Changing Risk in Human Spaceflight
Drivers for Healthcare Automation and Vehicle Integration

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• From Conclusion 6:
• “The human being must be integrated into the space mission in the same way in which all other aspects of the mission are integrated.”
Outline

• Where NASA is headed?

• What kind of risk does that incur?

• PHM is part of the solution

• The larger context
  – Medical Data Architecture
  – Medical Systems Engineering
  – Vehicle and Mission Integration

• What are the obstacles?
  – Data limitations
  – Evidence-based predictive analytics
  – Program Expectation and System Integration
Phase 1: Gateway
Trans-Mars Cruise
About 9 months
Coming Home
About 9 months

• Unlike the reactive approach being currently employed in the space medicine domain, the suggested PHM-based concept is about real-time monitoring of the healthy crew, where the monitoring is augmented with predictive diagnostic capabilities.

• Given the limited responses on health compromises during exploration-class space missions and the uncertainty inherent to the missions, the ability to predict versus react can mean the difference between mission success and mission failure.
How well can we use what we already know?

- Real Time Communications
- Medical Evacuation Capability
- Consumables Resupply
Medical and Non-medical Risk

- Mass/Volume of Medical System
- Mission Risk
- Total Risk
- Non-Medical Risk
- Medical Risk

Notional
Changing Mission Risk

Mission Duration (Days)

- **Launch**: 730 days
  - Transit Hardware
  - Transit Medical - LOCL

- **365 days**
  - Deep Space Hab

- **128 days**
  - Shuttle/ISS

- **42 days**
  - Gateway

- **21 days**
  - EM2

- **14 days**
  - Space Shuttle

Mission Risk (LOC)
PHM techniques

- 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;
- Identification and analysis of precursors on health compromise;
- Statistical techniques and machine learning methods for diagnostics and prognostics;
- Environment anomaly detection.

Fink et al. IEEE 2014
Implementation requires a Human System

Transit 1

Depart

Transit 2

Planetary

Ground Support

Crew Autonomy
International Space Station

All Data Analyzed and Interpreted by Ground Support
Example Interfaces with the Flight System
Medical Systems Engineering

DESIGN TEAM OPERATIONS

TELECOMUNICATIONS

SCIENCE

STRUCTURE

POWER

PROPULSION

END-TO-END SYSTEM

SENSOR

MISSION OPERATIONS

USER

06/14/91

SYSTEM ENGINEERING AT JPL

From “System Engineering at JPL” training course material, June 1991.
### NASA Engineering Life Cycle Phases

<table>
<thead>
<tr>
<th>Project Life-Cycle Phases</th>
<th>Approval for Formulation</th>
<th>Formulation</th>
<th>Approval for Implementation</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Phase A:</td>
<td>KDP A</td>
<td>KDP B</td>
<td>KDP C</td>
<td>KDP D</td>
</tr>
<tr>
<td>Concept Studies</td>
<td>Δ MCR</td>
<td>Δ SRR/SDR</td>
<td>PDR</td>
<td>Δ CDR</td>
</tr>
<tr>
<td>Phase A:</td>
<td>KDP B</td>
<td>KDP C</td>
<td>KDP D</td>
<td>Δ SIR</td>
</tr>
<tr>
<td>Concept &amp; Technology Development</td>
<td>Δ SRR/SDR</td>
<td>Δ PDR</td>
<td>Δ CDR</td>
<td>Δ SIR</td>
</tr>
<tr>
<td>Phase B:</td>
<td>KDP C</td>
<td>KDP D</td>
<td>KDP E</td>
<td>Δ ORR</td>
</tr>
<tr>
<td>Preliminary Design &amp; Technology Completion</td>
<td>Δ PDR</td>
<td>Δ CDR</td>
<td>Δ SIR</td>
<td>Δ ORR</td>
</tr>
<tr>
<td>Phase C:</td>
<td>KDP D</td>
<td>KDP E</td>
<td>KDP F</td>
<td>Δ FRR</td>
</tr>
<tr>
<td>Final Design &amp; Fabrication</td>
<td>Δ CDR</td>
<td>Δ SIR</td>
<td>Δ ORR</td>
<td>Δ FRR</td>
</tr>
<tr>
<td>Phase D:</td>
<td>KDP E</td>
<td>KDP F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Assembly, Integration &amp; Test, Launch &amp; Checkout</td>
<td>Δ SRR/SDR</td>
<td>Δ PDR</td>
<td>Δ CDR</td>
<td>Δ SIR</td>
</tr>
<tr>
<td>Phase E:</td>
<td>KDP F</td>
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<td></td>
<td></td>
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<tr>
<td>Operations &amp; Sustainment</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Phase F:</td>
<td></td>
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<tr>
<td>Closeout</td>
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</tbody>
</table>

*See 7120.5E for acronym definitions.*
Crew Health and Performance System Must…

• Protect from environmental hazards
  – Radiation protection
  – Noise, vibration, CO₂, etc.

• Keep healthy crew well
  – Exercise
  – Other physiological countermeasures
  – Food
  – Behavioral health

• Prevent, diagnose, treat, manage long-term health care
  – Data system
    • Medical Data Capture
    • Medical Training
  – Medical devices
  – Medical supplies

• Support crew to accomplish mission tasks
  – Procedures
  – Training
  – User interfaces
Vehicle/Mission Architecture Integration

Habitat System

- Crew Health and Performance
  - Natural and Induced Environments Protection
  - Medical
  - Mission Task Performance
  - Health and Wellness
- Structures
- Command & Data Handling
- Guidance, Navigation and Control
- Comm & Tracking
- Power
- etc.

Ground System

- MedOps

Crew as Physician

Crew as Explorer or Patient
Stepwise Progression

**Gateway**
2024

**Deep Space Transport**
2027

**Precursor**
2029

**Mars**
2033

*Human System Requirements*

- Test System Data Management
- Ground Optimize for 42 Day Mission
- Deploy System Data Handling
- Initial Ground Operations Changes
- Exercise Deep Space Comm, Autonomy, and Decision Paths
- Deploy Revised Ground Ops
- Optimally Autonomous Crew
- Redefined Ground Operations Paradigm

*Ground System Requirements*
• Given the limited responses on health compromises during exploration-class space missions and the uncertainty inherent to the missions, the ability to predict versus react can mean the difference between mission success and mission failure.
Medical Support Capability

- Preventive Care
- Knowledge Support/Known Algorithm Provision
- Automated Image/Data Analysis
- Differential Diagnosis Generation
- Condition Specific Guidance
- Integrative Health Prediction
- Full AI
• Physicians are fond of saying, the only unambiguous diagnosis is death. Everything else is typically subject to argument. That is why a big data approach must be cautious to use relevant data and interpret the data correctly. Not to speak about making predictions outside of what has been quantified.
What could go wrong?
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.

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.

Popov et al. 2016
Human System Performance

- Cognition
- Sleep
- Team Cohesion
- Team Dynamics
- Training Capabilities
- Mood
- Physical Strength
- Stamina
- Exercise Equipment
- CO2 Levels
- Oxygen
- Water Quality
- Air Quality
- Radiation Monitoring
- Waste Management
- Food and Nutrition
- Pharmacy
- Medical Skills Maintenance
- Medical Equipment
- Emergency response
- Ground Support
- Biomonitoring
System Performance Threatened by Sleep Deficit
Sleep Deficit Affects Other System Aspects
Cross Collaboration Priorities

- How do we monitor the human system state to enable prediction and prevention of medical issues?

- How do we model Human Performance so that we can plan for systems that optimize that?

- How do we balance medical specific training/understanding with the larger mission training needs?

Medical is a small part of the Crew Health and Performance System

Medical, Veh/Env, HHC, HFBP, Gnd, Med, (HHC), (SR)
• COTS hand-held reportable smart devices with increased capability and reduced mass, volume, and power make the technology implementation feasible for the crewed vehicles, expected to be used for more advanced missions.

• What happened when we put iPads on the ISS?
A PHM-type system vision

The Human System Data Architecture

These technologies exist today

Notional
PHM Must Complement The Paradigm

• Conception of Medical and Performance Operations
• Quantification of Medical and Performance Risk
• Data Systems Development
• Human Systems Engineering for Vehicle and Mission Integration
The Requirements Process

Began with DST (Mars transit) to develop body of work and using that infrastructure for DSG in FY18.

- Stakeholder needs, goals
- NASA Standards
- Program requirements & architecture
- System functions & behaviors
- System requirements & architecture
- Subsystem requirements & architecture
- Characterize system
- Analyze & trade
- Design & Build

Do we have the capabilities to meet the needs? What allocations are necessary?
Where are we today?

Data Sources Layer
- Structured
  - Health Records
  - Medical Records
  - Clinical Trials
  - Other
- Unstructured
  - Medical devices
  - Monitoring System
  - Images
  - Logs & Notes
  - Exercise Machine
  - Other
- Streams
  - Bio Sensors
  - Env. Sensors
  - Other

Data Storage Layer
- Data Assets
  - Knowledge Models
    - EHR
    - Documents
    - Sensor
    - Other
  - Vitals
- Integrated Data Platform
  - Annotate
  - Correlate
  - Classify
- API, Information Services
  - Clinical Decision Support System
  - Knowledge Base
  - Analytics Data Mart
  - Databases
  - Data Warehouse
  - Decision Data Mart

Analytical Layer
- Data Models
  - Annotate
  - Correlate
  - Classify
- Clinical Decision Support System
- Knowledge Base
- Analytics Data Mart
- Relational Data Mart
- Non-relational Data Mart

Discovery & Analytics
- Reports
  - Dashboard
- Data Mining
  - Text Classification
  - Computational Statistics
- Modeling & Analytics
  - Diagnostic
  - Predictive
- Discovery
  - Ontological Search
- Real Time Apps
  - Alerts
- Cognitive Computing
  - Adaptive, Interactive, Contextual

User Interface
- Applications & Prototypes
- User Interface & Visualization

Data Virtualization

Metadata & Data Standards

Federated Access & Delivery Infrastructure (FADI)
Provision of Training and Crew Support

TAKING A GOOD IMAGE: COMPOSITION

Tips for good composition:

To move the optic disc down the subject needs to look up.

To move the optic disc right the subject needs to look right.

In a good composition the optic disc is centered.

Bad composition

In poor composition, the optic disc is not centered or not visible.

Bad composition

Optic disc is too far right

Bad composition

Optic disc is too low

Good composition
Remote -> Autonomy

Augmented Reality Training
Tietronix
Data Sent/Collective by MDA System via Telemetry with CFS (CCSDS Protocol)
Conclusions

• PMH is the future of human spaceflight.

• The goals of the discipline complement ongoing work at NASA that targets the Exploration Missions.
  – Program expectation for integration with vehicle and mission
  – Medical Data Architecture
  – Systems Engineering Pathway

• Evidence Base Challenges
  – What do we need to bring?
    • What do we monitor?
    • How do we validate predictive capability?
  – Big Data Analytics
    • How do we build the evidence base that we trust?
    • Analogs first – Testing and Evaluation Pathway
BACKUP
NOT Official – best guess on requirements context

Lev 0
HEOMD

Lev 1
ESD

Lev 2
DSG
The DSG shall…

Lev 3
DPG
PPE Hab Logistics Airlock
The DSG habitat shall…

Lev 4
The CH&P system shall…
Crew Health & Perf Crew Health & Perf Structures Power Etc

Lev 5
The habitat medical system shall…
Health & Wellness Ground Medical Mission Performance Environment Health & Wellness Habitat Medical

The ground medical system shall…
The XYZ device shall…
Data System Devices Supplies
27Apr17 crew note from HMS-ULTRSND-SCAN-CMO:

You know what would really help us? If we had pictures of a "perfect case" for each type of image. Given the time lag between ground and ISS - and the minute adjustments we are making for the correct image- the ground is like "3 seconds ago". If we had a picture of what we should make each image look like, we will print it out and have it above the machine so we can more quickly get to what you want and then stabilize for the ground to catch up. I think it will also help cosmonauts considerably given the high amount of commanding/translation. Just a thought - but I think it would help us be more efficient.
• PHM concepts are the future

• Systems engineering for CHP needs requires early integration with vehicle and respect for the engineering design life cycle.

Table 1. PHM-based Healthcare Concept vs. Conventional Medicine

<table>
<thead>
<tr>
<th>The PHM-based Healthcare Concept</th>
<th>Conventional Medicine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focus on keeping astronaut healthy by predicting a deterioration or impairment in his/her health before a sign is detected or a symptom is manifested</td>
<td>Focus on detected signs and manifested symptoms in order to diagnose a medical condition, disease or disorder</td>
</tr>
<tr>
<td>Real-time 24/7 streaming monitoring and processing</td>
<td>One-off, snapshots made in doctor’s office</td>
</tr>
<tr>
<td>Astronaut generated data</td>
<td>Doctor ordered data</td>
</tr>
<tr>
<td>Individualized</td>
<td>Population-based</td>
</tr>
<tr>
<td>Panoramic</td>
<td>Data limited</td>
</tr>
<tr>
<td>Condition Based Maintenance (CBM)</td>
<td>Diagnosis-based treatment</td>
</tr>
<tr>
<td>Evidence-based health maintenance</td>
<td>Diagnostics and treatment limited to experience and knowledge of healthcare provider</td>
</tr>
<tr>
<td>Used in conjunction with COTS wireless sensor network communicating with custom smartphone-based (e.g., [4]) or tablet-based (e.g., [5]) apps, reasonably priced</td>
<td>Expensive, Big-Ticket Technologies</td>
</tr>
<tr>
<td>Intuitive and customizable dashboard-based interface with user-friendly language designed for astronaut as the only end-user</td>
<td>Medical language and an interface designed for healthcare professional</td>
</tr>
<tr>
<td>Astronaut healthcare autonomy paradigm, rather than the tele-medicine one</td>
<td>Medical Paternalism</td>
</tr>
<tr>
<td>Astronaut edited and owned his/her CEHR.</td>
<td>Non-shared EHR that owned by healthcare provider</td>
</tr>
<tr>
<td>Astronaut engagement</td>
<td>Compliance with healthcare provider directives</td>
</tr>
</tbody>
</table>