OPERATIONAL SENSE AND RESPOND LOGISTICS

A WHITE PAPER

PREPARED BY:
CACI INC - FEDERAL
NORMAN MESSENGER,
1100 NORTH GLEBE ROAD
ARLINGTON, VA 22201
nmessenger@caci.com
http://www.caci.com/

ABSTRACT

This white paper addresses an approach and notional sensor based solution with proven logistics methods/systems that significantly improves readiness at lower overall cost. The individual services are re-engineering maintenance processes through technology insertion and doctrinal change to achieve the Department of Defense JV2010 readiness goals through anticipatory maintenance, agility and velocity-based methods. To address the information currency shortfall for these improvements, especially in aircraft and ships, all of the services are attempting to implement advanced condition based maintenance (CBM) programs, which they call CBM+ or sometimes Prognostic, Health, and Utilization Monitoring Systems (PHUMS). By using easily installed wireless sensors, coupled with simple wireless data extraction (from the network sensors) and interfaces to readiness based sparing maintenance prediction tools (that have yielded hundreds of millions of dollars in cost avoidance / savings in the Navy), the notional system presented in this paper provides a possible basis for significant advances in USCG in anticipatory maintenance using nearly off-the-shelf components and software.

BACKGROUND

CACI was founded in 1962 as a simulation and modeling company. These early beginnings were soon followed by relationships with the Department of Defense involving military logistics, repair, maintenance, supply and readiness. Over recent years, CACI has worked with the DoD in these areas that have included numerous innovative approaches and technologies for logistics and maintenance management including such successes as readiness based sparing (RBS) and area where CACI remains active and is in part the subject of this notional approach to automation of operational maintenance. This approach combines emerging wireless sensor technologies with proven logistics solutions and minimizes risks while providing the best-value solution to improving logistics on existing and future major equipments, especially aircraft and ships.

DoD Joint Vision 2010 (JV 2010) places a great deal of emphasis on the combined benefits of anticipatory maintenance and pushed spare parts support to reduce the costs and logistics footprint of operating today's weapons systems. The key logistics reinvention and maintenance process attributes that are cornerstones of that vision are:

- Anticipatory Maintenance
- Agility
- Velocity-Based

While no one part of the system is more important than the other, anticipatory maintenance has to be considered foundational, without it logisticians will be unable to use the next two elements since there is insufficient knowledge of the equipments being supported. To address this shortfall all of the services are attempting to implement advanced condition based maintenance (CBM) programs, which they call CBM+ or sometimes Prognostic, Health, and Utilization Monitoring Systems (PHUMS). Traditional military maintenance is focused on preventative maintenance, as shown in Figure 1, CBM is focused on predicting maintenance needs and then planning/ reacting accordingly.

The following description and assessment of CBM+ is condensed from an Assessment of Condition-Based Maintenance in the Department of Defense, LG903B1, August 2000, by Steven W. Butcher, a Logistics Management Institute survey of CBM+ for DUSD(L);

> CBM is a set of maintenance actions based on real-time or near real-time assessment of equipment condition obtained from embedded sensors and/or external tests and measurements using portable equipment. The CBM strategy is to perform maintenance only when there is objective evidence of need, while ensuring safety, equipment reliability, and reduction of total ownership cost. CBM system

components include, hardware (e.g., sensors and computers), software (including decision support capability), and communications (e.g., data buses and communications links).

To gain a better understanding of the concept and functionalities proposed for CBM+ or prognostics, we have included a graphic and description from the LMI report, which succinctly covers the range of maintenance strategies and how predictive maintenance is the capstone goal.

FIGURE 1 CBM IS PREDICTIVE MAINTENANCE

	Maintenance Processes			
	Reactive	Proactive		
Category	Run-to-Fail	Preventive	Predictive	
Subcategory	Fix when it breaks	Scheduled maint.	CBM	Prognostic
When Scheduled	No scheduled maintenance	Static: maintenance based on a fixed time schedule for inspect, repair, and overhaul	Dynamic: maintenance based on current condition	Dynamic: maintenance based on forecast of remaining equip life
Why Scheduled		Failure modes and equipment maintenance requirements predicted during design	Maintenance is needed now based on real-time evidence to prevent equipment degradation	Maintenance need is probable within next mission time
How Scheduled		Modeling and simulation; no real-time feedback loop	Continuous collection of condition data	Forecast of remaining equipment life based on actual stress conditions

Butcher continues, "The key distinction between CBM and prognostics is that CBM identifies a failure that will occur shortly, based on current condition indicators, while prognostics forecasts remaining equipment life, based on stress loading (i.e. flight hours at specific "G" loads or time-stress measurements based on a cumulative vibration curve, as opposed to flight hours only). Another way of viewing the distinction between CBM and prognostics is that CBM determines a forecast of impending failure from physically measured indicators on the equipment, while prognostics adds the capability to forecast remaining equipment life."

Further, according to Butcher, "The ability to forecast remaining equipment life appears simple enough, particularly if a log of usage in hours or miles is kept which can be compared to a ceiling number of hours or miles, or if a graph of operating characteristics can be compared to threshold values. One fallacy of estimating remaining equipment life from a journal of usage is that it assumes the component fails according to a wear-out schedule, e.g., at x hours/miles. This may not be the case. A ceiling usage based on hours/miles does not factor in stress loads that can prevent realization of those hours/miles. The notion of stress loading that significantly diminishes mean time between failures (MTBF) is not new. Professional logistics engineers are familiar with the distinction between calculated MTBF and operational MTBF, in which operational MTBF may be lower by a factor of 20 or more than the calculated MTBF."

Finally, according to Butcher, “Prognostics attempts to know and factor the stress environment into remaining life calculations as a means of augmenting condition-monitoring information. A prognostic system may anticipate a failure further down the road than that which is predicted by current equipment conditions.”

An important note to make here is that the MTBF estimates of new systems or for existing systems with years of service are primarily based on just hours of operation. This number in turn begins to drive the whole sparing and manning profile for the equipment. It is no wonder that we see the wide variances in failure rates based on the observations above, or is there any reason to believe that we can improve our logistics performance much beyond what it is today until we can better determine and monitor the stress factors that cause failure.

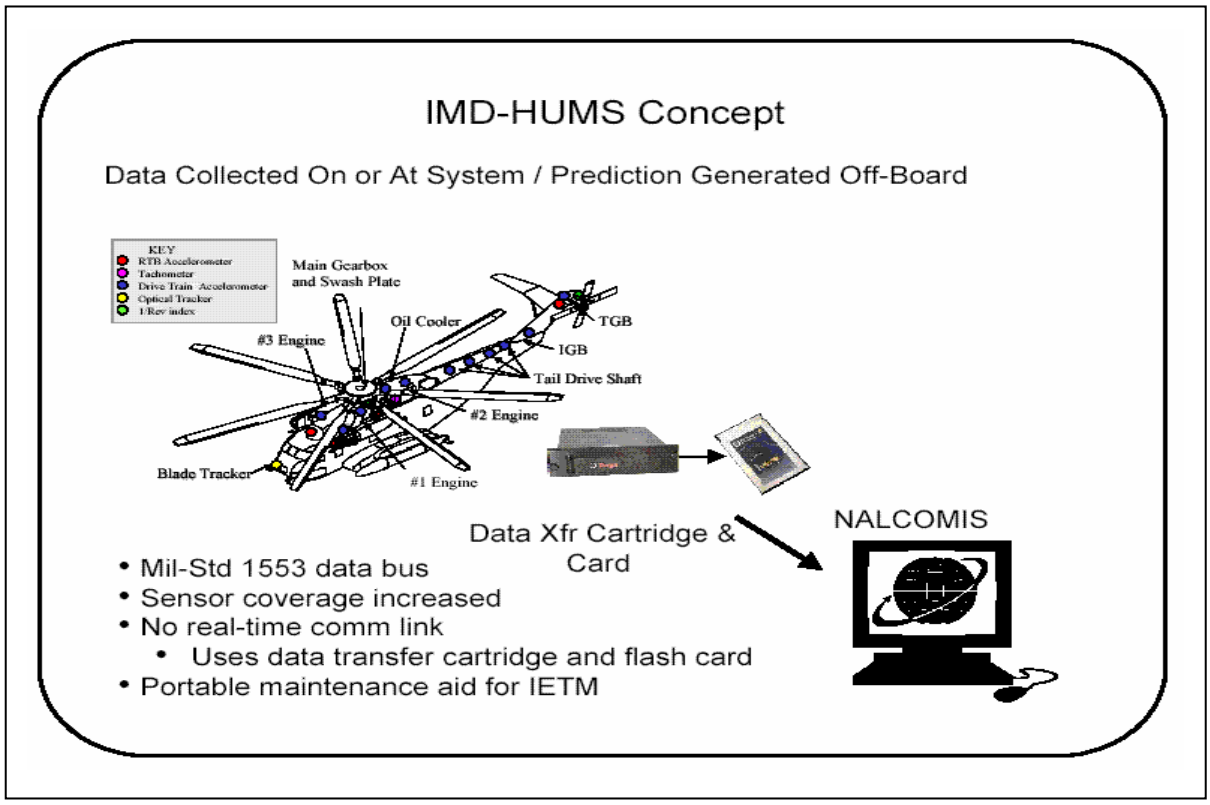
Although new systems like JSF and FCS are focusing on delivering prognostic systems as part of autonomic logistics packages, legacy systems pose substantive challenges to the post production implementation of CBM and prognostics. The three primary problems are:

- On-board (e.g., embedded) sensors often require substantial and costly modifications.
- The absence of installed communication buses can frustrate data collection and analysis.
- Off-board (e.g., manual data gathering and analysis) approaches may not be as comprehensive and burden an already overworked maintenance community

As an indication of the commitment to S&R concepts based on CBM+, Major General Ross Thompson III, Commander TACOM recently said,

> “The real key to our success is what I call 'Sense and Respond Logistics’. When we see a potential problem with a piece of equipment, we need to identify it quickly and get it repaired.” This was graphically illustrated to the CACI team recently by the Army Material Command’s vision of a Sense and Respond – Foxhole to Factory Integrated Information System, which included a presentation with a stop sign in the middle of the desert crossroads with the words “Stop here for parts you didn’t know you needed.”

FIGURE 2 USN IMD-HUMS SENSE AND RESPOND SYSTEMS



The services are interested in CBM+ but the path to achieving it has eluded them so far. For example, the Army and the USMC have both been piloting the installation of HUMS on various classes of helicopters (See Figure 2). This program was started in 1995 and there are still only a very small number of aircraft covered due to the costs of installation. We have estimated that cost based on budget submissions to be over $1M per helicopter just for the COTS equipment and engineering services. The systems being installed are Goodrich Fuel and Utility Systems Health and Usage Monitoring Systems. The LMI study documented the benefits of deployment in the Presidential helicopter squadron. No Return on Investment (ROI) analysis was included but at something greater than a million dollar per installation, it is understandable that the ROI may not be there.

This system represents the state of the market in COTS Health and Utilization monitoring systems, yet it is easy to see that there are significant problems with the implementation of this system in most legacy systems:

1) The system was integrated with helicopter's 1553 data bus, which makes it expensive to integrate. The use of the internal data bus requires a rigorous integration and testing period to insure that the system is compatible and will not cause critical failures in the helicopter system. Additionally there are many different variants of data buses in use in various aircraft, which require the whole integration process to be started over for each new platform.

2) The system has no real-time communications link and requires the downloading through a portable maintenance aid. If active maintenance is not being performed there is no way to gather information on the helicopter and transmit it to the logistics community.

3) The system is connected to the Naval Aviation Logistics Command Management Information System (NALCOMIS) Optimized Organizational Maintenance Activity (OMA**),** where it is analyzed for early identification and correction of degraded components in the engine, drive train, and rotor systems of the helicopter. There is no real time connection between NALCOMIS OMA and the extended logistics system. NALCOMIS does submit supply requisition data through the Navy's SNAP system, but the sensor data is not used to support a velocity based supply chain.

4) The local maintenance squadron performs data analysis, thus requiring additional man-hours that may not be available during a high Optempo period.

The system did provide documented benefits, at least for the Presidential Helicopter Squadron. They were:

- A 13% reduction in scheduled maintenance due to accurate flight hour recording.
- A 10% reduction in total aviation depot-level reparable/consumable costs due to reduction in vibration-related maintenance actions.
- A 6% reduction in depot costs.
- A 2.8% total flight hour reduction due to a decrease in functional check flights on H-60; 3.7%on H-53.

This shows that better capturing of actual operating hours avoided early performance of preventive maintenance actions and thus over the long run would actually extend the useable hours on the aircraft. Also, the use of improved sensing and monitoring of the equipment renders maintenance/support actions more effective throughout the entire supply chain. Although these benefits likely more than recoup the investment, the payback period may be too long because of the high initial investment costs. This may be the reason for the slow adoption rate.

MODERNIZING SENSE AND RESPOND

Similar to the Army's Sense and Respond Vision the CACI concept is based on the seamless collection and feeding of PHUMS sensor data from the foxhole to the factory or to the organic logistics support organization. The idea is that the sense and respond logistics system relies on sensor data collected from both the weapon system and the legacy logistics systems and combines them in a powerful analytic environment to:

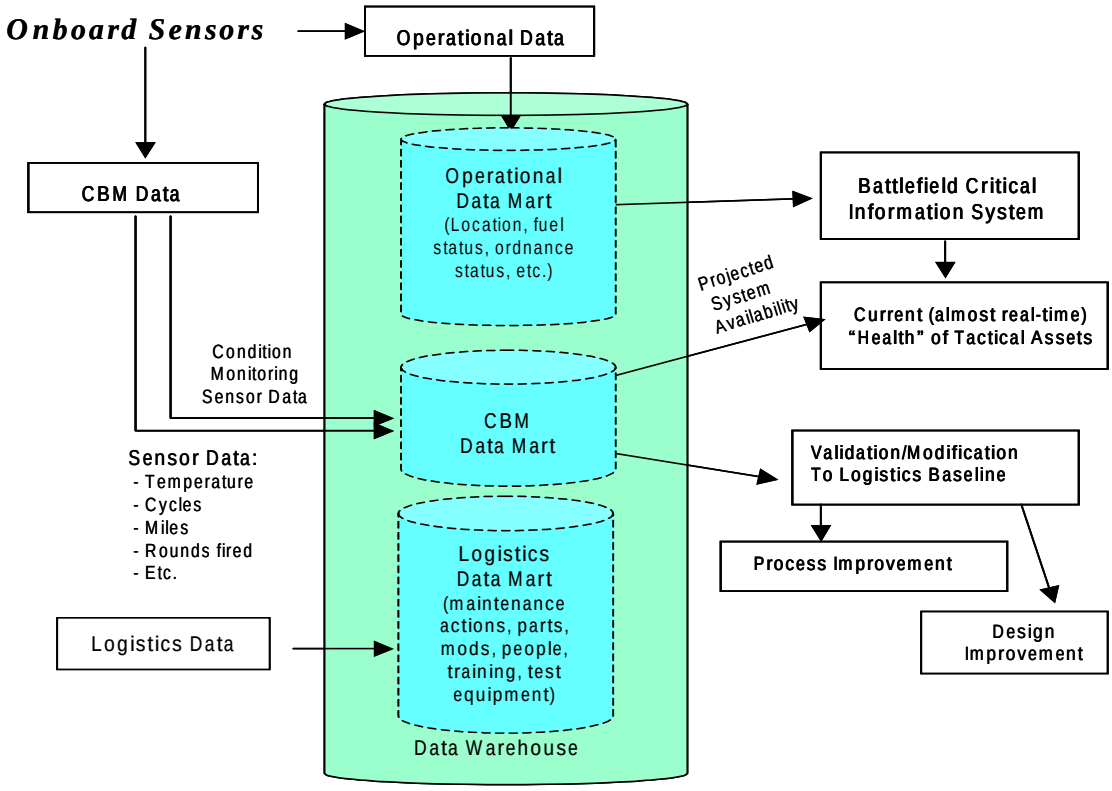
1) Detect problems that will cause near term operational or safety problems

2) Allow the service life cycle equipment manager to continuously improve the efficiency of the entire supply chain supporting the weapon system.

CACI has constructed a notional implementation of a modernized sense and respond configuration (See Figure 3) whose major system components are:

- **Wireless Network Sensors** - Low-cost, rapidly installable, grid of self-forming wireless network of sensors coupled to small computers sufficiently powerful to process the sensor and notify operators of conditions that demand attention immediately or pass the data at selected times upstream for further long term analysis.
- **Analytical Workstations** - Larger and more powerful machines using the predictive analysis methodologies developed by OSU for the AF Office of Science Research analyze the data sent upstream (from the airframe to receivers at the squadron or depot). Data is also be collected from the logistics systems supporting the equipment, which is in turn fed upstream to a large data warehouse.

FIGURE 3 MODERNIZED SENSE AND RESPOND LOGISTICS SYSTEM



- **Data Warehouse** - A SAS data warehouse would use multiple analytic techniques to mine the data and discover relationships that enable logistics decision makers at the tactical, operational, and strategic level to better manage the supply chain. Initial focus is on increasing the accuracy of failure rates to improve the ability to employ velocity management supply chain techniques.
- **RBS** - Readiness Based Support tools CACI has developed for the Navy and Marine Corps select the smallest spares pack up kit consistent with required operational availability goals and transportation availability. To test the effectiveness of the proposed alternative CACI will use the JWARS modeling environment to perform sensitivity and risk analysis for each recommended scenario.

Data Gathering and Communication - This configuration overcomes the three primary impediments to implementing the foundational components of the CBM+ that were identified earlier and enables all other capability:

- Wireless sensors minimize the modification to the managed equipment (airframe, for example). These are very small, low-power, low-cost wireless communications platforms that are coupled to very small, standard, low-power, low-cost MEMS- and nano-technology-based sensors.
- Wireless communications in a grid run in parallel to the airframe data buses thus lowering interference and testing concerns. This grid allows rapid installation of self-configuring networks that are autonomous and self-managing to ensure rapid reconfiguration, interoperability, reliability, availability, and maintainability.
- Data gathering is automated as the equipment returns to base through wireless downloads.

As a basis of comparison it would not be unreasonable to expect orders-of-magnitude reduction in the cost of implementing an equivalent system as the Presidential helicopter using the proposed system of wireless sensors. That hundred-to-one reduction works out to <$100,000 versus $1,000,000 in the case of the Presidential helicopter example.

Installation time/effort may also be reduced by an equivalent factor. The elimination of cabling for both power and communications makes the development and installation of mod kits dramatically easier. Likewise the non-intrusive nature of these micro devices makes the installation/attachment of these devices very simple. The incorporation of ultra efficient and very low power communication protocols like Ultrawide Band make sensing and communications from within highly shielded containers or parts of the aircraft very doable as well.

FIGURE 4 WIRELESS SENSOR ARCHITECTURE

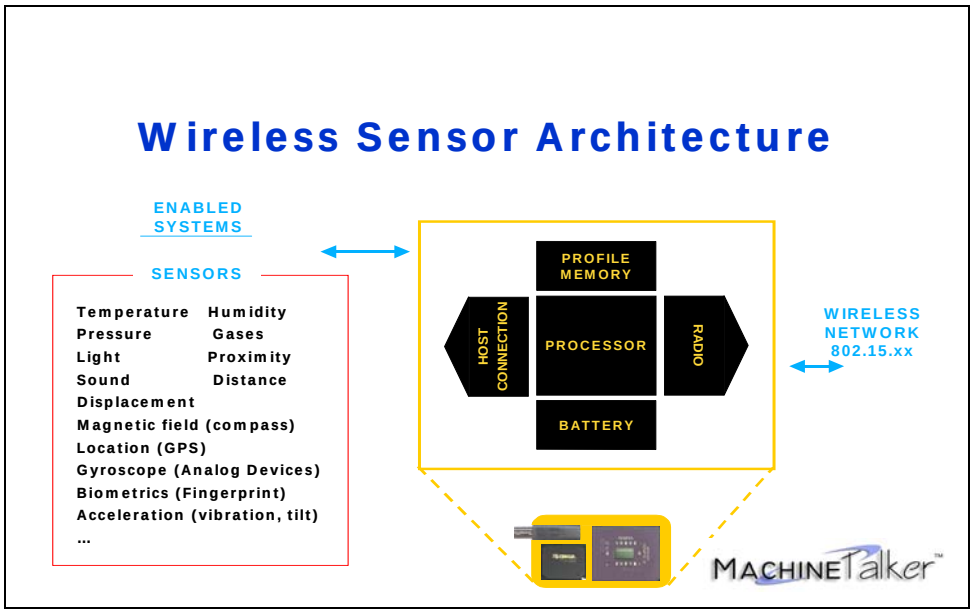


FIGURE 5 WIRELESS SENSOR FORM FACTOR

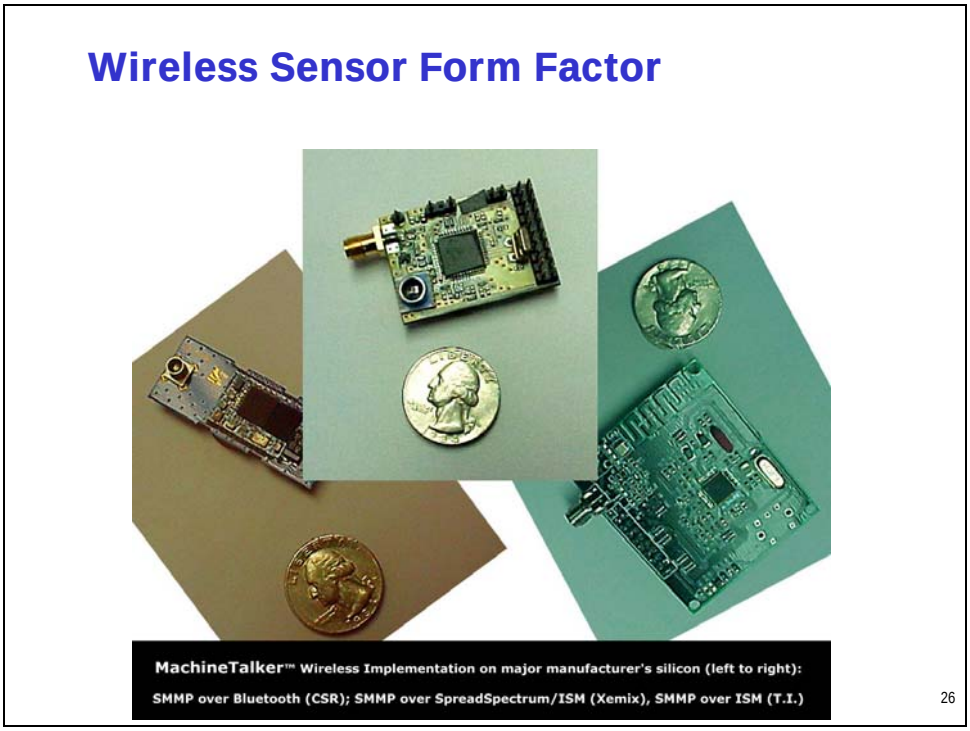


FIGURE 6 WIRELESS SENSOR EXAMPLES

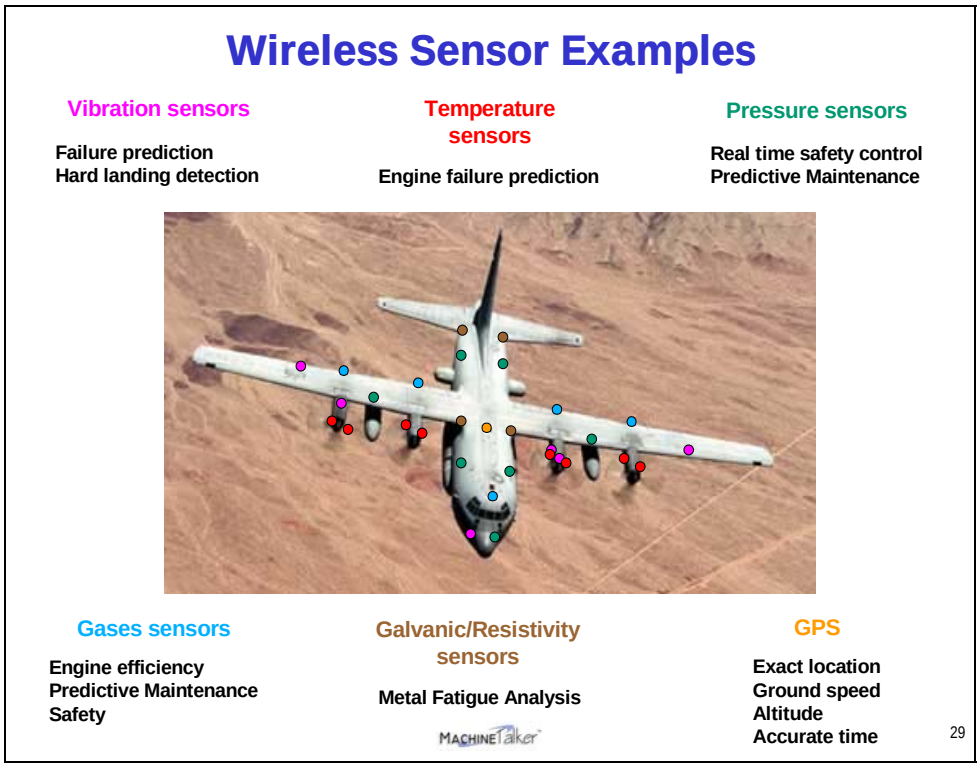
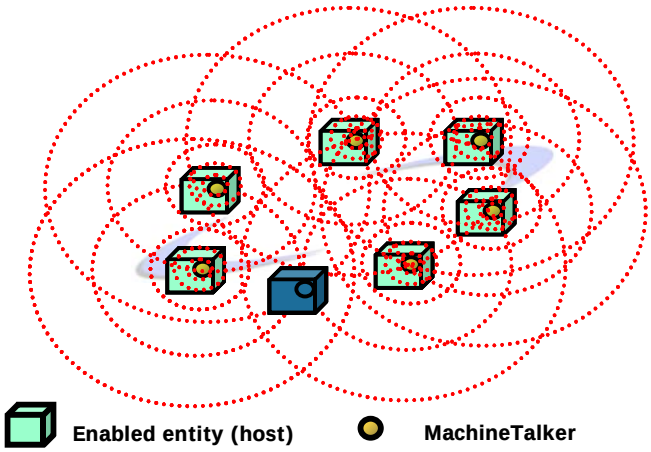


FIGURE 7 WIRELESS SENSOR COMMUNICATIONS



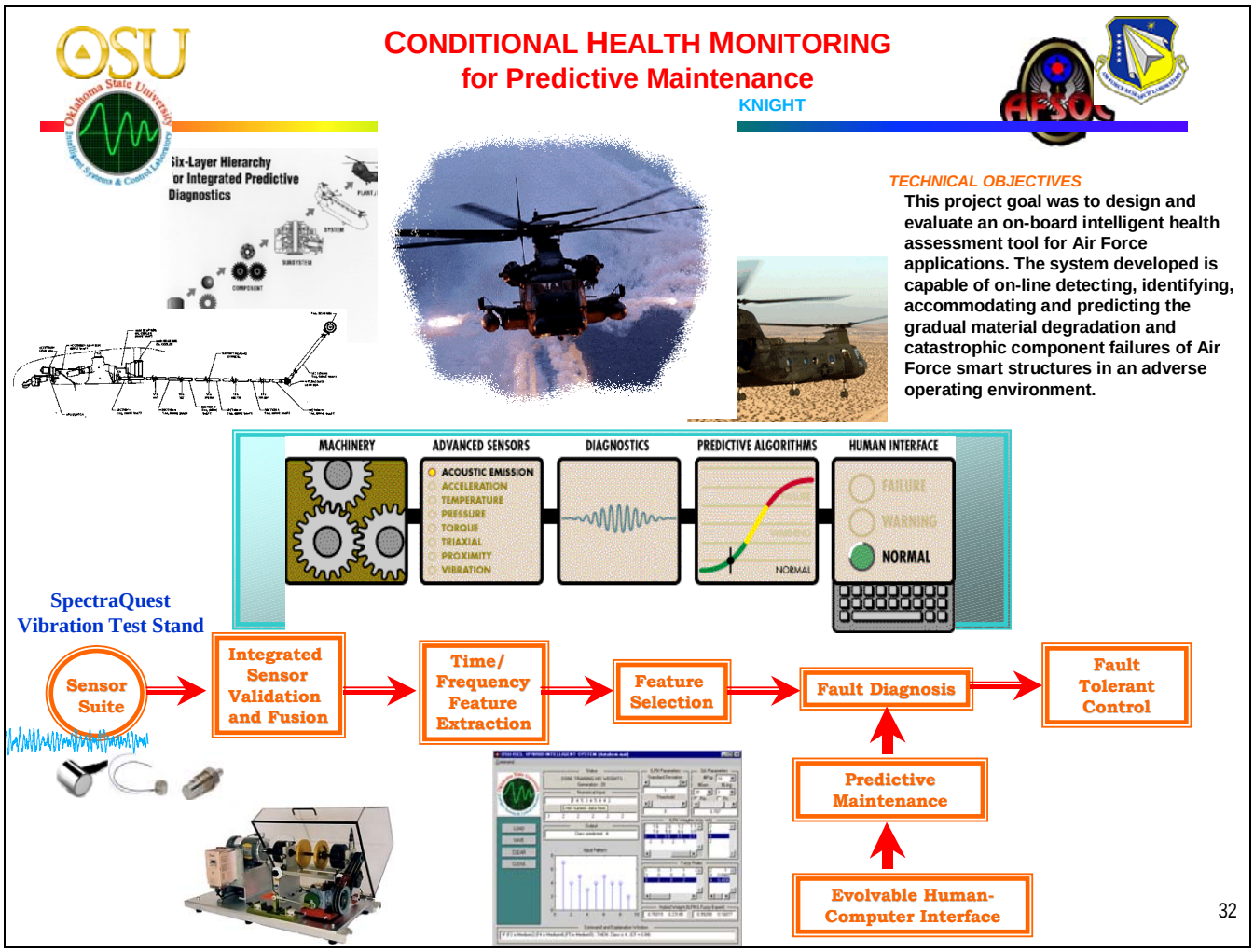
Machine Talker Modules – Communicating Sensors

- **Once within range (~30'), devices spontaneously form a network- a MachineTalker community**
- **New arrivals are automatically recognized and join the community. Likewise for departures**
- **The community is a resilient, self healing, peer-to-peer network.**

Conditional Health Monitoring Analysis - The next major portion of the project is to take the data emanating from the sensors and transform data into useful information concerning the health of the system being monitored and compress it and send it upstream to couple with other data and more powerful analytic tools. This is done through reuse of the equipment health analysis system built by Oklahoma State University (OSU) for the US Air Force Office of Scientific Research.

Supported by the Air Force Office of Scientific Research (AFOSR), OSU developed, designed, and validated an on-board intelligent health assessment system for Air Force vibration monitoring applications. The system developed is capable of promptly detecting, correctly identifying, properly accommodating and reliably predicting the gradual material degradation and catastrophic component failures of vibrating structures in adverse operating environments. In addition, the system is equipped with the ability to adapt the cause-and-effect relationship for the purpose of predictive maintenance. The highlights of the Conditional Health Monitoring program are recapped in Figure 8.

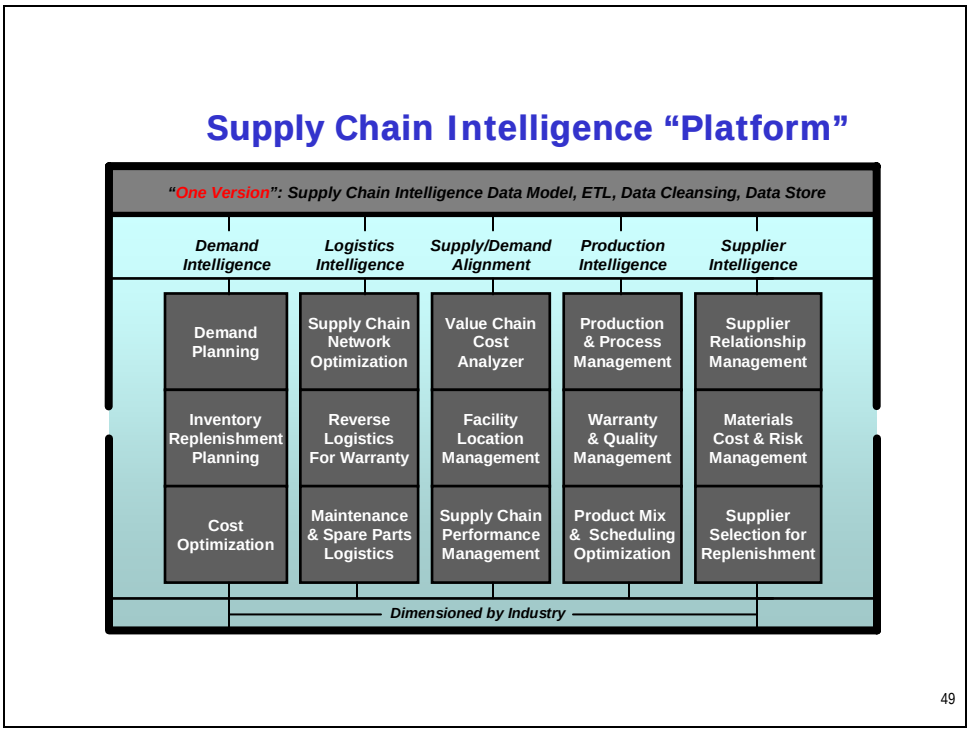
FIGURE 8 CONDITIONAL HEALTH MONITORING



Data Warehousing and Analysis - Using the SAS business intelligence suite of data warehousing, data mining and data discovery tools, relationships are discovered in the data that dramatically reduce the variances identified in the LMI study referenced earlier. These variances have a critical impact on the provisioning of spare parts for repair of equipment in the field. For most heavily used parts, forecasting is straightforward. However, the majority of spare parts used are “intermittent demand” parts. As an example, over half of the 40,000 parts used on the KC-135 experience a demand level of one part or less per year. Many of these parts are critical to the safe and effective operation of the aircraft and can cause extended unavailability of the aircraft when the parts are needed and not available. In a Sense and Respond environment, data from forward units on equipment usage and wear is used in existing reliability models to predict accelerated wear of parts, to calculate increased probability of parts demand as units move around on the battlefield, or around the country in defense of the homeland. This allows spare parts forecasting to be responsive, quickly adapting 'lessons learned' in the field. Such a fast adapting forecasting tool can be incorporated into a tactical logistics risk assessment system that allows logistics planners to instantly identify weaknesses and vulnerabilities caused by projected need of critical spare parts in the field.

SAS is currently helping other aerospace companies like Boeing implement similar functionality in their own companies as summarized in Figure 9.

FIGURE 9 SUPPLY CHAIN INTELLIGENCE "PLATFORM"



Using the power of the SAS supply chain platform one can generate improved estimates of mean time between failure rates and demand rates for the wireless sensor monitored equipment.

Readiness Based Sparing and Logistics Expertise - CACI has been the sole developer and provider of readiness based sparing (RBS) services to the Navy since 1978, providing performance benefits and cost avoidances to the Navy and Marine Corps customers using our readiness-based modeling tool sets. CACI developed the Multi-Echelon Readiness Based Sparing (ME-RBS) model for the Navy to identify the spares required to support a specific operational availability goal. The ME-RBS process provides cost avoidance and cost saving opportunities throughout the equipment system life cycle in order to achieve required system operational availability. Using a discrete event simulation of the design reference mission and a marginal cost inventory model it selects and positions spares by trading off between retail (user) and wholesale (backup) stocks and makes recommendations, which includes procurement and transportation delay times. ME-RBS starts the sparing analysis based upon proven reliability, maintainability, and supportability engineering best practice and optimizes sparing by balancing costs against a given readiness objective. ME-RBS considers the item's order and shipping time, wholesale requisition response time, and transportation alternatives, and makes not only inventory level decisions but also where to place the stock in the supply chain.

This is but one of many logistics successes accomplished by CACI in partnership with various services (Army, AF, Marines, Navy and Coast Guard). This vast logistic and readiness experience makes application of key technologies both practical and meaningful to CACI customers.

SUMMARY

Through the use of

- Modern wireless sensors in a communications grid on an aircraft (such as the Machine Talker examples)
- Modern on-board small computers for gathering and saving the data
- Home base receivers to extract the data from the aircraft upon arrival
- A data warehouse of this data, logistics data and historical data
- Oklahoma State University (OSU) tools for predictive maintenance analysis
- SAS tools for overall trend analysis
- CACI experience in readiness based sparing techniques and technology integration

there is significant opportunity to greatly reduce maintenance and readiness costs while improving readiness and maintenance quality on critical aircraft and other equipment. This approach can provide Sense and Respond Operational Logistics that has the potential of dramatically accelerating the achievement of JV2010 and Focused Logistics. And, the cost profile is an order of magnitude lower than those using older, wired-in sensor technology.

For more information on Readiness Based Logistics please contact:

CACI INC - FEDERAL
NORMAN MESSENGER,
14151 PARK MEADOW DRIVE
CHANTILLY, VA 20151-2218
nmessenger@caci.com
http:/www.caci.com/