Report on NASA Workshop "Telemetry-Based Biology for the Artemis Era and Beyond"

By Workshop Organizers: Jared Broddrick (NASA ARC), Egle Cekanaviciute (NASA ARC)
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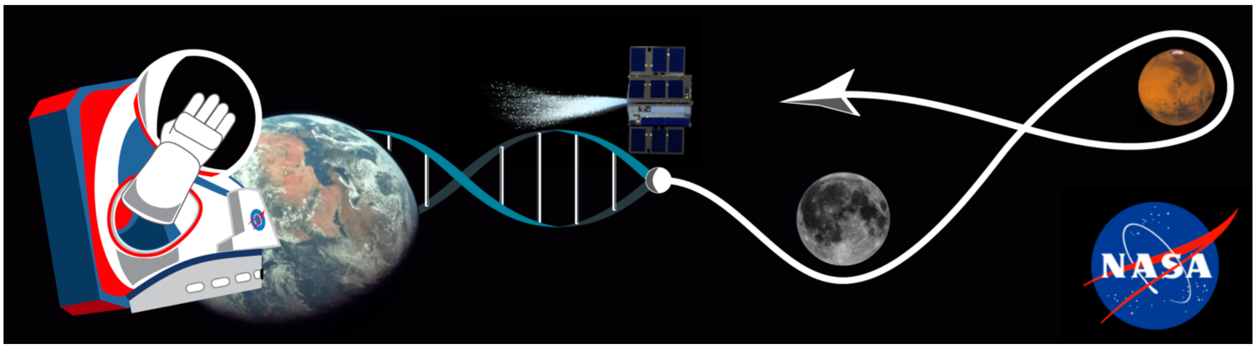
POC: egle.cekanaviciute@nasa.gov



On August 18th-20th, 2021, NASA ARC / NASA Space Biology held a workshop **"Telemetry-Based Biology for the Artemis Era and Beyond."** This was a highly targeted workshop with the purpose to identify focus areas and gaps in developing automated biological payloads for experiments beyond low-Earth orbit.

The workshop began with an **open conference on August 18th** (recording is publicly accessible here) with speakers from NASA and industry who covered the current state and proposed developments in flight hardware, data processing and transfer, microfluidic hardware for biological systems, and biological models for automated long-duration missions. The conference was followed by two **invitation-only white-paper drafting sessions on August 19th and 20th** for submission of a Campaign-level White Paper for consideration by the NASEM Decadal Study by the Committee for Biological and Physical Sciences in Space.

The seminars during the **Conference** part of the workshop included between 35-50 participants from multiple NASA centers (ARC, JPL, HQ), academia (e.g. Caltech, Colorado University Boulder, University of California San Francisco, Vanderbilt University, University of Wisconsin Madison, Georgetown University) and industry (e.g. eMulate, Space Tango, BioServe). The audience was primarily composed of scientists and engineers interested in automation and deep space applications of their research. The following talks covered a wide range of applications and focus areas for developing automated biological systems:

1) Small Satellites: **Therese Moretto Jorgensen**, NASA ARC. *The Small Spacecraft Landscape at Earth and Beyond – a look to the future.*
2) Hardware for Biology: **Antonio (Tony) Ricco**, NASA ARC. *Telemetric Studies of Microbial Cultures in Space using Autonomous Microfluidic Bioanalytical Systems.*
3) Integration: **Alan Berinstain,** Space Tango. *Flight Integration of Biological Models.*

4) Biological Models: **Christopher Hinojosa,** eMulate. *Human Emulation on the International Space Station: A Platform for Studying Human Biology in Microgravity.*
5) Data: **Abhijit Biswas**, NASA JPL. *Information Transfer from Space with Laser Beams.*
6) Current Biological Experiments on Small Satellites: **Sergio Santa Maria**, KBR Wyle / NASA ARC. *Lessons Learned from the BioSentinel Mission.*

Each presentation was followed by a Q&A session with emphasis on the following topics:
- Lessons learned from CubeSats and other autonomous payloads.
- Recommendations for technology development during the next decade:
  - hardware for maintaining the biological models;
  - biological models;
  - hardware for automated sampling and analysis;
  - data collection, processing and transfer.
- Expected bottlenecks and issues.
- Recommendations for expanding the technology to encompass:
  - Low-Earth orbit (LEO) to deep space missions;
  - A variety of biological models: from microorganisms human organoids;
  - An increased number of missions via reduced footprint and cost.

The **Drafting Sessions** included all speakers from the open conference, as well as the following additional participants: Jessica A. Lee (NASA ARC), Matthew Lera (NASA ARC), Nathaniel Szewczyk (Ohio University), Tobias Niederwieser (BioServe Space Technologies), Camilla Urbaniak (NASA JPL), Anand (Sunny) Narayanan (Florida State University).

A comprehensive outline and draft of the white paper was produced, including a summary of the current state of development of automated systems for space biology research, followed by an extensive list of recommendations together with a suggested timeline and key goals for a major research campaign to be announced in the next decade. The recommendations are briefly summarized below.

Technical recommendations to NASA:

- *Hardware*: both external (e.g. small satellite) and internal (e.g. microfluidics).
  - Development of a single hardware system and its utilization across multiple applications with limited modifications for each biological model, using a similar approach to LEIA as an extension of BioSentinel.
  - Defining a suite of essential technologies for biological support and biological measurement, followed by assessing their current availability in autonomous, space-ready format and funding to fill the technological gaps.
  - Development of a single integrated suite of automated instruments that could be utilized by multiple research groups to address a variety of experimental questions, while avoiding solicitations that would encourage each awarded investigator to create their own instrumentation.
  - Extensively testing hardware performance in increasingly complex environment: ground → scientific balloons → parabolic flights → low-Earth orbit → lunar orbit.

- *Data*:
    - Utilizing academic and commercial communications facilities for space-to-ground data transfer.
    - Focusing on data dimensionality reduction, on-board processing, and automated triage of outputs to minimize the quantity of data that has to be telemetered.
    - In addition to collecting and processing experimental data on biological responses to spaceflight, developing the most robust command sequences of complex autonomous actions to initiate and control on-board instruments and experiments.

- *Experimental design:*
    - Defining a minimum set of data parameters (e.g. radiation dose, temperature, carbon dioxide concentration) to be recorded for each experiment to allow comparisons between experiments.
    - Applying a subset of the following experimental techniques, depending on the biological model used:
        - automated sample preparation;
        - cryopreservation of samples;
        - nucleic acid sequencing;
        - metabolomics (note: technology will overlap with Planetary Science search-for-life missions);
        - microscopy;
        - videography for behavioral studies;
        - colorimetric, electronic and other sensors for biological measurements;
        - in-flight data pre-processing using AI/ML and similar approaches.
    - Minimizing the probability of biofouling and other types of contamination.
    - Including the following biological models:
        - 3D human organoids and tissue/organ-on-a-chip microfluidic systems, including personalized analysis.
        - Invertebrate multicellular organisms, such as *D. melanogaster* and *C. elegans,* for low footprint, high throughput, whole organism, multigenerational studies.
        - Single-cell organisms, both eukaryotes (e.g. *S. cerevisiae)* and prokaryotes (e.g. *E.coli*), used to generate fundamental biological knowledge of spaceflight effects, and to express an array of human proteins and analyze their interactions.
    - Proposing investigations of sufficient length to encompass the entire solar cycle and the associated changes in space radiation.

Programmatic recommendations to NASA:

- Extending the Cubesat Launch Initiative to incorporate small biological payloads in LEO, beyond LEO, to Gateway and to lunar surface via Commercial Lunar Payload Services (CLPS).
- Accommodating late handover (days instead of weeks/months) of biological experiments on deep space missions.

- Ensuring that NASA trains and retains sufficient scientists and engineers for leading long-duration missions. This topic is cross-correlated with two Topical White Papers: *Biological and Physical Sciences Outreach*, Principal Author: Egle Cekanaviciute; and *Enhancement and Retention of Space Bioscientists and Students*, Principal Author: Amber M. Paul.
- Collaborating with Planetary Science Division:
    - Including space biology experiments as secondary payloads on planetary science spacecraft.
    - Sharing institutional knowledge on autonomous operations in deep space. This topic is cross-correlated with a Topical White Paper: *Co-leveraging scientific advances in Space Biology and Astrobiology towards achieving NASA's life science objectives,* Principal Author: Jared Broddrick.
    - Planetary science payload testing in lunar orbit utilizing the equipment and facilities developed for space biology.
    - Adapting the existing planetary science / astrobiology instrumentation and techniques for sample and data collection and processing to space biology studies.
    - Applying the extensive expertise of developing requirements for instruments used in planetary science deep space missions (power and size limitations, radiation hardening, etc.) to biological sciences-relevant instruments.
- Funding large-scale projects and coherent requests of campaigns encompassing all aspects of an autonomous biological mission (hardware, biological models, data transfer) instead of multiple individual grants to principal investigators focused on separate aspects of the payload.

In summary, we call for a **major dedicated campaign to develop and fly autonomous biological payloads in lunar orbit and on the lunar surface** during the next decade, followed by expansion to Martian orbit afterwards. This ambitious goal will require dedicated effort to develop hardware, biological models and data acquisition and processing techniques. We believe that it would be best achieved as a single comprehensive, NASA-led and funded mission project, analogous to planetary science missions. Furthermore, technological developments should be accompanied by collaborations within and between agencies and a robust program for acquisition and retention of talented scientists and engineers.