HERON - An Open Source Microbiology Experiment Platform in Low Earth Orbit

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（√） We apply for Student Prize.
（ ） Please keep our idea confidential if we are not selected as finalist/semi-finalist.

UN Sustainable Development Goals
This project will further several of the United Nations sustainable development goals. Most evidently, the goal of ‘Good Health and Well-Being’ is explored by the experiment which elucidates the human response to long-term space travel and its biological feasibility in the future. ‘Industry, innovation and infrastructure’ is also a focus of this mission wherein new technological solutions are being applied to space-relevant research. Furthermore, this mission is intended to be implemented by student teams with open-source availability of the platform technology, offering the students unprecedented opportunities to supplement their academic studies with real-world design challenges and advancing the goal of ‘Quality Education’.

Need
The microgravity environment in low Earth orbit and beyond has been shown to affect humans by way of the millions of microorganisms that live in our bodies. When exposed to microgravity, these microorganisms change their behaviour in unexpected and possibly harmful ways, which directly impacts the health of their human hosts. [1]

To date, our understanding of these effects is limited, primarily by the prohibitively expensive nature of designing and executing autonomous space experiments, and the intensely competitive process required to run experiments on the ISS. This mission will act as a proof-of-concept, demonstrating an accessible, open-source platform with which microbiology experiments can be carried out in microgravity.

Specifically, this mission will focus on a particular opportunistic fungal pathogen, *Candida albicans*, an endogenous resident of the human gut microbiome. The on-board experiment aims to quantify the changes in the pathogenicity, drug resistance, and stress response of *C. albicans* in a microgravity environment. Understanding *C. albicans* may have important implications for understanding the long-term health of astronauts in extended space flight. [2]

Mission Objectives
1. Maintain suitable environment for microorganisms to survive the duration of the mission.
2. Generate statistically significant data on the changes in virulence and drug resistance of *C. Albicans*
3. Create detailed, open-source technical documentation to allow organizations around the world to replicate and use the platform on different microbiology experiments
4. Create educational materials to train and teach inexperienced persons who are interested in rebuilding the design with minimal pre-existing knowledge.
5. Keep the mission budget under 30,000 USD (excluding launch) make it accessible

Concept of Operations
<u>Phase 0**:** Microbiology Research and Gene Tagging</u> (L-12 months)
The organism of interest, *C. Albicans*, is investigated to isolate the specific genes that lead to increased pathogenicity and drug resistance. Once these are identified, a Gene Tagging method using plasmid vectors is utilized to tag the genes of interest with Green Fluorescent Protein, which allows the expression of the genes to be measured through optical measurements.

<u>Phase I: Assembly and Launch</u> (L-4 months to L)
The *C. Albicans* cells, which are classified as Biosafety Level 2 organisms, must be loaded into the payload bay of the nanosatellite in a facility certified to handle them. The cells will be loaded “in stasis”, meaning that their vital activities are suspended and they do not require nutrition or a strict temperature range to

survive. They will remain in stasis until Phase IV, when the actuation of growth media into the wells in which they are placed will bring them back to life. Once the organisms are placed within the bay, the payload is sealed and it can proceed to be integrated with the electronics bus and remaining structure of the satellite. Once satellite integration is complete, it is handed off to the launch provider to be integrated with the launch vehicle. It can be launched from any vehicle with a compatible 3U Cubesat launch pod.

<u>Phase II: Early Orbit</u> (L to L+2 weeks)
Upon launch, the satellite will go through a series of self-diagnostics to ensure that the systems have started up properly. Once this has been verified, the satellite will seek to establish communication with the Ground Station while charging its batteries to full capacity.

<u>Phase III: Experiment Preparation</u> (1 day)
Upon a command from the Ground Station to begin the experiment, the satellite will begin preparation for the experiment. The heaters will be turned on to bring the payload bay up to the required temperature. This will likely lead to the power margin of the satellite going negative, so the satellite will operate on the stored charge in the primary battery pack for Phases III and IV. The sensors will be calibrated within this period.

<u>Phase IV: Experiment</u> (48 hours)
Once the preparation is completed and a stable temperature environment is achieved within the payload, the experiment will begin. In order to start the experiment, a microfluidic actuation mechanism will introduce growth media and experiment media into the wells in which the cells reside. This will bring cells out of the stasis state and they will become active. Data collection will last 48 hours.

<u>Phase V: Diagnostics and End-of-life</u>
After the experiment is complete, the primary goal of the mission is completed. In the final phase, the satellite will be used to collect diagnostic data on the performance of the various subsystems on board. The satellite orbit will naturally decay in 25 years.

Key Performance Parameters

- C. Albicans must be gene-tagged with Green Fluorescent Proteins (eGFP) to allow its gene expression to be tracked
- The payload sensor setup must be sensitive to fluorescence on the order of 3 pW/mm^2
- Payload bay must be kept between 4-40°C throughout the entire mission.
- Payload bay must be kept at 33±5°C for the duration of the 48-hour experiment.
- Payload bay must remain at 1 atm, and 100% relative humidity during the entire mission.

Space Segment Description

<u>Structural</u>
HERON is a 3U Cubesat, and it followa all of the requirements in the Cubesat Design Specification [3]. The mass is 3.7 kg, and the physical envelope is within the specifications such that it will be compatible with the Poly-Picosatellite Orbital Deployer (P-POD).

Four rails that run along the edges of the satellite form the structural envelope of HERON. The batteries, transceiver, on-board computer and antenna are placed in the top segment, while the payload bay takes up most of the remaining space on the vessel. The solar panels, not pictured in Figure 1, cover the four long edges of the structure. To achieve the stringent thermal requirements imposed by the biological payload, the physical contact of the payload bay to the rest of the structure is limited to the 8 small attachment points, which reduce the bus-payload thermal conductance and limit the thermal power usage. A passive attitude control system is used by mounting hysteresis rods and permanent magnets along the rails. The mass budget of the entire satellite can be found in Table 1.

Figure 1. CAD Rendering of HERON

Table 1. Mass Budget

Component	Mass Breakdown	Total	Source	Margin	Total with Margin (g)
Structures Primary Structure	Railing: 39.71 g x 4 Braces: 24.11 g x 6 18.45 g x 2 8.21 g x 2 Brackets: 76.92 g 87.11 g Fasteners: 30g	543g	CAD Calculation	2%	554g
CDH	Board: 100g	100g	Estimated	5%	105g
Communications	Antenna: 85g Communications Board: 94g Wiring: 10g	189g	Datasheet	2%	193g
Power	Solar Panel Boards: 540g Battery Board: 500g EPS: 100g	1140g	Estimated	5%	1197g
ADCS	(Assuming 100g)	100g	Datasheet	10%	110g
Thermal	Coverings: 10g Mylar Sheet: 15g Aerogel: 50g	75g	Estimated	50%	113g
Payload	MF Chips: 100g Sensor Boards: 100g Clamps: 223.7g Blister Packs: 50g Wiring: 50g Pressure Reservoir: 275.3g Caps: 232 g Motors: 120g x 2 Fasteners: 55 g	1326g	Estimated, CAD Calculation, Measured	10%	1459g
Total		3473 g			3731 g

Electronics Bus

The thermal heating requirements when the experiment is running place a heavy load on the power subsystem. Due to the negative power margin during the experiment, HERON requires at least 20 Ah of charge storage; as such, a large part of the physical envelope of the electronics bus is taken up by the batteries. The power budget with the experiment on and off can be seen in Table 2.

Table 2. Power Budget with Experiment Off (left) and On

Subsystem	Mode	Instant Consumption (mW)	Time Active (%)	Constant Power Subtotal (mW)
EPS	On	100	0	0
	On + heater	300	100	300
OBC	On	100	100	100
Comms	RX	200	95	190
	RX+TX	2100	0.05	105
Beacon	On	100	100	100
Payload	On	100	0	0
	On + heater	2600	100	2600
Deployment*	Antenna	2650	N/A	2650
	Payload	10000	N/A	10000

*Deployment occurs once, right after satellite is launched. It is therefore discounted from the power calculations.

Consumed Power Const. Pwr/orbit (mWh)	Generated Power Const. Pwr/orbit (mWh)	Efficiency	MARGIN (mWh)
3395	3643	85%	−298.5
		80%	−480.6
		75%	−662.8

Subsystem	Mode	Instant Consumption (mW)	Time Active (%)	Constant Power Subtotal (mW)
EPS	On	100	0	0
	On + heater	300	100	300
OBC	On	100	100	100
Comms	RX	200	95	190
	RX+TX	2100	0.05	105
Beacon	On	100	100	100
Payload	On	100	0	0
	On + heater	1500	100	1500
Deployment*	Antenna	2650	N/A	2650
	Payload	10000	N/A	10000

*Deployment occurs once, right after satellite is launched. It is therefore discounted from the power calculations.

Consumed Power Const. Pwr/orbit (mWh)	Generated Power Const. Pwr/orbit (mWh)	Efficiency	MARGIN (mWh)
2295	3643	85%	801.6
		80%	619.4
		75%	437.3

The Communications and Command & Data Handling subsystems are responsible for establishing communication with the ground station and relaying the experimental data generated by the experiment. The data requirements are minimal, and a system with a storage capacity of 128MB and a duplex radio at 437 MHz will satisfy the requirements of HERON. There are no restrictions on the speed of data transmission. Table 3 demonstrates the amount of data generated in a single time point of the biology experiment. With 48 timepoints a day, and running the experiment for two days, the total experimental data is below 100 kB. Table 4 is the HERON link budget, which can be closed with a comfortable margin.

Table 3. Data Generated per Timepoint

Data Source	Size Per Measurement
ADC (Optical Sensors) 48 x 24b	1152b
Thermistors (MF Chips) ~8 x 12b	150b
Pressure Sensor 24b	24b
Temp Sensor (PCB) 14b	14b
Humidity Sensor 14b	14b
IMU 48b	96b

Table 4. Link Budget

Link Budget			8	
Item	Symbol	Units	Uplink	Downlink
Transmit Antenna Gain (net)	G_t	dBi	19	0
Equivalent Isotropic Radiated Power (EIRP)	EIRP	dBW	29.5	1.26
Space Loss (FSPL)	L_s	dB	140.07	140.07
Propagation & Polarization Loss	L_a	dB	0	0
Peak Receive Antenna Gain	G_rp	dBi	1	20
Receive Antenna Pointing Loss	L_pr	dB	1	1
Receive Antenna Gain (net)	G_r	dBi	0	19
System Noise Temperature	T_s	K	615	220
System Noise	T_sn	dB-K	28.00	23.00
Receiver Noise Figure	R_nf	dB	3.00	0.50
Receiver Noise	R_n	K	289.00	36
Recieved Power	P_r	dBm	-81.1	-89.3
	P_r	dBW	-111	-119
	P_r	W	7.84E-12	1.18E-12
Data Rate	R	bps	1,200	1,200
Eb/N0	Eb/N0	dB	57.35	34.58
Carrier-to-Noise Density Ratio	C/N0	dB-Hz	88.14	65.37
Bit Error Rate	BER	-	1.00E-06	1.00E-06
Required Eb/N0	Req(Eb/N0)	dB	15	15
Implementation Loss	ImL	dB	2	2
Margin	-	dB	40.35	17.58

Payload

The cells, stored in stasis media, are housed within the wells of an acrylic microfluidics chip that can be seen in Figure 2. They are connected through channels to fluid reservoirs which house growth media that will revive the cells, and in some cases, an anti-fungal drug that will be used to measure their drug resistance. These fluid reservoirs are blister packs, which burst inward when pressure is applied and deliver the experimental fluids through channels to the wells as pictured. As in Figure 3, the chips are attached to both caps of the payload bay, along with linear actuators that lower a platform to simultaneously burst all of the blister packs. An array of phototransistors with an amplifier chain will be used to detect the fluorescence and optical density of the cells, using a method of coherent detection to improve the Signal-to-Noise Ratio.

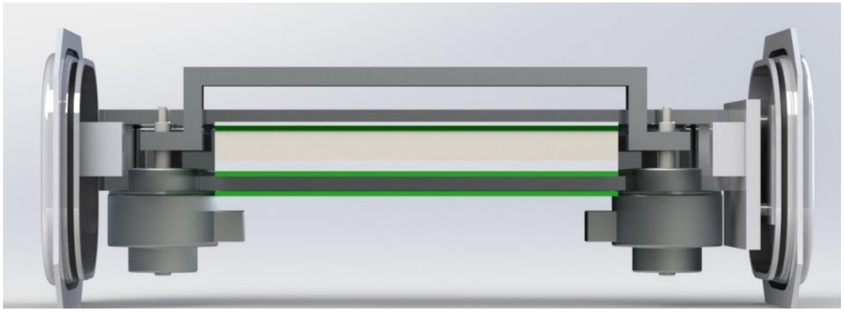


Figure 2. Side View of the internals of the payload bay attached to the caps

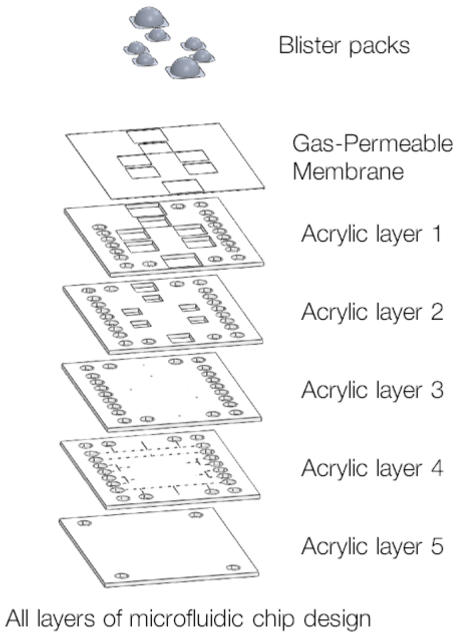


Figure 3. Microfluidics Chip Layers - Exploded View

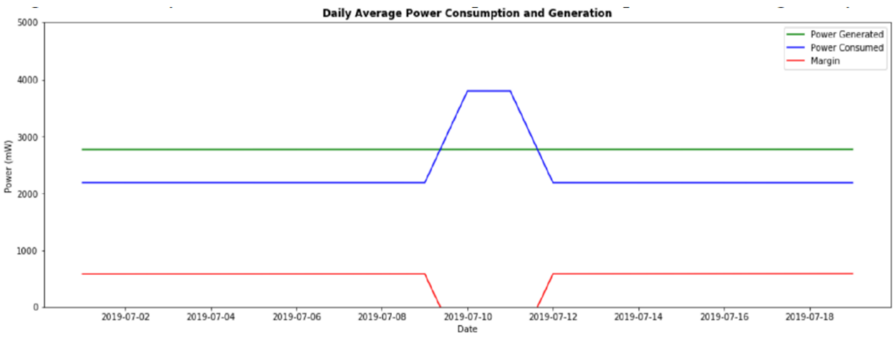
Orbit/Constellation Description

Orbit Selection

The orbit selection was driven by the thermal constraints outlined above. Two types of orbit were considered during our orbit selection were (1) International Space Station Orbit (ISSO), with a 400 km altitude and 51.6 inclination, and (2) Sun Synchronous Orbit (SSO), with a 550-600 km altitude and 98.6 inclination. Based on the results of our calculations and in-house simulations, operating in SSO is desirable due to its moderate range of beta angles, which the thermal design to meeting temperature constraints, as shown in Table 5 and Figure 4 below.

Table 5. Steady-State Orbit Average Payload Temperature using One Node Analysis [4]

	SSO	ISSO
Optimal a/e ratio	1.17	1.09
Hot Case Temperatures	Avg = 33.0°C, Max = 33.3°C	Avg = 29.2°C, Max = 50.1°C
Cold Case Temperatures	Avg = -16.6°C. Min = -16.8°C	Avg = -19.7°C, Min = -21.9°C



<u>Figure 4.</u> 30 Day Power Generation and Consumption in SSO, Experiment Starting on Day 10
Note: The power is -1020 mW during the experiment, and the battery is drained. However, based on our transient battery charge simulation, the battery charge does not go below our allowed minimum, 2250 mAh. [5] [6]

On the other hand, ISSO is not desirable because there are large beta angle fluctuations, which results in larger temperature range and would make mission planning challenging. Since HERON is launched as a secondary payload, it is unlikely to accurately select a launch window to meet our temperature and power constraint. If operating in ISSO, HERON needs to withstand all the temperature fluctuations and survive orbits without an eclipse. In short summary, operating in SSO would allow the HERON design to meet both power and thermal constraints while avoiding extreme hot and cold cases.

Implementation Plan

The HERON mission can be undertaken by a team of undergraduate students. An example of such a team is the Space Systems Division of the University of Toronto Aerospace Team (UTAT-SS). The administrative tasks, planning, and technical leadership are split between the Project Manager, Systems Designer and the Director, while Subsystem Leads manage their own teams of members to design, build and test a specific component of the satellite. The Business Development Lead is responsible for collecting in-kind and monetary sponsorships to support the team. Since the development of the satellite itself is less than $30,000 USD, it is possible to find educational or other institutions that can partner with the student team to raise the required funds. To secure a launch, other avenues might be necessary. It is possible to go through competitions or government-supported initiatives, however these are not the only options. For example, UTAT has managed to secure its launch funding through a campaign at the University of Toronto that instituted a student levy of $2.77 per semester for two years over 40,000 undergraduates on campus.

A high-level timeline for the development of the mission can be seen in Table 6. Throughout the development, the top project risks are:

1. Loss of leads and members due to the high turnover in student design teams
2. Loss of funding or facilities to continue the operation of the team
3. Power deficit during the experiment causing the death of cells
4. Cells not surviving the time between handoff and launch
5. Leaking of the payload bay

Table 6. Mission Timeline

<table>
<tr><th></th><th>L – 20 Months</th><th>L – 12 months</th><th>L-12</th><th>L – 4 months</th><th>L-4</th><th>L</th><th>L + 2 months</th></tr>
<tr><td>STR</td><td>Preliminary structure, thermal models</td><td>Manufactured structure, begin thermal testing</td><td rowspan="3">Qualification Testing</td><td>Manufacture flight model</td><td rowspan="3">Acceptance Testing</td><td rowspan="3">Launch</td><td rowspan="3">Mission Management and Data Collection</td></tr>
<tr><td>BUS</td><td>Begin low-fidelity breadboard prototype of EPS and CDH systems</td><td>Functioning EPS, CDH and COM systems on printed circuit boards</td><td>Establish and test ground station, manufacture flight model.</td></tr>
<tr><td>PAY</td><td>Begin investigating organism of interest</td><td>Developed microfluidics chips and initial optical sensors</td><td>Begin “land run” of experiment, manufacture flight model of payload</td></tr>
</table>

References

[1] G. Hornacek, D. M. Klaus and R. Mancineelli , "Space Microbiology," *Microbiology and Molecular Biology Reviews* , vol. 74, no. 1, pp. 121-156, 2010.

[2] C. A, "Spaceflight Enhances Cell Aggregation and Random Budding in Candida albicans.," *PLoS ONE,* vol. 8(12):, p. e80677, 2013.

[3] The CubeSat Program, Cal Poly SLO, "Cubesat Design Specification Rev.13," 20 February 2014. [Online].

[4] D. G. Gilmore, Spacecraft Thermal Control Handbook, Volume I: Fundamental Technologies., El Segundo, Calif: Aerospace Press., 2002.

[5] Spectrolab, "PV UTJ Cell Specifications," [Online]. Available: http://www.spectrolab.com/DataSheets/cells/PV%20UTJ%20Cell%205-20-10.pdf..

[6] Panasonic, "CGR18650CH Lithium Ion," [Online]. Available: http://www.bto.pl/pdf/04444/cgr18650ch.pdf .