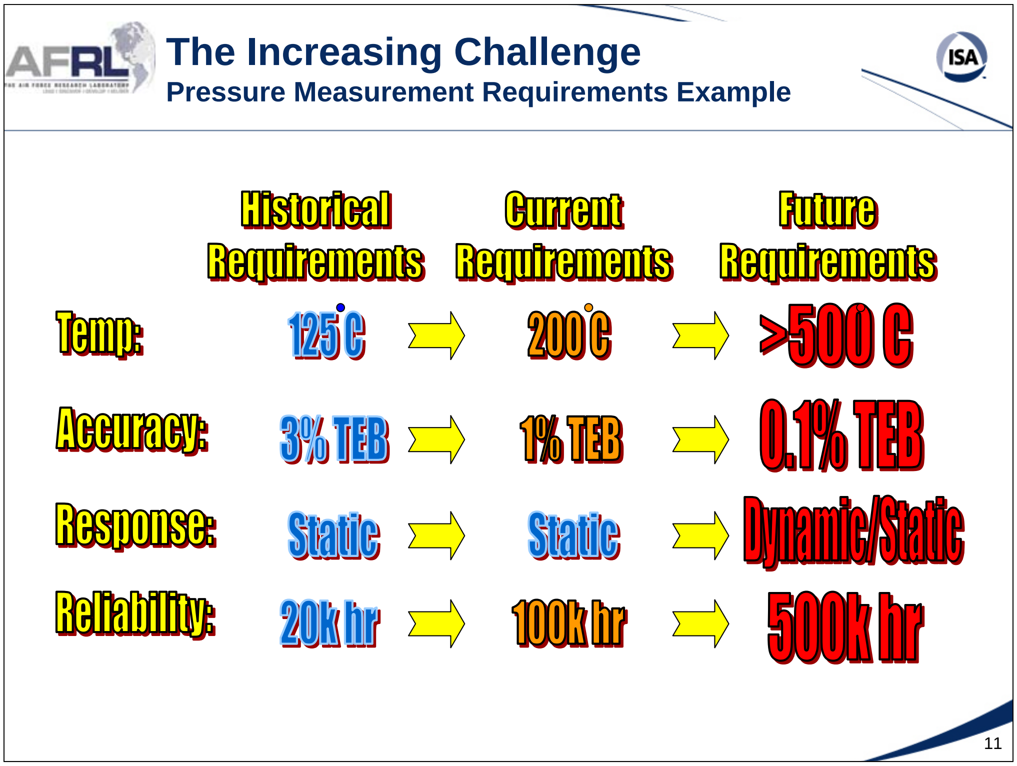
Obviously, the greatest need for sensors are in health management and monitoring. There is a need for supporting software to interpret sensor and instrument outputs; correlate them to the machine's condition; provide the interpretative analyses; forward projections of servicing intervals; estimate remaining component life, etc. Thus, in addition to developing the basic sensor and instrumentation systems, there is a need to acquire long term data from sensors and instrumentation systems installed and operating in a commercial environment. These operating data will be necessary to complete the development of the sensors and instrumentation systems (i.e., develop robust commercial designs at acceptable cost) and build the data base from which to develop reliable predictive models.



Present sensors fall short in several categories. First, few alternatives based upon advanced technology have progressed to the point of commercial readiness to address some of the important plant operating issues, such as **component life**, **component degradation**, or **risk** associated with maintenance interval expansion. Second, it is difficult to apply existing sensor technology to robustly provide useful online input in the gas turbine environment, most notably in the combustion zone and gas turbine stages. Finally, the hardware and software are still at an early stage of development and the commercial application of many possible sensors and health monitoring systems is prohibitively expensive at this time.

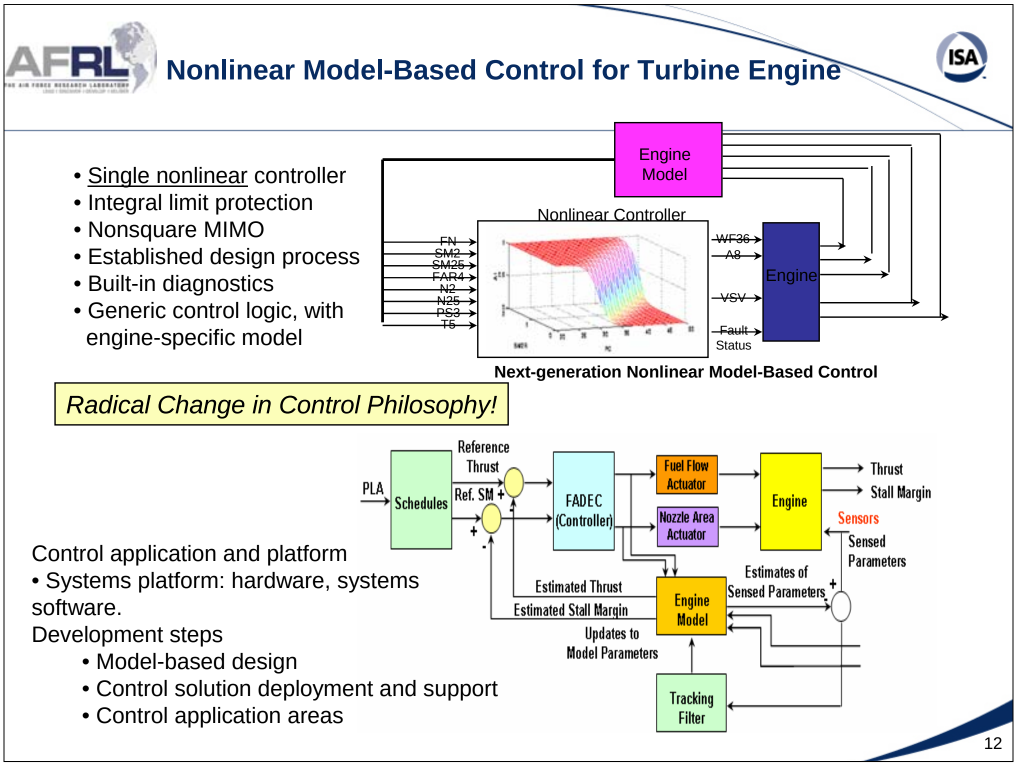
Some of the unmet needs for turbine sensors and monitoring include:

1. Component Life Monitoring either through direct or indirect monitoring of component properties.
   - On-line monitoring of component life would allow some assessment of when the next shutdown might occur.
   - On-line indication of component degradation could alert operators to failures that could propagate through the unit. For example, on-line monitoring of the combustor status or blade coating integrity would alleviate downstream consequences.
   - Off-line Non Destructive Evaluation (NDE) of component life would help determine if component replacements are needed before the next scheduled shutdown.
2. On-line risk assessment of extending the outage schedule would also be useful to determine whether it is possible to operate for extended periods.
3. Sensors that map the blades and vanes for integrity. For example, a temperature profile of the blades and vanes could indicate blocked cooling passages or coating failures.



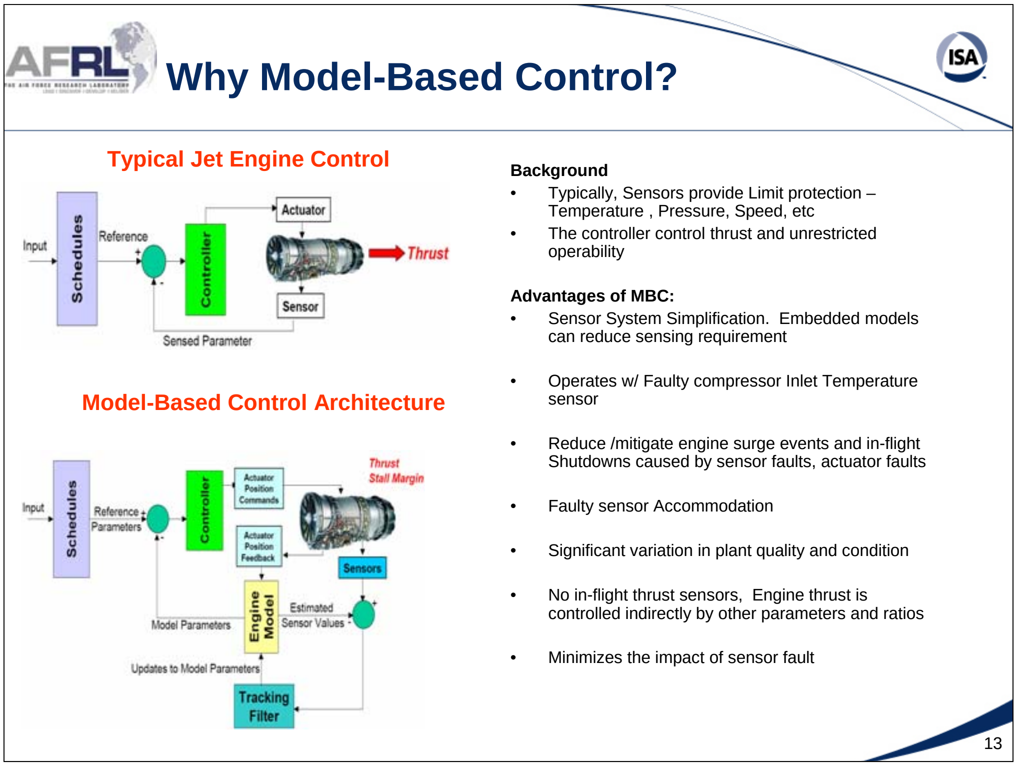
Compares current and future of a typical temperature sensor

There is a clear need for sensors and instrumentation systems which can operate in the turbine hot gas path and provide information to address the above issues. Here, we are showing he four factors: Temperature, accuracy, response, and reliability from historical perspective to current and future requirements.   Of course cost is also a factor that is not mentioned often enough!



In traditional control techniques, all sensors are hard wired to a central controller. A new concept to control the aircraft engines uses a collection of heterogeneous sensor data to collect damage and performance information to potentially achieve significant maintenance and safety improvements. Using, Ethernet communication, and in-situ sensor systems containing physics-based data and health information, we can achieve improved efficiency, productivity, and reliability. Additional benefits of the new control system are engine health management is now an integral part of its function (integrated control and engine health management).

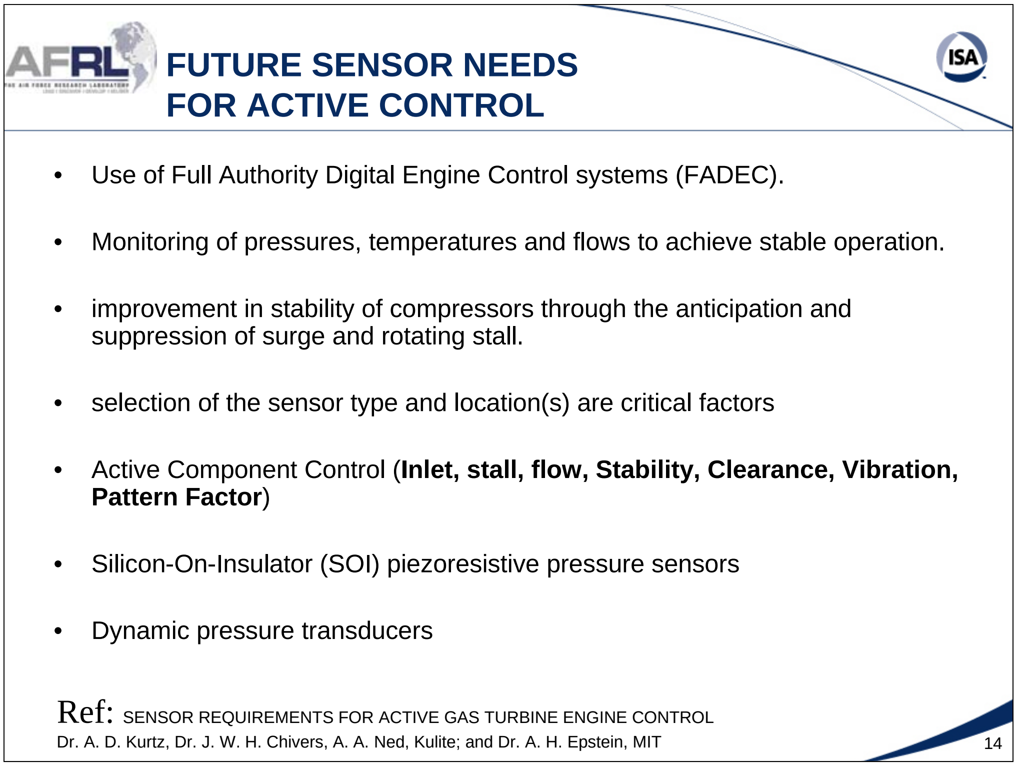
Model-Based Predictive Control (MBPC) are the future of controls since it can address variations from engine to engine. There are variations in each engine and non-linearity's due to large range of operating conditions and power levels experienced during a typical mission. There are restrictions in turbine operation due to mechanical, aerodynamics, thermal, and flow limitations. Because of the dynamic characteristics of turbine engines, MBPC requires fast computational requirement with robust and fast response sensors to perform in the required timeframe. This also requires sophisticated software to account for failures and determine a plan of action. MBPC is based on constrained optimization which uses a plant model to describe the evolution of the outputs and commences from an assumed known initial state.



Model-Based Control/Diagnosis

A typical formalization of the discrete control problem is a Markov decision process. For a process to be Markov, the current state and action must provide all of the information available for predicting the next state. That is, if we know the current state of the system, knowing the previous state of the system cannot not add information when attempting to predict the next state of the system.

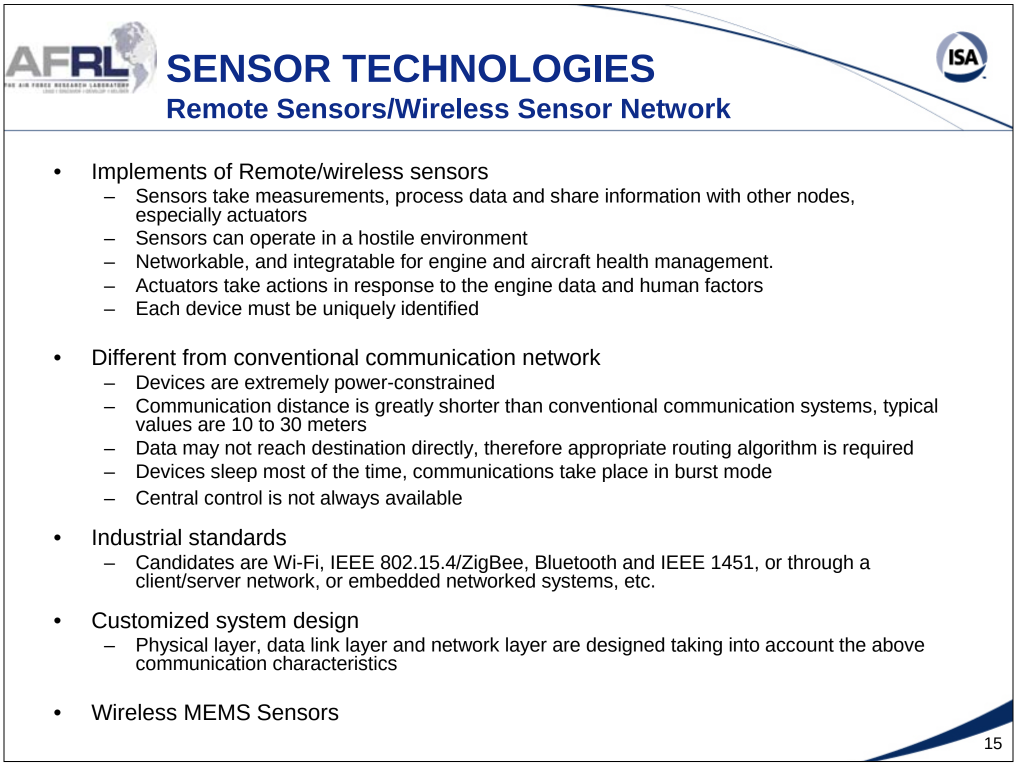
Techniques from model-based diagnosis take a different approach, incrementally generating members of the belief state in best-first order. In this approach, the device is typically modeled as a set of components. Each component has a set of variables and one or more states, or modes, that it can occupy. Each mode has a (typically) propositional model that constrains the values of the components variables. Thus, setting the mode of each component induces a set of constraints on the variables of the complete model. Some of these variables are directly observable from the device, meaning that certain assignments of the modes will not be consistent with the observations. The task is then to assign each component's mode so as to cause consistency with the observations.



Many modern turbomachines, in particular multistage axial flow compressors, rely on complex scheduling of stator vanes, bleed valves and monitoring of pressures, temperatures and flows to achieve stable operation. The ability of a FADEC to process the many sensor inputs from an engine, to apply sophisticated control laws and control a range of actuators simultaneously, enables many modern gas turbines to function economically and reliably.

Active control is poised to tackle three fundamental challenges: near-real-time measurement of the temperature of combusting mixtures, rapid and inexpensive measurement of key species in combustion exhaust, and diagnostics. Active component control can be categorized as active **Inlet, stall, flow, Stability, Clearance, Vibration, and active Pattern Factor.**

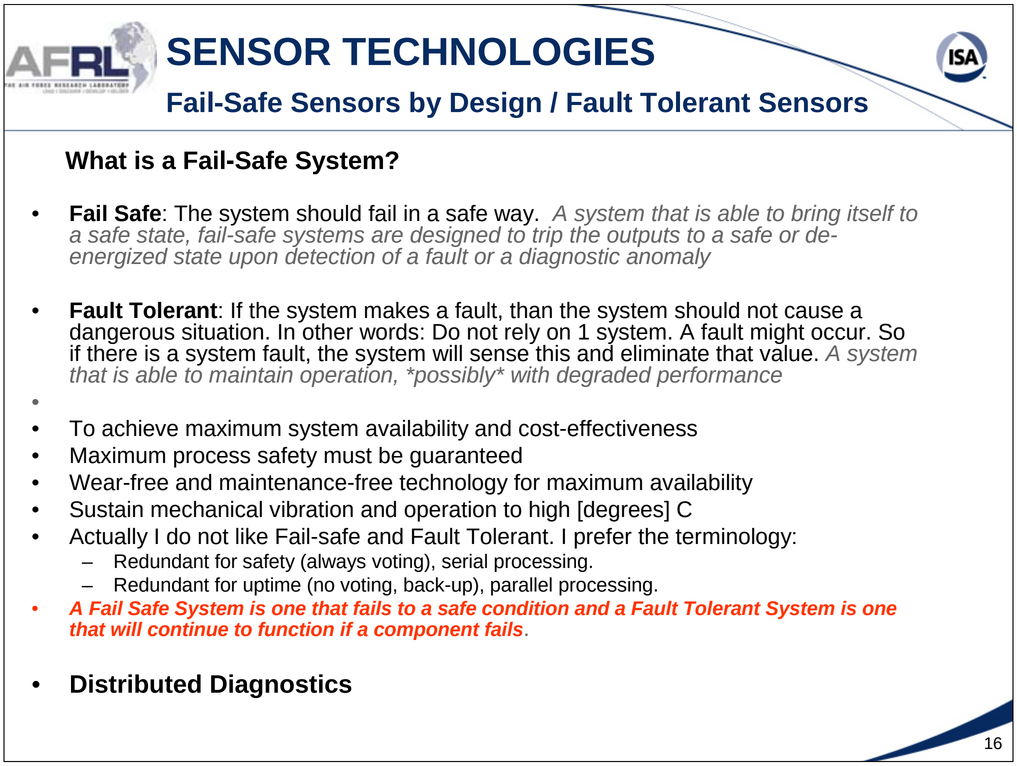
Real-time temperature measurement will enable combustion engineers to control the combustion process and therefore extract the most work possible from a reacting mixture. Emerging laser technology combined with high-speed laser control and data processing will continue to provide an opportunity to develop such a control system.



Wireless MEMS Sensors :

There is a need to develop wireless sensors for modern control. One such a device is MEM-based sensor. Here, there is a need to develop fast (unsteady) sensors for high temperature environments.

Wireless pressure (and temperature) sensors based on ceramic packaging technology passive circuit element, no power supply: antenna readout



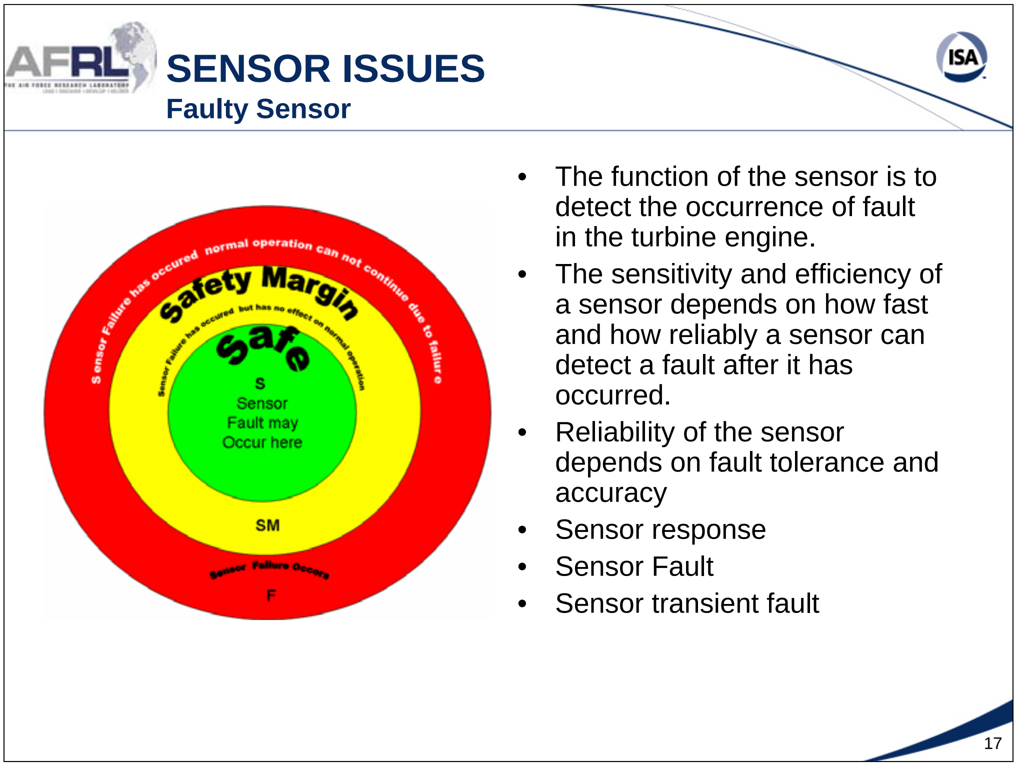
In most cases, this is accomplished through either diagnostic intervention or process input changes. In a FADEC system, however, special consideration must be given to the functional readiness of the system. For these applications, a single sensor can be configured as a one-out-of-one system by simply implementing "I" pattern outputs.

In this configuration, a turbine engine can be monitored by two communication channels, each receiving a heartbeat used to verify the operation of the system. The "I" pattern output is built around an intelligent I/O device that periodically detects this system wide pulse. If either of the output module interval timers is not reset within a pre-defined time frame, the system outputs will be de-energized.

This back-up or secondary means of de-energizing the outputs allows each system to operate in an unrestricted time-out mode. The outputs of these secondary diagnostic channels are configured to "OR" with the primary logic solver outputs providing shutdown coverage from the field inputs, diagnostic failures, and hardware anomalies.

The flexibility inherent in the Genius I/O and the communication subsystem allow you to add an additional layer of protection by implementing redundant I/O and communication channels.

Distributed Diagnostics
In addition to the continuous communication checks, all standard diagnostic features found in dual and triplicated FADEC systems are active. Furthermore, FADEC I/O circuits incorporate current and voltage sensors that provide loop continuity as well as output and load state diagnostics. Faults are handled by a software alarm processor function that time-stamps and logs I/O and system faults in two diagnostic tables. These tables can be displayed or uploaded to a host computer or other coprocessor.



In order to talk about issues related to sensor, we need to understand terms related to sensor performance. Terms Used to Define Performance of sensors:

• **Accuracy**: difference between measured and true values; typically specified by a maximum value.

• **Precision**: difference between measured values during repeated measurements of the same quantity.

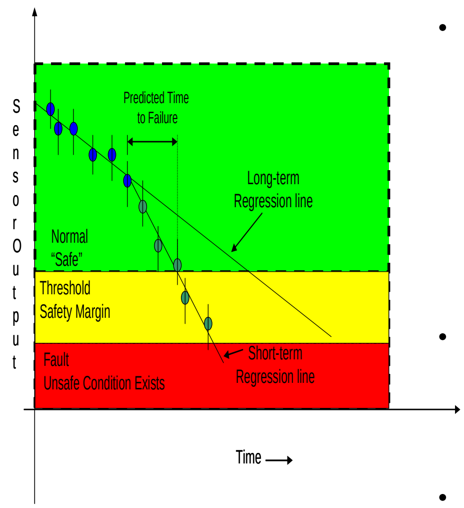
• **Resolution**: smallest increment of change in the measured value that can be determined reliably (repeatedly).

• **Sensitivity**: change of an instrument's output per unit change in the measured quantity; may or may not be related to above quantities for a given instrument.

In the above picture, a sensor may fail, but the system is still safe (green zone). If the sensor has failure, and needs to be fixed as soon as possible, then we are in the yellow zone, or another word we are within the safety margin. In the red zone, the failure has occurred and the safety of the system is in jeopardy. We do not want to be in this zone!

SENSOR ISSUE

Predicting Time until a Failure, Minimizing the impact of Failure

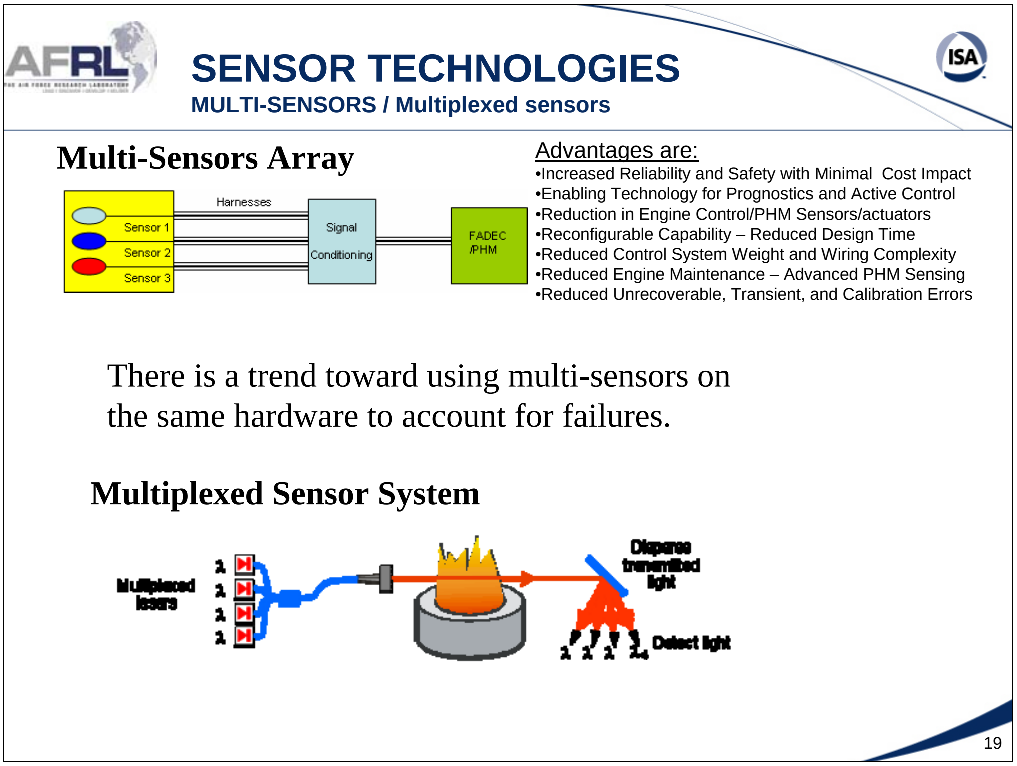


- Prognostics is the process of predicting the future state of a Prognostics systems comprise sensors, a data acquisition system, and microprocessor-based software to perform sensor fusion, analysis, and reporting/interpreting of results with little or no human intervention in real-time or near real-time.
- Offers the promise of:
  - Minimizing failures
  - Extending the time between maintenance overhauls,
  - Reducing life-cycle costs
- **Sensor Validation**

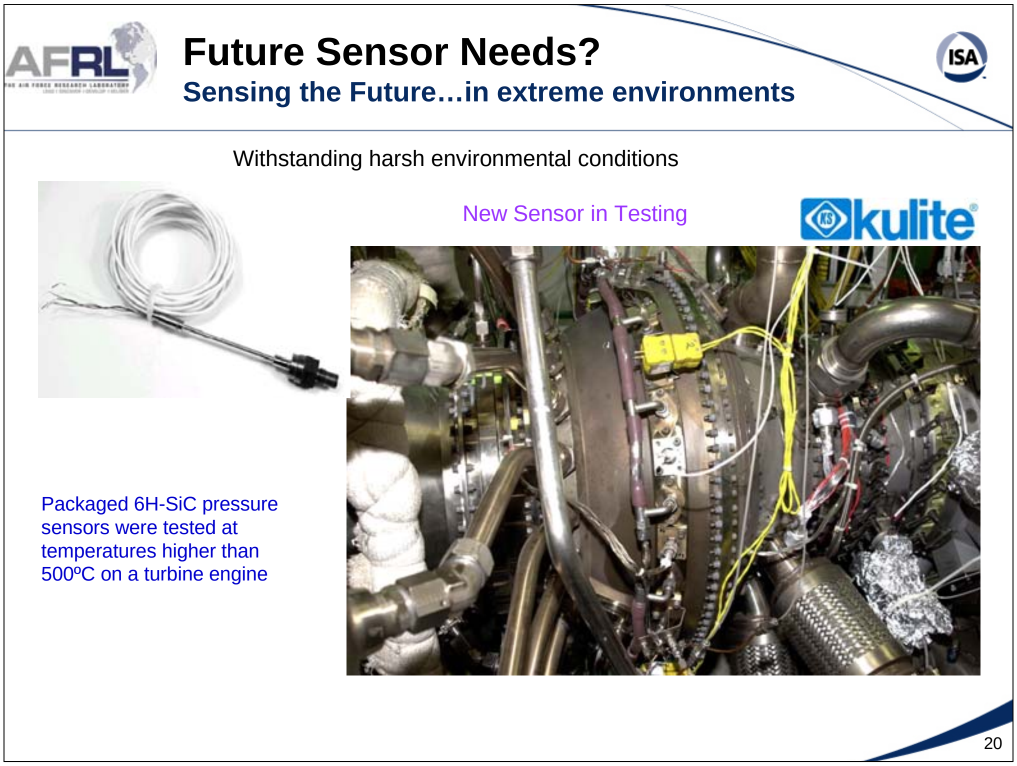
18

Predicting a failure is the best approach to minimize the impact of failure. To be effective, prognostics needs to be done on real-time or near real time, and requires a robust sensor. Any sensor failures can not be tolerated. That is why we need a robust sensor.

Sensors are the prime source of information about operational state of the engine for both control and EHM perspective. Therefore, we need to know the confidence level of quality of data for each sensor. Sensor validation are absolute necessity to minimize over-all system failures.

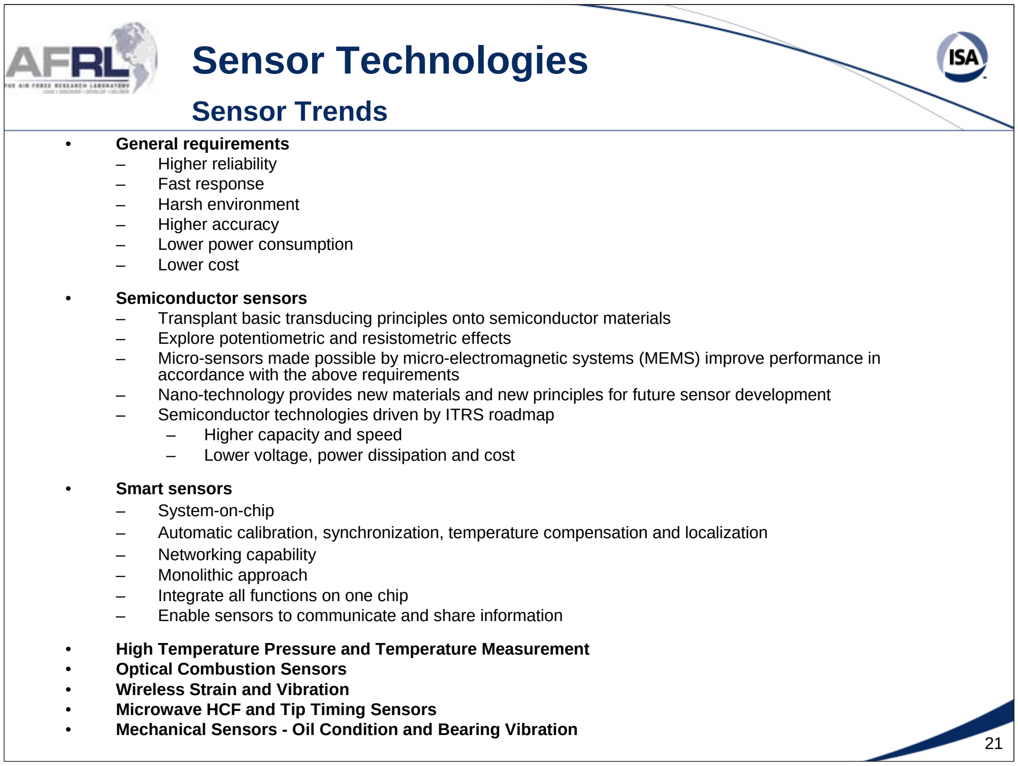


Two possible technologies that may not have been utilized for turbine engine control. There is a trend toward using multi-sensors on the same hardware to account for failures. Multiplexed sensors are in the stage of R&D and needs to be transitioned to turbine engines.



Future vision of "intelligent" aircraft engines for enhancing the affordability, performance, operability, safety, and reliability of aircraft propulsion systems.

Intelligent engines will have advanced control and health management capabilities enabling these engines to be self-diagnostic, self-prognostic, and adaptive to optimize performance based upon the current condition of the engine or the current mission of the vehicle. Sensors are a critical technology necessary to enable the intelligent engine vision as they are relied upon to accurately collect the data required for engine control and health management. This paper reviews the anticipated sensor requirements to support the future vision of intelligent engines from a control and health management perspective.



Semiconductor sensors

Basic transducing principles transplanted to semiconductor sensors by micro-electromagnetic systems (MEMS) and nano-technologies

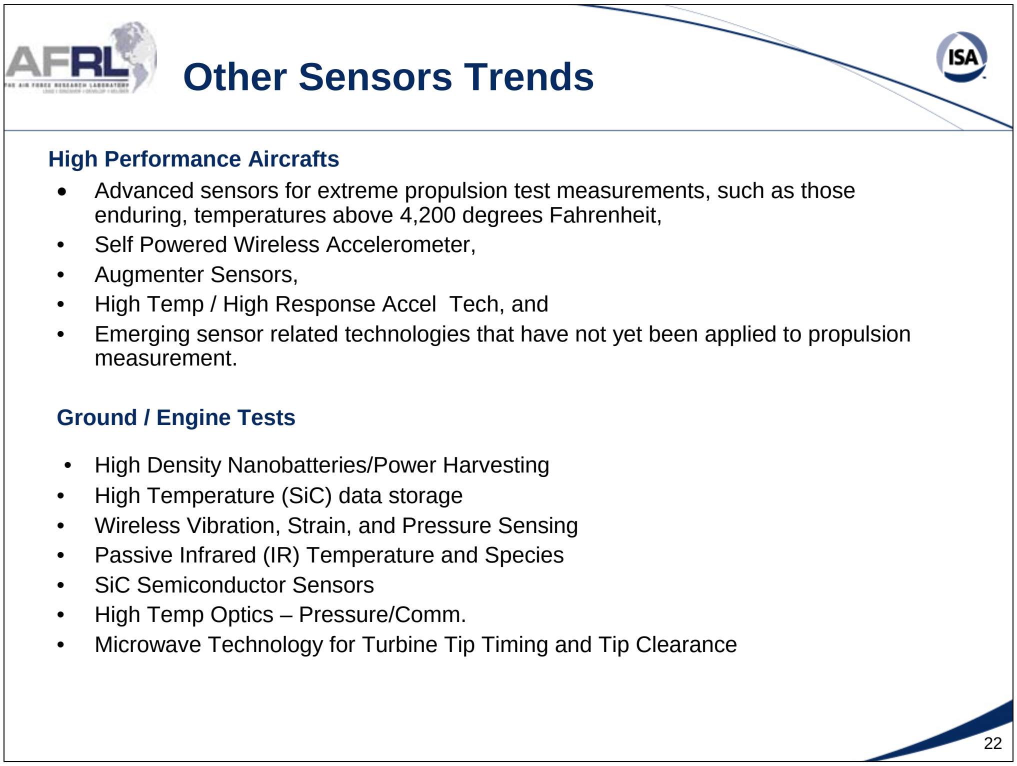
Higher reliability

Higher compatibility with semiconductor circuits

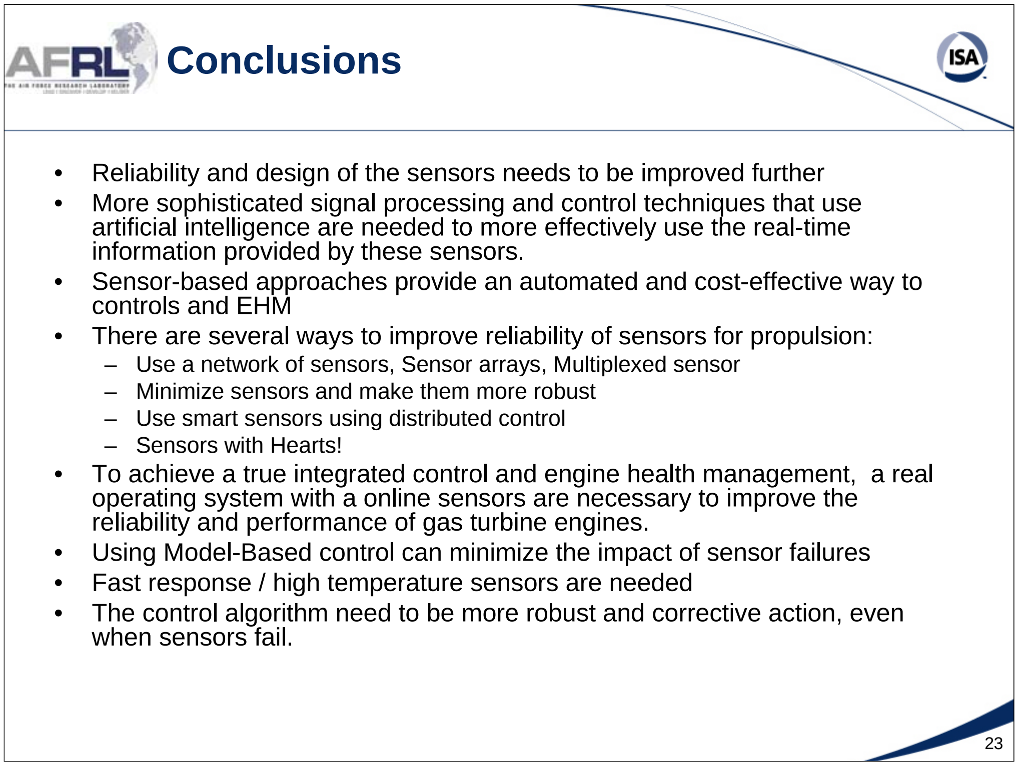
Lower power consumption

Use of Tunable Diode Laser (TDL) Absorption sensors for Temperature and Gas Composition

Pattern Factor Sensing and Control Based on Diode Laser Absorption



Several applications for both high performance and ground test are listed. Self explanatory. Read the slide.



Intelligent sensing holds promise for fail-safe distributed control for turbine engines. If the sensor fails or experience inadequate application quality, a separate discrete output must be provided. To achieve a true integrated control and engine health management, a real operating system with a online sensors are necessary to improve the reliability and performance of gas turbine engines. Perhaps the hope for the future may lie on a sensor with a heart! A sensor of the future has a "heartbeat" that is capable of monitoring the sensor, wiring, and application characteristics. It will issue a continuous pulsed signal, or heartbeat, that will ceases transmission in the event of sensor failure, open or shortened wiring, or unstable sensing conditions, or perhaps extremity high or low condition. It can then send control and diagnostics information on the same wire mesh networking. Sensor networking and model-based control may be other ways to minimize sensor failures.

Thank you!

AFRL's Propulsion Directorate

CONTROLS AND ENGINE HEALTH MANAGEMENT

Please excuse the cymbalism!

Powering the Air Force 1917

Developing practical engine control and health management technologies

24