A Paradigm Shift from Telemedicine to Autonomous Human Health and Performance for Long-Duration Space Missions

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Abstract

This paper discusses a *Prognostics and Health Management* [PHM]-based approach to implementing *Human Health & Performance* [HH&P] technologies. Targeted specifically are NASA's "Autonomous Medical Decision" and "Integrated Biomedical Informatics" of "Human Health, Life Support, and Habitation Systems" in *Technology Area 06* [TA 06] of NASA's integrated technology roadmap [April 2012]. The proposed PHM-based implementation is to bridge PHM, an engineering discipline, to the HH&P technology domain to mitigate space travel risks by focusing on efforts to reduce countermeasure mass and volume, and drive down risks to an acceptable level. NASA's Autonomous Medical Decision technology is based on wireless handheld devices and is a result of a necessary paradigm shift from telemedicine to HH&P autonomy. The Integrated Biomedical Informatics technology is based on *Crew Electronic Health Records* [CEHR], equipped with a predictive diagnostics capability developed for use by crew members rather than by healthcare professionals. This paper further explores the proposed PHM-based solutions for crew health maintenance in terms of predictive diagnostics to provide early and actionable real-time warnings to each crew member about health-related risks and impending health problems that otherwise might go undetected. The paper also discusses the paradigm's hypothesis and its innovation methodology, as implemented with computed biomarkers. The suggested paradigm is to be validated on the *International Space Station* [ISS] to ensure that crew autonomy in terms of the inherent predictive capability and two-fault-tolerance of the methodology become the dominant design drivers in sustaining crew health and performance.

1. Introduction

For manned space exploration missions beyond *Low Earth Orbit* [LEO], regular resupply of consumables, delivery of new supplies and replacement components, as well as emergency quick-return options may not in general be easy, timely, or feasible. Success in such space missions requires solutions to difficult technical challenges, built on proven capabilities, which may require the development of new capabilities arising from the development of novel cutting-edge technologies.

The key to supporting the objectives of the "Global Exploration Roadmap" report (ISECG, 2013) lies in the development of technologies and capabilities that enable the testing of new and innovative concepts, approaches, countermeasures, and techniques to maintain crew health and performance.

Specific requirements and recommendations (Williams, 2011 and Volkov, 2013) have been provided by experienced astronauts, including crew members, who have extensive first-hand experience aboard the *International Space Station* [ISS]. These requirements and recommendations have triggered the development and validation of PHM-based technologies to enable autonomous health monitoring and tracking on space exploration missions requiring the paradigm shift from telemedicine to HH&P autonomy.

1.1. Definition of Prognostics and Health Management (PHM)

As defined in (Uckun, Goebel, and Lucas, 2008) *Prognostics and Health Management (PHM)* is an engineering discipline that focuses on the fundamental principles of system failures in an attempt to predict *mean time between failures* [MTBF], and links the principles to system life cycle management. PHM-based technology is a key enabling technology to provide early warning of failure, and assesses the potential for life extension. PHM concept implementation is now a required design feature for space systems (Uckun et al., 2008); as such, all new space systems must have built-in PHM elements such as failure tracking. As a concept, PHM also enables 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.

1.2. The "PHM for Astronauts" Paradigm

One particular PHM-based paradigm, "PHM for Astronauts" (Popov et al., 2013), with corresponding solutions could bring *Human Health and Performance* [HH&P] technologies to the required *Technology Readiness Level* [TRL] in order to mitigate the HH&P risks of manned space exploration missions.

To validate the "PHM for Astronauts" paradigm on the ISS, this paper discusses in detail particular PHM-based solutions for HH&P technology candidates, such as "Integrated Medical Equipment and Software Suite" (a.k.a. "Integrated Biomedical Informatics" and "Autonomous Medical Decision" per (NASA, 2012)) and "Integrated Prevention and Treatment for Visual Changes and Non-Invasive Intracranial Pressure Measurement", as per NASA designation (NASA, 2015). The technology candidates are identified in the 2015 NASA Technology Roadmap for Human Health, Life Support, and Habitation Systems [Technology Area 06] (NASA, 2015). The roadmap takes under consideration a wide range of needed technology candidates and development pathways for the next twenty years. It discusses developing technologies that enable long-duration, deep-space, human exploration with a minimal resupply of consumables, and increased independence from mission control centers and ground-based personnel. The benefits offered by the use and effectuation of PHM capabilities and predictive analytics will be an enabling part of this paradigm shift for deep-space, long-duration space missions.

The PHM-based paradigm and corresponding technology solutions bridge PHM to the HH&P domain to mitigate space travel risks by focusing on efforts to reduce countermeasure mass and volume, and drive down risk to an acceptable level. The technology solutions include wireless handheld devices and are supportive of the paradigm shift from telemedicine to health support autonomy. A key component of the technology solutions is a *Crew Electronic Health Records* [CEHR]-based system with predictive diagnostics capability, developed for crew members rather than for healthcare professionals.

This paper explores the proposed PHM-based solutions for crew health maintenance in terms of predictive analytics, diagnostics, and prognostics providing early and actionable real-time warnings of health-related risks and impending health problems that otherwise might go undetected. Warnings are sent to each affected member of the crew for the purpose of individual health awareness, and to provide timely countermeasures, as required. The use of these capabilities and associated applications can apply before, during, and after missions.

To elevate HH&P technology to a TRL-6 level, this paper also discusses employing PHM principles such as *Condition Based Maintenance* [CBM], as well as techniques with data fusion and data mining capabilities. The purpose is to assess the value of CEHR augmented with real-time data monitoring for accurate predictive diagnostics on manned space exploration programs. The primary benefit of the development and deployment of these technologies for the HH&P domain, bringing them up to a TRL-6 level, is the ability to successfully achieve and sustain affordable human space missions to Low Earth Orbit and beyond. Continued space missions on the *International Space Station Program* [ISSP] directly contribute to the knowledge base and advancements in HH&P, as the ISS is currently the only test platform for crewed space missions in an actual space environment. Ground- and space-based test beds such as long-term Mars Space Habitat simulators and the ISS are crucial to the development and validation of the technologies needed for long-term, manned space exploration missions.

Also, according to (NASA, 2016) and NASA's guidelines and procedures, actual ground testing is mandated of any technology/system before and in parallel with an end-to-end test utilizing NASA testbeds for the purpose of fulfilling NASA's requirements and certifications for space missions. By default, such ground testing must always be part of the space technology/system development lifecycle.

Early self-diagnostic, prognostic, and autonomous identification of proper preventive responses to negative trends are critical in order to keep astronauts healthy with limited medical support. Personal health-tracking and health-management tools are required to predict future health conditions if no preventive measures are taken.

1.3. Verification and Validation of PHM-based Technology

Verification and Validation (V&V) activity is essential for TRL development and maturation to ensure proper maturity and performance of the PHM-based technology. Roychoudhury, Saxena, Celaya, and Goebel (2013) suggest the following definition of the V&V activity. Verification of a product/technology is the process in which stakeholders answer the query "are we building it right?", while validation of a product/technology is the process in which stakeholders answer the query "are we building the right thing?" In other words, verification is the quality control process of evaluating whether or not a product/technology complies with testable constraints imposed by requirements at the start of the development process. In contrast, validation is the quality assurance process of evaluating whether or not a product/technology accomplishes its intended function when fielded in the target application domain.

2. NASA TECHNOLOGY ROADMAP: HUMAN HEALTH, LIFE SUPPORT, AND HABITATION SYSTEMS

Since neither early return nor mission abort are feasible options for deep space exploration missions, new technologies must be developed, verified, and properly validated in accordance with (NASA, 2016) in order to enable HH&P autonomy. Due to the known constraints and limitations in communications with ground-based personnel for diagnosis of medical events and consultation, autonomous healthcare technologies with predictive capabilities have become ever more critical to space exploration mission success and safety.

(NASA, 2015) identifies promising new technology candidates for HH&P integration in space exploration missions. The document is a high-level requirements document for Technology Area 06 and considers both a wide range of necessary technologies and development pathways for the next twenty years (i.e., 2015-2035). Its focus is on *Research and Development*, i.e. R&D activities, including technology validation to ensure TRL-6 and higher. The document was derived from (NASA, 2012) and provides a summary of key capabilities and technologies, with focus on the development of technologies that enable manned space exploration missions, namely: long-duration, deep-space, human exploration with minimal resupply of consumables and increased independence from Earth; in other words, HH&P autonomy. Sub-goals include transitioning from partially-closed life support systems on the International Space Station to a more fully-closed integrated system, and improving in-space crew health diagnostics, treatments, and countermeasures.

The development of next-generation on-board personal health maintenance systems for such missions in terms of autonomy will be heavily dependent upon the incorporation of new technologies integrated into *Personal Area Networks* [PANs]. A PAN should interface with wireless *Local Area Networks* [LANs] to incorporate health-related data in electronic health records. A *Health Support System* [HeSS] with a predictive advanced diagnostics and prognostics capability incorporated into smart checklists and PHM-based algorithms could enhance the healthcare delivery on long-duration space missions. Data mining of historical and current biomedical and clinical data (beginning with the earliest space missions, up to and including current ISS missions) has been identified by a number of experts as a critical task in order to customize and further define and validate the PHM-based algorithms (Popov, Fink, McGregor, and Hess, 2016).

Both (NASA, 2012) and (NASA, 2015) provide technology candidates in the specific domains of *Human Health, Life Support, and Habitation Systems* [TA 06], necessary to achieve NASA's goals in human space exploration over the next few decades. The technology area breakdown structure is represented in Figure 1 and refers to the *sub-technology areas* [sub-TAs] included in the roadmap.

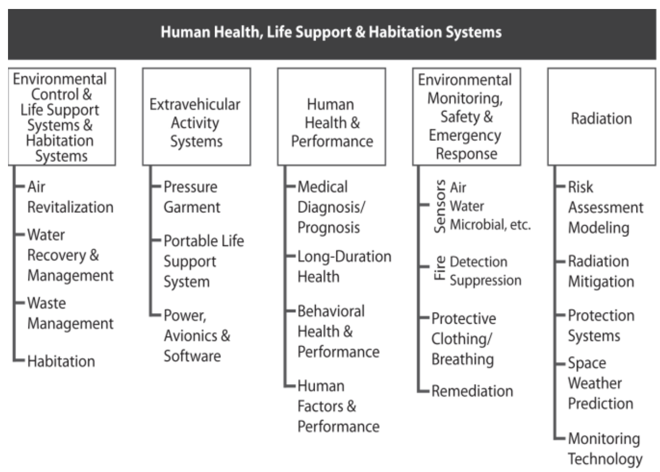

Figure 1. Technology Area Breakdown Structure from (NASA, 2015).

Because the HH&P technologies are specifically oriented to help maintain the health of the crew and support optimal and sustained performance throughout the duration of a mission, the HH&P domain includes the following four functional focus areas as shown in (NASA, 2012) and (NASA, 2015):

- Medical diagnosis/prognosis;
- Long-duration health;
- Behavioral health and performance;
- Human factors and performance.

Additional focus areas include:

- Tracking before and after missions;
- Providing lessons-learned feedback as input for follow-on mission planning.

2.1. Medical Diagnosis/Prognosis

The objective of the Medical Diagnosis/Prognosis functional area is to provide advanced medical screening technologies for individuals selected to the astronaut corps, which is to be implemented prior to crew selection for specific missions; this is a primary and resource-effective means to ensure crew health.

2.2. Long-Duration Health

The focus of the Long-Duration Health functional area is on providing validated technologies for medical practice to address the effects of the space environment on human systems. These capabilities can provide significant benefits for after-mission follow-up.

2.3. Behavioral Health and Performance

The objective of the *Behavioral Health and Performance* [BHP] functional area is to provide technologies to reduce the risks associated with extended space travel and Earth return. Technology advancements are needed for assessment, overall prevention, and treatment to preclude and/or manage deleterious outcomes as mission duration periods extend beyond six months (e.g., a trip to Mars).

Novel technologies are needed to identify, characterize, and reduce BHP risks associated with space exploration missions. As shown in (NASA, 2012) and (NASA, 2015) these technologies include:

1. Prevention technologies such as reliable, unobtrusive tools that detect biomarkers of vulnerabilities and/or resiliencies to help inform health advisory recommendations;
2. Assessment technologies for in-flight conditions such as microgravity, and elevated levels of CO_2, air pressure, noise, and radiation that may exacerbate health risks;
3. Countermeasures aimed at preventing behavioral health decrements, psychosocial maladaptation, and sleep and performance decrements; also, countermeasures aimed at treatment if decrements are manifested.

2.4. Human Factors and Performance

The *Human Factors and Performance* [HFP] functional area focuses on technologies to support the crew's ability to effectively, reliably, and safely interact within mission environments. Such elements include user interfaces, physical and cognitive augmentation, training, and *Human-Systems Integration* [HSI] tools, metrics, methods, and standards.

A successful human spaceflight program heavily depends on the crew's individual ability to effectively, reliably, and safely interact with the mission environment. The HFP functional area represents a commitment to effective, efficient, usable, adaptable, and evolvable systems to achieve mission success, based on fundamental advances in understanding human performance (i.e., perception, cognition, action) and human capabilities and constraints in the context of the operation or activity being performed. The most critical elements of HFP are listed in (NASA, 2012) and (NASA, 2015) and are as follows:

- User interfaces, such as multimodal interfaces and advanced visualization technologies;
- Physical and cognitive augmentation, such as adaptive automation based on in-situ monitoring of work activity;
- Training methods/interfaces;
- HSI tools, metrics, methods, and standards, as well as related concepts for fitness-for-duty.

2.5. Technology Readiness Level

Notably, some technologies in (NASA, 2012) and (NASA, 2015) are currently at a low Technology Readiness Level, but further development could provide significant advancement of the current *state-of-the-art* [SOTA] and/or drive new approaches or techniques in accomplishing mission implementation. Identification of requirements on the to-be-developed HH&P technologies for crewed exploration missions is a crucial task in order to ensure safety and success before, during, and after proposed missions in the context of the HH&P autonomy paradigm, rather than in the Earth-bound telemedicine paradigm currently in use on the ISS program.

Some of the key requirements of the to-be-developed HH&P technologies for crewed exploration missions are addressed in ASEB/NRC (2011), Williams (2011), Volkov (2013), NASA (2012), and NASA (2015). The papers (Fink, Popov, and Hess, 2014), (Popov, Fink, and Hess, 2013), (Popov, Fink, McGregor, and Hess, 2016), and (Kevorkova and Popov, 2016) also provide examples of technologies and solutions, but these should not be considered all-inclusive or decisive without rigorous survey of SOTA and proposed technologies and further review/study.

Some subject matter experts authoring NASA (2015) believe that each activity or milestone represented in the roadmap does indeed have a technology solution to pursue at the present time, or will have one within the time frame suggested in the roadmap. Particular technology candidates, namely the Integrated Biomedical Informatics and Autonomous Medical Decision technologies of the roadmap, are discussed in the following sections. This discussion provides further explanation of the technologies as well as a summary table of the priority technologies and system functional areas of interest, the current SOTA, the major challenges for advancement, and the recommended milestones and activities to advance to a TRL-6 and higher, i.e., demonstration of the technology in a relevant mission environment or simulation thereof.

3. WHAT MAKES THE PROPOSED PARADIGM DIFFERENT

Manned space exploration objectives present significant new challenges to crew health, including the psychological and physiological effects of long-duration space missions. The limited communication with ground-based personnel for diagnosis and consultation of medical events creates additional challenges during such missions. Providing healthcare capabilities for space exploration missions necessitates the definition of new requirements and development of technologies in order to ensure crew health, and thus mission success. As we go deeper into space and mission durations greatly increase, the dependence on telemedicine will need to decrease and the use of autonomous solutions, many enabled by PHM capabilities, will need to increase.

Table 1 from Popov, Fink, McGregor, and Hess, (2016) below articulates the features and novelties that make the proposed PHM-based healthcare different from both conventional medicine and current healthcare practice, including space medicine. New approaches for personalized medicine on Earth have similar requirements to those proposed by our PHM-based healthcare paradigm. As a result, there is great potential to bring the PHM-based healthcare paradigm back to Earth to provide new approaches to personalized medicine, with the potential for cutting healthcare costs while improving healthcare outcomes.

Implementation of the proposed PHM-based healthcare paradigm enables identification of predictors and early detection of deterioration or impairment of astronaut health − before signs are detected or symptoms are manifested (see also “stressors” in Popov et al., 2013). The predictors could be *implicit* or *explicit*. For clarity, a discovered pattern or correlation as a result of data processing could serve as an example of an implicit predictor, while increase/decrease of a parameter measured by a sensor network could serve as an example of an explicit predictor or onset detector. Imbalance in skin pH resulting from impending dehydration is an example of an explicit onset detector of the associated medical condition, while heart rate variability as an *electrocardiogram* [ECG] morphology parameter is an example of an implicit predictor.

PHM-based HH&P Paradigm	Conventional Medicine Paradigm
Focus is on keeping astronauts healthy by predicting a deterioration or impairment of health before a sign is detected or a symptom is manifested	Focus on detected signs and manifested symptoms in order to diagnose a medical condition, disease, or disorder
Real-time 24/7 streaming, self-monitoring and processing	One-off snapshots made by clinic-based healthcare professionals
Astronaut-generated data	Doctor-instigated data
Individual-based	Population-based
Panoramic	Data limited
Condition Based Maintenance (CBM)	Diagnosis-based treatment
Evidence-based health maintenance	Diagnostics and treatment limited to experience and knowledge of healthcare provider
Used in conjunction with COTS wireless sensor network communicating with affordable custom smartphone-based or tablet-based apps (e.g., Fink, Popov, and Hess (2014))	Expensive, big-ticket technologies
Intuitive and customizable dashboard-based interface with user-friendly language designed for the astronaut as the ultimate end-user	Medical language and an interface designed for healthcare professionals
HH&P autonomy paradigm	Medical paternalism
Astronaut-edited and owned CEHR	Non-shared EHR that is owned by healthcare provider
Astronaut engagement	Compliance with healthcare provider directives

Table 1. PHM-based Healthcare Paradigm vs. Conventional Medicine (Popov, A., Fink, W., McGregor, C., & Hess, A., 2016).

Similar to the approach taken to develop successful PHM systems for mechanical and electronics industries, a multidisciplinary system engineering approach to diagnostics and prognostics allows the development of a PHM system related to human health support on manned space exploration missions. This is part of the engineering element for *Condition Based Management plus* [CBM+] that provides a key element and focused approach to making this happen. Such an approach and criteria will need to be developed for all system hardware and software elements. The thoughtful and effectuated integration of this approach is key, as is an integrated organization team made up of the necessarily diverse domain member experts. Predictor identification, onset detection, and real-time monitoring followed by CBM+-based responses are key features making the proposed new paradigm different.

Moreover, it is to be noted that most, if not all, of the wireless medical devices existing in today's market are limited to data acquisition, transmission, and conventional representation. As has been shown in Fink, Popov, and Hess (2014), Popov, Fink, and Hess (2013), and Popov, Fink, McGregor, and Hess (2016) the real-time health monitoring architecture should include all standard elements from data acquisition to processing to interpretation (and potentially intervention).

Inherent to the HeSS proposed for HH&P, a built-in diagnostics and encompassing self-test capability as part of CBM+ for the hardware of the PHM-based system as a whole and its components helps to ensure reliable and assured information. The properly implemented capability for space exploration missions in terms of HH&P autonomy should ensure data consistency and eliminate false indications, e.g., false-negative or false-positive test results that otherwise could cause crew stress and unnecessary responses to incorrect messages received from the system.

4. COMPUTATIONALLY GENERATED BIOMARKERS

A biomarker refers to a broad subcategory of medical signs – that is, objective indications of the medical state observed from outside the patient – which can be measured accurately and reproducibly (Popov, Fink, McGregor, and Hess, 2016). Medical signs stand in contrast to medical symptoms, which are limited to those indications of health or illness perceived by the patient. A biomarker is a health-related characteristic that is objectively measured and evaluated as an indicator of normal biological processes, pathogenic processes, or pharmacologic responses to a therapeutic intervention. Electrocardiogram (ECG), sweat diagnostics, and other laboratory tests, such as cholesterol and blood sugar level assessment, are examples of biomarkers.

However, in addition to biomarkers defined by the medical community, there is the notion of derived "computational" biomarkers, invented by data analysts. By definition, these are biomarkers that are generated indirectly by applying computation to health-related data. For example, some computational biomarkers, such as ECG morphological variability (a.k.a. heart rate variability), are used in cardiovascular risk stratification to help match patients to therapies. Other examples, related to vision testing and ophthalmology pertaining to *Vision Impairment and Intracranial Pressure* [VIIP] syndrome, can be found in (Fink, Popov, and Hess, 2014). The heart is a muscle designed to pump blood through the body, and as such it can be viewed as an electrical device of sorts. The premise of morphological variability is that electrical instabilities in the human heart do not occur without cause. Rather, there are generally numerous smaller issues which are typically asymptomatic; these issues can collude in specific ways such that the set of smaller issues becomes a larger problem culminating, for example, in myocardial infarction.

Small issues may not be detectable with the human eye or with a single measurement or test instrument, leading a cardiologist looking at an ECG to determine that a patient's heart health is normal. But using ECG morphological variability as a computational biomarker would draw the cardiologist's attention to the cause of the variability. For example, while some ECGs would be considered sub-threshold, others may be determined to be supra-threshold in terms of high risk, i.e., while some patients are at low risk, others are at high risk.

A key objective of the implementation of the suggested PHM-based paradigm and resulting technology solutions with predictive self-diagnostic capability is the identification of such computational biomarkers in order to stratify health-related risks and then match them to a corresponding health maintenance plan or regimen.

5. INTERFACE DESIGN

Crews on space exploration missions beyond LEO will be required to function without timely support from a mission control center or ground personnel. That is why a person-centered design of health monitoring, and a support system with an intuitive interface and effective information architecture, are critical for PHM-based solutions in terms of HH&P autonomy. As the paradigm shift from telemedicine to crew-based healthcare autonomy takes place, the interface design will assume a high-priority task. Built-in self-training modules of the suggested PHM-based technologies that support initial, recurrent, and just-in-time instructions on health support and healthcare delivery should ensure that crew members with potentially (and often likely) limited medical skills can apply the proper knowledge to both normal and abnormal health situations.

The current interface design and training methodologies on the ISS program reflect decades-old technology. For crewed space exploration missions with limited ground-based support (e.g., missions to and ultimately settlement on Mars), a more intuitive dashboard-based interface is required. The interface should be also customizable and equipped with a user-friendly language designed for astronauts, rather than for healthcare professionals. As shown in Popov, Fink, McGregor, and Hess, (2016) the interface should require minimal astronaut training and provide intuitive common (i.e., cross-cutting) operability between different systems, as well as increased capability, usability, and reliability. The design of such interfaces is another challenging but critical task.

6. CREW ELECTRONIC HEALTH RECORDS

The expected growth of both *electronic medical records* [EMR] and *electronic health records* [EHR] is spurred by the emergence of technologies and tools for self-diagnosis and autonomous preventive health maintenance based on predictive capabilities. Yet, such technologies combine advanced improvements with new risks. Although EMR and EHR have been in existence for over ten years, the self-diagnostics and autonomous health maintenance technologies still have not been widely adopted (Popov et al., 2013). Aboard the ISS, the EHR-based healthcare that is provided and maintained by the *Crew Medical Officer* [CMO] is not an exception, since crew members should have the assurance that they properly interpret and understand the received recommendations, as well as know how to implement them in order to have the best chance possible of achieving the desired outcome. But most importantly, safety considerations should be always a part of any system design. Given that there is limited-to-CMO medical support on space exploration missions, personal health-tracking, self-diagnostic, and health management tools are required to predict future health conditions if no preventive measures are taken.

In addition to standard EHR items, such as vital signs and body mass measurement, at least the following types of information should be included in CEHR:

- Nutritional and caloric intake;
- Circadian actigraphy;
- Sleep logs;
- Cognitive performance measurement tools;
- Physiologic audiometry;
- Ocular tonometry;
- Visual acuity;
- Musculoskeletal assessment of muscle strength;
- Bone mineral density.

Traditional EHR could be integrated with all available information collected before, during, and after a mission, including non-traditional but relatable information. Some examples of non-traditional information include:

- Environmental exposure histories;
- Family and other psychological stressors;
- Financial stressors.

NASA has extensive experience with electronic records systems used as research data repositories embedded into decision support systems (NASA, 2018). The life sciences data archive was created to retain human research data from both ground and flight experiments on astronauts and other test subjects. The *Longitudinal Study of Astronaut Health* [LSAH] in (NASA, 2018) is similar to those used to record clinical data collected during routine healthcare, from medical data acquired during a mission, and from occupational health surveillance data. A number of features have been incorporated to ensure data security while providing access to research data.

The increasing application of informatics in medicine has resulted in enhanced application of clinical decision support systems, i.e., information systems to enhance clinical decision making in healthcare. These are defined as “active knowledge systems which use two or more items of patient data to generate case-specific advice” based on the integration of a database of medical knowledge, patient data, and some form of artificial intelligence or inference engine (Fink, Hess, and Popov, 2014). The application of such systems is to enhance on-board clinical diagnosis and adherence to the condition-specific guidelines outlined in the respective health status checklists that are used by the ISS *Integrated Medical Group* [IMG].

Numerous experts have articulated a series of controversial statements regarding decision support systems, asserting that the field of biomedical informatics is inherently aimed at enhancing the quality of decisions made by health professionals rather than by the patients themselves. The focus on a health support system with predictive capability coupled with an advice-on-response feature would be an enabling factor to healthcare autonomy for long-duration spaceflight. As shown in Fink, Hess, and Popov, (2014) other controversial statements of relevance to healthcare in space include unproven assumptions that the crew will use knowledge-based systems and standalone decision-support tools. The current paradigm is to integrate decision support tools into electronic medical records that incorporate protocols, guidelines, and educational materials into the development of information-enabled, decision-supported health data and intervention management systems (NASA, 2015).

The feature of using medical monitoring technology to raise alerts in the case of deteriorating health conditions is widely used in current medicine practice. However, despite the presence of such systems to alert healthcare professionals, significant physiologic change in the crew has taken place often before these critical alert systems are activated, as shown in (ASEB/NRC, 2011).

An individual monitoring PHM-based technology has also an additional advantage that current health approaches do not provide: If a crew member receives an alert message, the technology could check related datasets directly for each crew member for common precursors or biomarkers before symptoms manifest. Unlike current tools, the technology provides an early protection method for exposure to unknown materials or environments which are detrimental to the space exploration mission. Such a powerful approach could help with the ontological risks to protect the crew as well.

7. CONCLUSION

Extending ISS operations into the following decade will facilitate sustained testing and associated technology advancements in preparation for deep-space, long-duration missions. The development of realistic ground-based simulators and an in-space test bed are crucial to the development, verification, and validation of technologies.

To achieve HH&P autonomy paradigm goals relating to long-duration missions, a series of critical operational, programmatic, research, and development questions must be addressed in a timely manner.

The inclusion of autonomous healthcare into space exploration programs should be accomplished through the development of advanced technologies to assist the crew in their health management in terms of this paradigm shift. In particular, there is a requirement in NASA (2012), NASA (2015), and Williams (2011) to develop a suite of integrated advanced healthcare technologies that will assist in the real-time monitoring of the health status of the crew and the environment. Such a PHM-based system is tentatively called a *Health Support System* [HeSS].

A PHM-based modular decision support system with predictive capabilities would integrate digital physiologic sensors and data management technologies, as well as imaging technologies, into an integrated Web-based system. The system would have an intuitive and customizable interface with user-friendly language designed for use by an astronaut, rather than by a healthcare professional. This amounts to a far-reaching requirement for the development of an advanced technology with predictive capabilities that will assist in the monitoring of a crew's health status. This allows for prediction of impending health issues, keeping crew members cognizant of their health status, and provides for timely advisory countermeasures before such issues impact crew health and performance.

The ISS is an invaluable asset in the race to develop future healthcare requirements for long-duration missions. To maximize the benefits received, proper health data collection, analysis, reporting, and discussion amongst the space community, including engineering and medical communities, are required. Healthcare planning for the next decade of ISS utilization should be based on analysis of in-orbit experience and lessons learned in the first decade of ISS utilization. Building additional healthcare test objectives into the research priorities of the ISS program to develop a mature PHM-based predictive capability should help to further fulfill the role of the ISS as an exploration-enabling research platform.

A health support system with predictive capabilities incorporated into smart checklists and PHM-based algorithms could enhance the delivery of healthcare on space exploration missions. This capability is particularly important as signal latency increases in proportion to the increased distance from Earth. The healthcare planning for such missions should begin immediately to prepare capabilities that will meet the unique requirements of providing the highest health support standards. Also, there is a need for a modular design of the proposed PHM-based system to allow for incremental adjustments to improve the system as it becomes available. The modularity that is implemented in terms of a two-fault-tolerance solution could also provide for commonality in components reducing the logistic footprint and enabling both interchangeability and operations continuity. Such modular design solutions should be inherent to any modern space system and, particularly, for crewed space exploration missions, since mass and volume are crucial mission design elements.

Data mining biomedical and clinical data from the earliest to current space flights has been identified by a number of experts as a critical task. Along with conventional data analytics the *"Big Data" analytics* [BDA], another essential PHM component, could help to overcome some of the challenges involved. BDA is defined as an information management approach and a set of capabilities for uncovering additional value from health information. "Big data" provides new opportunities to store and index previously unusable, siloed, and/or unstructured data for additional use by healthcare stakeholders. Applying BDA creates new business value by transforming these previously unusable data into new predictive insights and actionable knowledge. Getting the crew members engaged with their health maintenance at a proper level is necessary to improve the healthcare on manned space programs (Williams, 2011).

Being mindful of benefits of traditional PHM components, such as predictive data analytics, the authors suggest that to ensure success in HH&P autonomy the best strategy integrates the capabilities of both of the following:

1. A combination of the fundamental understanding of biological, physical, chemical, and electrical processes (a.k.a. *model-driven approach*);
2. Empirical methods (a.k.a. *data-driven approach*).

Many of the currently available *commercial-off-the-shelf* [COTS] biosensors and physiology-monitoring handheld devices with related software are more akin to beta versions than properly certified products. Nevertheless, the products could be an option to validate wireless PHM-based healthcare technologies with predictive capabilities on space exploration missions. A major barrier to greater adoption of COTS wearables is that they continue to be used as stand-alone devices instead of being integrated into an interoperable ecosystem, including "Big Data" applications, to provide healthcare at the required levels.

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BIOGRAPHIES

Alexandre Popov is an AIAA Senior Member and NASA Emeritus Docent at U.S. Space and Rocket Center. He received his M.Sc. in Systems Engineering from Moscow Aviation Institute (National Research University) in 1983 and B.Sc. in Applied Mathematics from Moscow State University in 1988. From 2000 to 2003 he served as an advisory member of Engineering with Lockheed Martin Canada working on the ISS program (ISSP) at Canadian Space Agency (CSA). At 2003 he joined CSA and from 2003 to 2014 served as a mission planner and operations engineer on the ISSP at CSA and contributed to the ISSP process and data integration effort. 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 has been an international member of AIAA Systems Engineering Technical Committee since 2009.

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. He was a Visiting Associate in Physics at the California Institute of Technology (2001–2016), a Visiting Research Associate Professor of Ophthalmology and Neurological Surgery at the University of Southern California (2005–2014), and a Senior Researcher at NASA's Jet Propulsion Laboratory (2001–2009). 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 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 PHM Fellow, AIMBE Fellow, a Senior Member IEEE, and the 2015 da Vinci Fellow and 2017 ACABI Fellow of the University of Arizona. He has over 240 publications (including journal, book, and conference contributions), 6 NASA Patent Awards, as well as 19 US and foreign patents awarded to date in the areas of autonomous systems, biomedical devices, neural stimulation, MEMS fabrication, data fusion and analysis, and multi-dimensional optimization. Most recently Dr. Fink founded the *Center for Informatics and Telehealth in Medicine* (InTelMed; InTelMed.arizona.edu) as an operational unit of the Visual and Autonomous Exploration Systems Research Laboratory in line with the 4^{th} Industrial Revolution. The charter of the InTelMed Center is to devise and deploy biofeedback-controlled devices by integrating wearable sensors, bi-directional data exchange, cloud-based data analysis, health and disease status modeling and prediction, and prescribed intervention/treatment onto human smart service platforms. In addition, Dr. Fink holds a Commercial Pilots License for Rotorcraft. He is regularly called upon by the public media.

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. In 2017 he was honored with a Lifetime Achievement Award by the PHM Society.

Mark A. Tarbell is a Senior Research Scientist at University of Arizona's *Visual and Autonomous Exploration Systems Research Laboratory* with more than 30 years of large-scale computer architecture and biomedical systems analysis, design, and development. He earned his B.A., B.S., and M.S. degrees in computer science and applied mathematics from CSUF. He has over 60 publications (including journal, book, and conference contributions) as well as 6 patents awarded to date in the areas of autonomous systems and biomedical devices. Among numerous accomplishments, he designed and implemented the *Space Shuttle Radar Topography Mission* (SRTM) ground data processor control infrastructure for NASA's *Jet Propulsion Laboratory* (JPL), which processed an unprecedented number of terabytes of spatial in-flight data into ultra-high resolution 3D digital topography of the entire globe. For the Visual and Autonomous Exploration Systems Research Laboratory at Caltech, he co-designed, implemented, and demonstrated a remote telecommanding control system for a testbed for autonomous planetary surface exploration. Using novel image processing and data classification techniques, he co-developed a biomedical *Artificial Vision Support System* (AVS^2), which uses instantaneous vision processing algorithms to interface to blind patients' implanted microelectrode retinal array prostheses in real time. He developed a novel customizable satellite telemetry generator/decommutator for JPL's *Jason Telemetry Command & Control Subsystem* (JTCCS) project, which was the first to support real-time telecommanding of earth-orbiting satellites from wireless handheld smart devices. He is the recipient of NASA Shuttle Radar Topography Mission Group Achievement Awards for algorithm development, data product processing and validation for the design, development, and operation of the world's first fixed-baseline radar interferometer, flown on STS-99, and for the data processing that produced a unique 3D digital elevation model of the Earth's surface. He also holds the *National Imagery and Mapping Agency* (NIMA) Shuttle Radar Topography Mission Award, the NASA Certificate of Recognition for Creative Development of Technical Innovation award as well as the NASA BOARD award for field-deployable integrated air-ground multi-agent autonomous remote planetary surface exploration, the NASA Space Act Award for the development of significant scientific/technical contributions to aeronautical and space science, and the R&D 100 and R&D 100 Editors' Choice awards, both for the DOE-funded *Artificial Retina* project. He is an active member of the Association for Computing Machinery and the Institute of Electrical and Electronics Engineers.