PHM for Astronauts – A New Application

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ABSTRACT

This paper introduces a concept and approach on bridging Prognostics and Health Management (PHM), an engineering discipline, to Space Medicine (SM) in order to mitigate the Human Health and Performance (HH&P) risks of exploration-class space missions by focusing on efforts to reduce countermeasure mass and volume and drive the risks down to an acceptable level. The paper also discusses main risks of missions such as autonomous medical care risk (i.e., mission and long-term health risk due to the inability to provide adequate medical care throughout the mission) and Behavioral Health and Performance (BH&P) risk (i.e., mission and long-term behavioral health risk). The main objective of the HH&P technologies being developed for exploration-class missions is to maintain the health of the crew and support optimal and sustained performance throughout the duration of a mission. A PHM-based technology solution augmented with predictive diagnostics capability could be the one that meets the main objective. In discussing the similarities of and differences between the PHM and SM domains, the paper explores available solutions on crew health maintenance in terms of predictive diagnostics providing early and actionable real-time warnings of impending health problems that otherwise would have gone undetected. The paper discusses the use of PHM principles and techniques with data mining capabilities to assess the value of Electronic Health Records (EHR) augmented with real-time monitoring of data for accurate predictive diagnostics on manned space exploration programs. The proposed technology concept with predictive diagnostics capability and a pilot implementation of the

technology on the International Space Station (ISS) includes evaluation and augmented research/testing of the technology, which will regularly and efficiently provide advancements during the development phases.

1. INTRODUCTION

Long duration missions present numerous risks to crew health and performance. The international space community is actively studying these effects and possible mitigation techniques, but much work remains to be done. As such the space community and space agencies are increasingly cooperating to enable timely answers in support of exploration mission needs (2013 "Global Exploration Roadmap" report). This is very important because with a common understanding of risks and effective mitigation approaches, the space community has the opportunity to leverage investments in the research and technology development to mitigate risks.

Crew health and performance are critical to successful human exploration. Long-duration missions bring numerous risks that must be understood and mitigated in order to keep astronauts healthy, rather than treat a diagnosed health disorder. Crewed missions venturing beyond Low Earth Orbit (LEO) will require technology solutions for crew health care to address physiological, psychological, performance, and other needs in-situ, e.g., self-sufficiency, as an emergency or quick-return option will not be feasible. Therefore, onboard capabilities that would allow for early self-diagnosis of impending health issues, and autonomous identification of proper responses on negative trends to keep astronauts healthy are critical. With the absence of real-time medical ground support, personal health-tracking tools for health monitoring, health risk assessment and management

are required for any crew member to predict her/his future health condition if no preventive measures are taken.

Per the 2013 "Global Exploration Roadmap" report, published by the International Space Exploration Coordination Group (ISECG) in August 2013, a key supporting objective to develop exploration technologies and capabilities is the following: test concepts, approaches, countermeasures and techniques to maintain crew health and performance. This paper suggests a concept using PHM-based technologies, such as real-time health monitoring and condition-based health maintenance in terms of predictive diagnostics. Discussing similarities of PHM vs. Space Medicine, the paper introduces a predictive diagnostics concept for crew health maintenance. Furthermore, it explores PHM solutions based on real-time monitoring, which could be applicable to crew health risk assessment and management.

While the International Space Station is an excellent platform and currently the only "test bed" on which to prepare for future manned exploration missions, the exploration beyond low-Earth orbit will require a new generation of capabilities and systems, which build on existing capabilities and incorporate technologies yet to be developed.

It becomes necessary to develop alternative, evidence-based, effective methods and tools to predict and prevent health problems in a timely manner, rather than to follow reactive approaches, which are inherent to conventional medicine, but largely prohibitive in the operational environment of space because of lack of accessibility of health problem resolutions.

Interdisciplinary research is underway to develop computer-based, self-diagnosis and self-directed treatment programs for astronauts to autonomously predict, prevent, and manage potential health problems (e.g., Fink, Clark, Reisman, and Tarbell, 2013). In the 2010 Interim Report "Life and Physical Sciences Research for a New Era of Space Exploration" the National Research Council emphasizes a priority on bringing the programs to the required technology readiness level (TRL), i.e., corresponding to a representative laboratory environment for exploration-class missions (TRL 6 per NASA designation), so that they can be systematically evaluated in comparative treatment outcome studies.

2. UNDERSTANDING THE TECHNOLOGY

Prognostics and Health Management (PHM) is an engineering discipline that focuses on the fundamental principles of system failures in an attempt to predict when they might fail, and links the principles to system life cycle management. Sometimes this engineering discipline is also referred to as System Health Management (SHM) (Uckun, Goebel, and Lucas, 2008). In recent years, PHM has emerged as a key enabling technology to provide early

warning of failure and assess the potential for life extension, thereby leading to potential monetary and downtime savings.

Prognostics is about predicting the future performance of a component by assessing the extent of deviation or degradation of a system from its expected normal operating conditions. The science of prognostics is based on the analysis of failure modes, detection of early signs of wear and aging, and fault conditions. Technical approaches to building models in prognostics can be categorized broadly into data-driven approaches, model-based approaches, and hybrid approaches.

As an engineering discipline PHM includes the following:

- Health monitoring (i.e., monitoring the extent of degradation or deviation from an expected normal condition);
- Methods for in-situ monitoring;
- Sensors for prognostics;
- Data collection, pre-processing, reduction, and feature extraction;
- Methods for identifying and analyzing precursors based on failure mechanisms;
- Damage assessment;
- Anomaly detection;
- Diagnostics;
- Prognostics;
- Risk and uncertainty analysis;
- Software tools for diagnostics and prognostics.

PHM concept implementation is now a required design feature for space systems (Uckun et al., 2008). Space systems have built-in PHM elements such as failure tracking. In the future, PHM will enable systems to assess their own real-time performance (self-cognizant health management and diagnostics) under actual usage conditions and adaptively enhance life cycle sustainment with risk-mitigation actions.

Human health is one of the application areas of PHM, while health records and health care delivery are going digital (see, e.g., Health Information Technology (Health IT): "Policymaking, Regulation, & Strategy" on the HealthIT.gov website of the U.S. Department of Health and Human Services). As multiple intersecting platforms evolve to form a novel operational foundation for health and health care – the digital health utility – the stage is set for fundamental and unprecedented transformation. Progress in computational science, information technology (IT), and biomedical and health research methods have made it possible to foresee the emergence of a learning health system that enables both the seamless and efficient delivery of best care practices and the real-time generation and

application of new knowledge (Grossman, Powers, and McGinnis, Rapporteurs and Editors (2011)).

Prognostics as an engineering discipline is focusing on predicting the time at which a system or a component will no longer perform its intended function, while *predictive diagnostics* is built on the powerful foundation of predictive analytics. But whereas predictive analytics and PHM methods are to identify what is going to fail and when a particular element is going to fail, in-flight predictive diagnostics also tells the cause(s) of the failure as well as potential factors contributing to and the priority of the impending failure. Direct, contributing, and root causes as well as priority of the impending failure with a corresponding probability are other notions introduced by predictive diagnostics. That makes predictive diagnostics different from predictive analytics. The terminology is not commonly adopted yet.

Like PHM, predictive diagnostics provides early and actionable real-time warnings of impending health problems that otherwise would have gone undetected. Based upon the differences between real-time health status and predefined normal status, predictive diagnostics detects and isolates abnormal dynamics and negative trends in the context of operating conditions. An underlying concept in predictive diagnostics in space missions is that every crew member is unique. This requires the development of a unique data set ("set of fingerprints") for each individual in a number of areas: medical history, genetic predisposition, recent medical events, baseline health assessments including vital signs in terms of operational (e.g., extra-vehicular activity) and emotional contexts (e.g., anxiety (2010 Interim Report "Life and Physical Sciences Research for a New Era of Space Exploration")).

A PHM-based system augmented with predictive diagnostics capability would be required to perform real-time health assessment followed by evaluating the assessment results against a crew member health baseline, i.e., a health pattern corresponding to a "normal" health state in which the crew member is identified as a physically and mentally healthy person meeting in-flight specific requirements. Based upon the differences between real-time assessment and normal health state, predictive analytics would detect negative trends and isolate abnormal dynamics in the context of the current operational environment.

PHM technologies augmented with predictive diagnostics capability on manned space exploration programs include, but are not limited to the following:

- Proven engineering techniques, data analysis, and statistical methods to astronaut health maintenance in order to translate complex data into accurate knowledge and informed actions;

- Methods for in-situ monitoring of astronaut health using unobtrusive and non-invasive sensors/devices;

- Implementation of telemetry and data processing concepts to improve health care delivery;

- Data-driven approaches, algorithms and models for large-scale health data processing and extraction of features of interest;

- Health damage assessment;

- Identification and analysis of precursors on health compromise;

- Statistical techniques and machine learning methods for diagnostics and prognostics;

- Anomaly detection.

The absence of real-time medical ground support requires a shift in health care delivery on manned exploration-class space programs from a telemedicine paradigm to that of medical autonomy (i.e., onboard health care). It used to be that all the information on crew member health and all the controls were residing with the medical ground support team (Integrated Medical Group (IMG) or MED Ops Team) and on-board health care professional (Crew Medical Officer (CMO)). This paradigm may have to shift to where the consumer, i.e., the crew member, is gathering his/her own supplemental data through various means, and decides whether he/she wants to share these data with the medical ground support team and when. These data are additional to those data the medical ground support team receives on a regular basis as the routine part of the space program. Having accepted the inherent risk of autonomous medical care (2013 "Global Exploration Roadmap" report) the crew should be in control until a disorder symptom is identified or a disease is diagnosed. Given that predictive diagnostics is the key to keep the crew healthy, it appears that in addition to the current responsibilities, which the IMG usually has on space programs, the new role of the ground support team is to provide the crew with more health assessment software applications rather than more pharmaceuticals. Yet, this could/should be largely done at the mission design stage though. The paradigm shift could yield solutions to known issues related to health care delivery on manned space programs, such as underreporting, reluctance to discuss health status, etc.

The technology implementation could bridge PHM with the space medicine domain by introducing proven engineering techniques coupled with advanced information technologies that could help the space medicine community to build scientific- and evidence-based health care delivery in terms of individualized medicine and autonomy paradigms.

3. SIMILARITIES BETWEEN SPACE MEDICINE AND ENGINEERING

There has been a growing interest in monitoring the "health" of both the operational environment and astronauts in order to predict failures and provide early warning to avoid health

compromise. Here, health is defined as the degree of normal condition. The following are the PHM techniques used in real-time health monitoring:

- Built-in-test (BIT);
- Usage of "canary devices"[1] and/or (bio-) markers;
- Monitoring of and reasoning over failure precursors;
- Modeling of accumulated damage.

All of these techniques could be successfully employed to astronaut health real-time monitoring as well. For example, like certain biomarkers, the "canary devices" (Pecht, 2008), which are usually integrated into a system, have incorporated failure mechanisms that occur first in the embedded device.

Thus, it is possible to make continuously updated predictions based on the actual environmental and operational condition monitoring of astronaut health (see also Figure 1).

Medicine vs Engineering
Similarities

► Concepts of natural history, clinical course, and disease progression are similar to component aging, damage accumulation and fault progression
► Risk factors in medicine are similar to prognostic indicators used in PHM
► In medicine, prognostics is used to select optimal treatment/intervention policies
► In PHM, RUL estimation is used to determine optimal maintenance policies

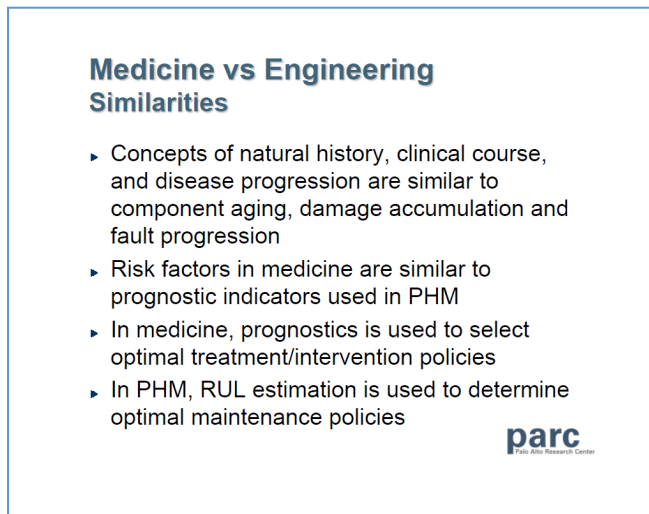**parc**
Palo Alto Research Center

Figure 1. Comparison of Health Care vs. Engineering (Uckun et al., 2008)

Health management in both engineering and medicine domains requires that considerations of the appropriateness of interventions are based on scientific evidence. Given the similarities of the two domains focusing on prognostics, a common scientific foundation for both of the domains could be established. However, to ensure maturity of this foundation, a common language, singular methodology, and benchmarking are required to be implemented. For more details, Uckun et al. (2008) provides an excellent summary on PHM methods and techniques, whereas Lucas and Abu-Hanna (1999) do the same for prognostic methods and techniques in medicine.

It should be stressed though that a fundamental difference exists between components of complex machinery/processes and the human body or organs/processes within. While machine/process components may have well-defined and well-understood failure modes, the failure modes of a human body or organs/processes within are far less predictable: (1) the human body is not a machine, and (2) it is characterized by far more complex (and often unknown) interactions of failure modes. Rapid, unpredicted, and unforeseen changes in the health status of a patient can occur within seconds.

4. MANAGING HEALTH AND HUMAN PERFORMANCE RISKS FOR SPACE EXPLORATION: THE VALUE OF PREDICTIVE DIAGNOSTICS

The promise of data-driven decision-making is now being recognized broadly. Decisions that previously were based on guesswork, or on painstakingly constructed models of reality, can now be made based on the data itself. Decision-making in the areas of health and human performance management is not any different.

It is widely believed that the use of the particular data-driven information technology can reduce the cost of healthcare while improving its quality, by making care more preventive and personalized, and by basing it on continuous monitoring.

To understand the value of new technologies a differentiation has to be made between two things that are often confused by analysts: *capabilities* and *functions*. Capabilities are derived from combinations of functions. Functions are the basic tasks or activities that can be performed with a new technology. Broadly speaking, a capability is what can be achieved with the technology, i.e., "what it is for", whereas a function is what the technology does.

Predictive analytics is a new information management approach and set of capabilities for uncovering additional value from health information. Within the health care sector it provides new insights that have the potential to advance personalized care, improve patient outcomes, and avoid unnecessary costs.

Predictive analytics is the process of examining large amounts of data, from a variety of data sources and in different formats, to deliver insights that can enable decisions in real or near real time. Various analytical concepts such as data mining, natural language processing, artificial intelligence (e.g., expert systems), machine learning, and predictive analytics itself can be employed to analyze, contextualize, and visualize the data. The analytical approaches can be employed to recognize inherent patterns, correlations and anomalies, which can be discovered as a result of integrating vast amounts of data from different data sources (e.g., sensor-data fusion). Also, computer-based

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[1] Usage of "canary devices" is one of the PHM techniques: an early-warning device derived from the use of a canary bird to detect the presence of poisonous gases in a mineshaft. For example, certain bacteria and microbes could serve as canary devices to detect an impending health issue.

self-diagnosis and self-directed treatment programs could be a solution to known issues, such as underreporting on health challenges. It appears that sharing information with personal devices rather than with MED Ops Team (MEDical Operations Team) or CMO is a preferred option for astronauts.

The variety of predictive diagnostics techniques, which are based on predictive analytics, is usually divided into three categories (Langreth & Waldholz (1999)):

- **Predictive models** look for certain relationships and patterns that usually lead to certain behavior and predict system failures;

- **Descriptive models** aim at creating segmentations and find clusters of data elements with similar characteristics;

- **Decision models** use optimization techniques to predict results of decisions.

In predictive models the outcome of the dependent values could be predicted by determining the explanatory values. Where predictive models focus on a specific event or behavior, descriptive models identify as many different relationships as possible. Decision models, another branch of the predictive analytics, lean particularly heavily on operations research, including areas such as route planning, resource optimization, etc. This classification is very practical, since it provides an immediate understanding of the areas where predictive analytics add value.

The following are data types proposed for digitizing the data as Electronic Health Records (EHR) and using predictive diagnostics to support astronaut health maintenance on space exploration programs:

- Clinical data (up to 80% of health data is unstructured as documents, images, clinical or transcribed notes);

- Publications (clinical research and medical reference material);

- Clinical references (text-based practice guidelines and health product data, i.e., drug information);

- Genomic data (significant amounts of new gene sequencing data) (Langreth & Waldholz (1999));

- Streamed data (health monitoring with handheld and sensor-based wireless or smart devices).

There are many sources of data within the health care sector. However, it is unrealistic to assume that all data can be put to use for predictive diagnostics due to a range of operational and technical challenges (mainly interfacing and incompatibility issues) and privacy considerations.

5. REAL-TIME MONITORING FOR ASTRONAUT HEALTH MANAGEMENT

In order to assess the effects of environmental and operational factors on the health status, and to allow early detection of negative trends, real-time health monitoring is required. The ultimate goal of real-time monitoring as an essential component of a predictive capability is its potential for providing meaningful and up-to-date data for detecting trends in astronaut health status during a mission. In this context, "status" should be considered to include the capacity to perform mission-related tasks and the level of health/well-being. The challenge is to provide not only valid and reliable data, but also data sensitive to potentially subtle physiological and neuropsychological deficits caused by stressors. Typical stressors are listed below that can potentially lead to undesirable developments such as overgrowth of certain bacteria, decreasing immune response, anxiety, depression, tension, fatigue, daytime sleepiness, stress-related cardiac arrhythmias, memory impairments, etc. (2010 Interim Report "Life and Physical Sciences Research for a New Era of Space Exploration"):

- Exposure to solar and space radiation;

- Prolonged period of exposure to microgravity;

- Confinement in close, relatively austere quarters;

- Limited contact with family and friends;

- Isolation (small number of crew members);

- Chronically inadequate sleep;

- Work overload;

- Atmospheric composition (e.g., CO_2 concentration);

- Volatile organic compounds;

- Variation in light spectrum;

- Vibration;

- Noise;

- Monotony;

- Environment pollution.

A real-time monitoring approach (2010 Oracle white paper: "Predictive Analytics: Bringing the tools to the data") is presented in Diagram 1 below.

Real-time monitoring as a predictive capability component is common for both PHM and astronaut health care based on predictive diagnostics. Unlike conventional medicine, which is based on taking "snapshots" (i.e., medical check-ups) to track health status, PHM with a predictive analytics capability takes advantage of analyzing additional information acquired during manned space exploration programs on a real-time basis.
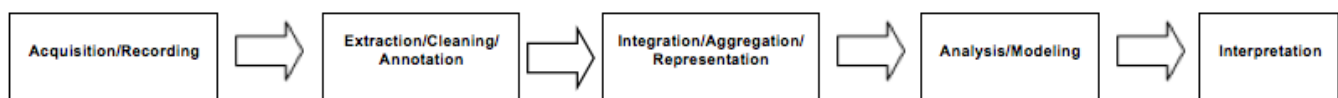

Diagram 1. Real-time monitoring (conceptual architecture)

6. DISCUSSION & CONCLUSION

The primary benefit of the successful technology implementation is the ability to successfully achieve affordable human space missions to LEO and beyond (e.g., human settlement on the Moon and Mars). An implementation of the proposed technology with predictive diagnostics capability on the ISS, as a unique human-occupied test platform in space, will directly contribute to the knowledge base and advancements in managing health and human performance risks for space exploration. In addition to research, the ISS provides the capability to validate countermeasures and mitigation strategies. While countermeasures used on the ISS are largely effective at managing health and performance risks, the technology implementation could lead to a better understanding of the risks and to the development of novel countermeasures against these risks. The proposed technology with on-board predictive capability coupled with countermeasures against cardiovascular, musculoskeletal, and neurological or behavioral challenges associated with space flight is critical for human space exploration. Nutritional countermeasures are also essential, given the impact of diet and nutrition on human health both in space and on Earth. In addition, there are other potential factors being investigated, which might predispose individuals to certain changes in the visual system during space flight (e.g., "Longitudinal Study of Astronaut Health" (LSAH) and 2012 NASA Evidence Report "Risk of Spaceflight-Induced Intracranial Hypertension and Vision Alterations"), which could cause problems on future long-duration exploration missions and for which no countermeasures are currently known. However, progress on all these issues must be made before long-term exploration missions can be successful.

Since crew health and performance are primary, critical concerns, the space community and the ISS program should actively take advantage of ISS-based research to extend human space mission durations while ensuring crew health and performance (Popov, 2012). The health risks are significant enough to drive decisions related to planning of exploration missions beyond LEO.

In order to develop a mature PHM-based technology with a predictive capability the following recommendations on further research, detailed in the 2010 Interim Report "Life and Physical Sciences Research for a New Era of Space Exploration", need to be implemented:

- Determination of the mission-specific effects and other relevant stressors, alone and in combination, on the general psychological and physical well-being of an astronaut. Emphasis should be on determining the extent to which such stressors constitute a risk to mission success;
- Development of interventions to prevent, minimize, or reverse deleterious effects during extended missions.

To assess the effects of environmental factors on crew health and to enable early detection of negative trends a real-time monitoring is required. The monitoring challenge is to provide not only valid and reliable data, but also data sensitive to potentially subtle physiological and neuropsychological deficits caused by the stressors.

To build a sustainable human space exploration endeavor that lasts decades, the international space community should maintain a focus on delivering value to the public (2013 "Global Exploration Roadmap" report). The proposed technology concept with predictive diagnostics capability and a pilot implementation of the technology aboard the International Space Station includes evaluation and augmented research/testing of the technology, which will regularly and efficiently provide advancements during the development phases. The pilot implementation could serve as a contribution to the exploration-class mission readiness since it would demonstrate autonomous crew operation capability coupled with a reduced supply chain on health care delivery. Investments in the technology development, with bringing the technology to TRL 6, can lead to improvements in the quality of life here on Earth and create benefits of national and global interest.

History has repeatedly shown that finding ways to meet the challenges of safe and sustainable human space flight results in solutions that are applicable far beyond space flight (2013 "Global Exploration Roadmap" report). It is important to ensure consistent realization and broader dissemination of the benefits generated by the technologies validated on the ISS in order to meet requirements and challenges of exploration-class space missions.

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BIOGRAPHIES

Alexandre Popov received a M.Sc. in Computerized Control Systems Engineering from Moscow State University of Aerospace Technologies (former Moscow Aviation Institute) in 1983 and M.Sc. in Applied Mathematics from Moscow State University in 1988. As a test-engineer with Tushinsky Machine Building Enterprise (Russia) he had conducted verification tests of navigation and landing systems on the BURAN space program. At a later date he - as a data architect and business analyst – had led software development for mission planning on MIR and International Space Station (ISS) programs at the Energia Rocket Space Corporation (Russia) [1988-1998]. From 2000 to 2003 he served as an advisory member of Engineering with Lockheed Martin Canada working on the ISS program (ISSP) at the Canadian Space Agency (CSA). He joined the Canadian Space Agency as a mission planner in 2003 and has contributed to the ISSP process and data integration effort. From 2011 to 2012 he led CSA efforts on developing requirements for and prototyping of a space medicine decision support system for exploration class missions with predictive diagnostics capability. He is currently working as an Operations Engineer on the ISS program at CSA.

Wolfgang Fink is currently an Associate Professor and the inaugural Edward & Maria Keonjian Endowed Chair of Microelectronics with joint appointments in the Departments of Electrical and Computer Engineering, Biomedical Engineering, Systems and Industrial Engineering, Aerospace and Mechanical Engineering, and Ophthalmology and Vision Science at the University of Arizona in Tucson. He is a Visiting Associate in Physics at the California Institute of Technology, and holds concurrent appointments as Visiting Research Associate Professor of Ophthalmology and Neurological Surgery at the University of Southern California. Dr. Fink is the founder and director of the Visual and Autonomous Exploration Systems Research Laboratory at Caltech (http://autonomy.caltech.edu) and at the University of Arizona (http://autonomy.arizona.edu). He was a Senior Researcher at NASA's Jet Propulsion Laboratory from 2000 till 2009. He obtained a B.S. and M.S. degree in Physics and Physical Chemistry from the University of Göttingen, Germany, and a Ph.D. in Theoretical Physics from the University of Tübingen, Germany in 1997. Dr. Fink's interest in human-machine interfaces, autonomous & reasoning systems, and evolutionary optimization has focused his research programs on artificial vision, autonomous robotic space exploration, biomedical sensor/system development, cognitive/reasoning systems, and computer-optimized design. Dr. Fink is a Fellow of the American Institute for Medical and Biological Engineering (AIMBE). His work is documented in numerous publications and patents. Dr. Fink holds a Commercial Pilots License for Rotorcraft.

Andrew Hess is a 1969 graduate of the University of Virginia (BS Aerospace Engineering) and the U. S. Navy Test Pilot School. Andy attended George Washington University working towards a Masters in Technology Management and has completed many Navy and DOD sponsored professional and acquisition management courses. Andy is world renowned for his work in fixed and rotary wing health monitoring and is recognized as the father of Naval Aviation propulsion diagnostics. Working for the Naval Air System Command and beginning with the A-7E Engine Monitoring System program of the

early 70's, Andy has been the leading advocate for health monitoring in the Naval Aviation. He has been actively involved in every NAVAIR aircraft program since the F-8, leading to the evolution and development of not just engine monitoring; but also aircraft structural life usage, comprehensive health monitoring and management capabilities for most all other aircraft subsystems and advance maintenance concepts like Condition Based Maintenance (CBM+). For the last 10 years of his government career, Andy worked leading and managing the vision, the development, and integration of the Prognostic and Health Management (PHM) system the AL support concept for the Joint Strike Fighter program. Andy's consulting interests are now leading him and his clients to exploring the application of PHM capabilities and CBM+ related support concepts to many new industry sectors such as: industrial gas and steam turbines, ships and fast patrol boats, unmanned vehicles, wind energy, nuclear energy, ground vehicles, mining, and gas and oil. Serving on the Board of Directors, Andy helped establish and grow the new and very successful PHM Society professional organization and has just been named president of the society. Recently, Andy was named an Asset Management Fellow with the International Society of Engineering Asset Management and is a member of the new SAE HM-1 committee on Integrated Vehicle Health Management Systems.