68th International Astronautical Congress (IAC), Adelaide, Australia, 25-29 September 2017.

IAC-17,C3,3,6,x40041

Planetary Exploration Habitat Energy Requirements and Forecasting

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Abstract

Travel to other planetary bodies represents a major challenge to resource management. Previous manned exploration missions of long duration were resupplied with food, water, and air as required with regular resupplies. Manned missions traveling to other planetary bodies will have duration of years, with little to no possibility of resupply. Consequently, the monitoring and forecasting of resource consumption is a mission critical capability. The Hawaii Space Exploration Analog and Simulation, a long duration planetary analogue simulation, has recently completed its fifth long term isolation mission gathering energy, food, and water demands for six-person long term planetary missions. A novel method for forecasting energy consumption is presented that incorporates the emotional state of the habitat crew. Gathered data show that small environments can be heavily influenced by the actions of a single crew member resulting in dramatic changes in consumption, throwing forecasting models off to the point of total failure. Previous work has shown that the inclusion of the daily astronaut activities and psychological state allow for higher accuracy in forecasting for longer duration. Currently psychological surveys in the form of the Positive and Negative Affect Schedule, and a generalized artificial neural-modulation method are used to incorporate emotional response into machine learning forecast methods. Using these lessons and developments, a large scale smart habitat control and forecasting system is proposed that will monitor, control, and forecast habitat resources for future manned missions. This new system requires the incorporation of psychological and physiological data from crew members, crew activities, and schedule.

Keywords: (Analog, Simulation, Manned missions, Machine learning, Mars habitat, planetary habitat)

Acronyms/Abbreviations

Hawaii Space Exploration Analog and Simulation (HI-SEAS), Positive and Negative Affect Schedule (PANAS), National Aeronautical Space Agency (NASA), Human Factors and Behavioral Performance (HFBP)

1. Introduction

NASA has designated a number of red flag problems that must be solved prior to extending manned missions deeper into the solar system, with crew performance and cohesion being a major concern over long duration and isolation. The HFBP has funded a number of campaigns (NNX11AE53G, NNX13AM78G, NNX15ANO5G) in the form of HI-SEAS to investigate crew composition and cohesion for long duration, 8-months or longer, in an isolated and confined environment. Studies included the Team Performance Task/ Price of Cooperation Test, continuous monitoring of face-to-face interactions with sociometric badges, mitigation of the effects of isolation using immersive 3D Virtual Reality interactions with the crew's family and friends, measurement of emotional and effective states using automated analysis of multiple forms of textual communications provided by the crew members to identify relevant and effective teamwork behaviours, and multiple stress and cognitive monitoring studies. The study has completed one 4-month mission in early 2014, one 8-month mission in 2014 – 2015, a 365 day mission in 2015-16. Studies dealing with team risk and performance. [1] Crew selection is studied as part of the development of a model for crew composition. Autonomy is varied throughout each mission, with low crew operational autonomy in the first and last two months of the mission and high crew autonomy during the middle months of the mission. Table 1 shows the dates of each mission with the male/female crew composition. This paper is opportunistic research that focuses on the energy consumption during the mission simulations on top of the funded main psychological and teamwork studies.

Table 1. *HI-SEAS mission dates, duration, crew composition*

Mission	Start	End	#Days	Male/Female
M1	4/12/13	8/12/13	120	3/3
M2	3/26/14	7/26/14	120	3/3*
M3	10/7/14	6/17/15	240	3/3

M4	8/28/15	8/28/16	365	3/3
M5	1/19/17	9/19/17	240	4/2

*M2 reduced to M/F of 2/3 four weeks into experiment.

1.1 HI-SEAS Habitat

The HI-SEAS habitat is a 36-foot diameter dome that has two levels. The main floor consists of a work area, kitchen, dining room, laboratory, bathroom with shower. It is attached to a 8-foot square airlock that is connected to a 20 foot sea container. This area contains the washer and dryer, and the networking/telemetry room. The area of the first floor is 878-square feet that are usable, however it totals 993-square feet. [2]

Fig. 1*. HI-SEAS habitat with 10kW solar array and solar water heater with tank. Photo credit: Ansley Barnard.*

1.1.2 Power resources

Figure 2 shows a simplified schematic of the habitat power system. Power is provided by a 10W solar array, hydrogen fuel cell, and a propane generator. The simplified systems diagram in Figure 2 shows how power from each source enters the habitat, is converted from DC to AC if applicable, and sent to the habitat power loads on the outlets.

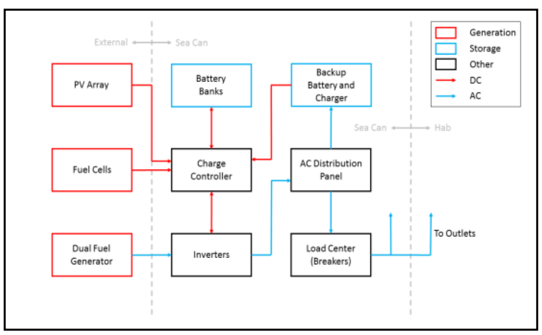

Fig 2: Simplified habitat power system diagram. *Credit: Alex Velhner, Blue Planet Research Ltd.*

When battery is low and there is not enough solar generation the propane generator is activated. The hydrogen generator will switch on automatically should the battery levels get too low in the evening. The propane generator is started manually by the crew.

Fig.3*. HI-SEAS battery bank. Photo credit: Ansley Barnard.*

A 10kW solar array is located south of the habitat and is visible from the lab window. The modules generate 275 W at maximum power point. They are monocrystalline silicon wafers. During the day, the solar array will charge the batteries and the habitat will run on battery power over night. The solar array generally starts charging the batteries around 0800 and stops charging around 1630, although there is seasonal and weather variation. On cloudy days the solar panels are not able to fully charge the battery bank as shown in Figure 3. [2]

Fig. 4*. HI-SEAS habitat propane fuelled backup generator. Photo credit: Ansley Barnard.*

The propane generator seen in Figure 4 is used strictly as a backup generator. The Hab stores energy in three Sony battery banks, Figure 2, up to 28.5 kWh. The DC current from the batteries passes through an inverter and is converted to AC for use at the Hab outlets. Generally, the batteries are charged from the PV array during the day, and the batteries will reach full charge in the late morning or early afternoon. With full sun, 80% of the battery can be charge by 1600, and the habitat will normally have enough power to make it to sunrise the next day. Smart power management by the crew can extend the duration of the batteries. [2]

1.1.3 Water resources

Hot water for the habitat is provided by a solar water heater. This solar water heater heats water contained in a 150 gallon insulated tank. Hot water was available to the crew well after sundown. This is a passive system and required no maintenance from the crew Engineer.

Fig. 5*. HI-SEAS external water tanks containing 3785 L (1000 gal) of water. Photo credit: Ansley Barnard.*

1.1.4 Sensors and telemetry

The habitat system was outfitted with a sensor telemetry routing system. A ControlByWeb X-310 web interface is utilized to control and collect sensor information and distribute to a remote location. The X-319 is a Ethernet I/O module with four digital inputs that allows for support of up to four temperature and humidity sensors. Sensor are interfaced by the web and could be controlled externally to the environment. Using this technology, the habitat was enabled to monitor and log power supply using a customization through a web based control page. Software allowed for graphing of telemetry and also the extraction of the data into CVS files allowed for statistical analysis.

Sensors were located in a variety of spots in the habitat. All power consumption was routed through a X-310 module attached from each circuit breaker. This was broken up into the Laundry room, Downstairs washroom and laboratory, Upstairs rooms and bathrooms, Living Room, Dining Room, and Kitchen. Power used in any of these areas could be monitored separately. A carbon-dioxide sensor was placed in the dining area of the dome. Temperature sensors were then placed in the Dining Room, One of the bedrooms, and the telemetry room. The main water tank had a laser level sensor, and the Planetary Power Generator computer was able to monitor and track power generation and distribution on its own. [2]

2. Resource consumption

Energy and water consumption is monitored during the analogue mission and this data will give a picture of what resources may be required for exploration or colonization on other planetary bodies. Mars missions could last as long as 2-½ years with no potential for resupply. [2] Due to this restriction, consumption must be monitored, controlled, and forecasted with a degree of high accuracy. This research investigates data from current and previous Mars analogue mission crew consumption rates to construct predictor models. These models are used to predict crew consumption rates and allow for changes in crew schedules and behaviour. Utilizing machine learning, the habitat water and appliance usage was modelled with the frequency and power consumption of each system. This information will aide in forecasting consumption rates of future missions with great accuracy.

2.1 Power consumption

Table 2. HI-SEAS Total Mission consumption in habitat areas in KWH.

(KWH)	M1	M2	M3	M4	M5
Living Room	4129	524	2243	4037	2557
Lab and Bath	847	221	6463	10663	7819
Washer Dryer	642	95	28	48	37
Kitchen	3544	990	3732	4478	3582
2nd Floor	392	969	3460	5967	2228
Heater	329	230	511	1034	840
Total::	9887	5043	16437	26230	15219

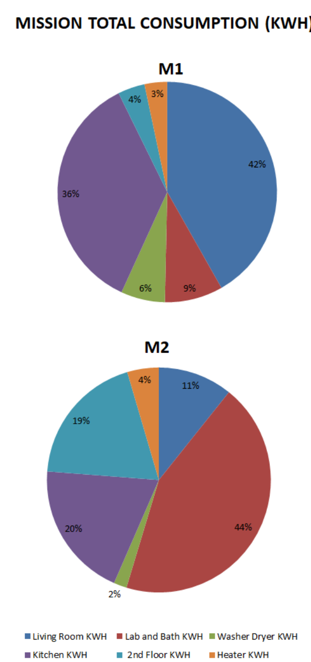

Fig.6*. Total power consumption (KWH) from both 120 Day missions. The major difference in kitchen power is*

due to a food study on M1. M2 crew aggressively conserved energy.

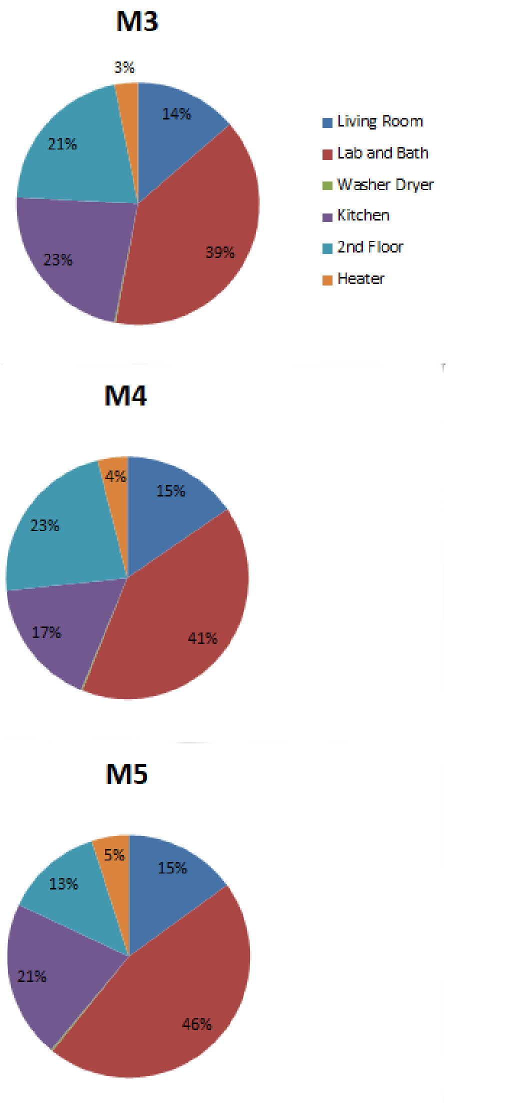

Fig.7. *Total power consumption (KWH) from M3 – M5. Distribution of power usage within the habitat remained consistent through all three mission with low variation.*

2.2 Water consumption

Total water consumption from all five missions varied greatly. M1 had an abnormally large amount of water consumption due to the use of flushing toilets, and a 500 gal. water tank making it difficult to compare to the other missions so it was removed from the study. All the subsequent missions used composting toilets and had double the capacity of 1000 gal. The total water usage for each mission is shown in Table 3.

Table 3. HI-SEAS mission water consumption rates Mission 1 data excluded due to major differences in water infrastructure.

Mission	Daily	Weekly	Month	Total
M2	53.4	449	1617	8088
M3	59.3	580	2240	15675
M4	61.7	299	1227	15256
M5	56.5	406	1659	14228

**- All values are in gallons*

3. Forecasting with crew emotional state

The HI-SEAS crew are inundated with a battery of daily psychological surveys and social experiments. Data used for this research project comes in the form of the Positive and Negative Affect Schedule (PANAS). The questionnaire is taken at the end of each day by crew members where the crew is shown twenty different words and are asked to rate how much they believe the emotion applies to them. This is done on a five point scale. Negative words such as guilty, hostile, irritable and words associate with positive emotions such proud, strong, active are rated between a value from 1-5. 1 being "not at all" to a value of 5 being "very much". For non-clinical experiments, the PANAS is considered to be a reliable measure of the population.

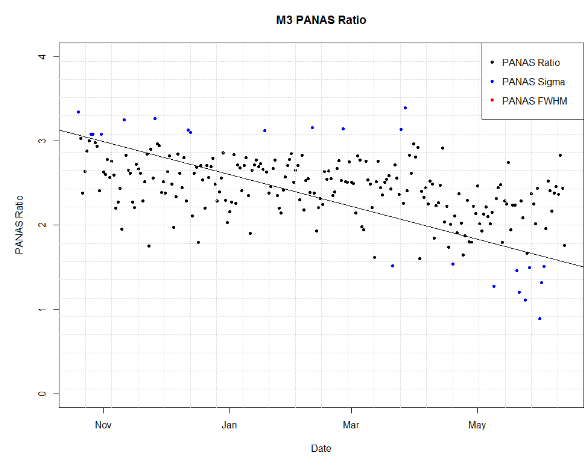

Fig 8: *M3 PANAS Ratio Median = 2.45, Max = 3.39, X-Intercept = 107.8 [3]*

In this research we will define a Disruptive Significant Event (DSE) as any kind of event that causes a major disruption in HI-SEAS crew routines and activities. These can range from power failures to water resupplies. Each DSE is taken from the crew commander's daily report and are categorized as follows: Another DSE that interferes with crew routines is Research in [3] showed that he psychological state of the crew has an effect on resource consumption rates. Significant events have minor to catastrophic effects on time-series forecasting models. Significant events and psychological state can be included in time-series forecasts to improve them.

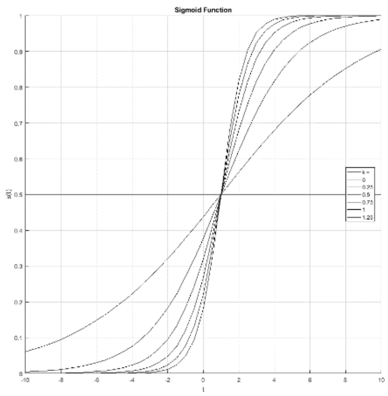

Fig.9: *The sigmoid function is used in neural networks as an activation function. The value of **k** is used to incorporate the PANAS score through changes in the slope, and therefore changes the probability of the sigmoid activating relative to a threshold value. [3]*

Human emotion in the brain is related to the neural modulation of synaptic responses. [4] Initial uses of artificial intelligence have been unable to recreate this aspect of emotion even through the introduction of fuzzy logic. Recent innovations have used embodied cognition to capture robotic movement and behaviours leading improved robotic capabilities. [4] [5] [6]. Research in neurology using EEG and MRI to examine emotional processing have found that emotions are fundamentally linked to the cognitive system. [7] Thus, current research in AI has recently been geared towards the inclusion of emotional processing.

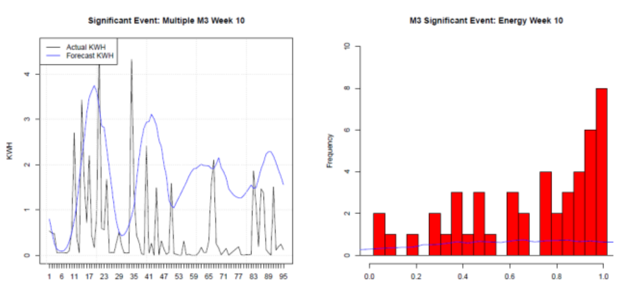

Fig 10: *Example of a forecasting failure due to the occurrence of a significant event correlating to an emotional change in the crew. [3]*

The HI-SEAS research only had a single measure of the crews emotions through the PANAS results available for this study. There is only the emotional ratio score,
and the relative daily change in that ratio score. The emotional score has a direct effect on the neural-modulation and its probability. To implement this computationally, the emotional score was incorporated into existing neurons in the ANN through the modification of the activation function. Within a general neural network, this has the effect of externally altering the weights of the network to enforce a new type of behaviour that is independent and external to training.

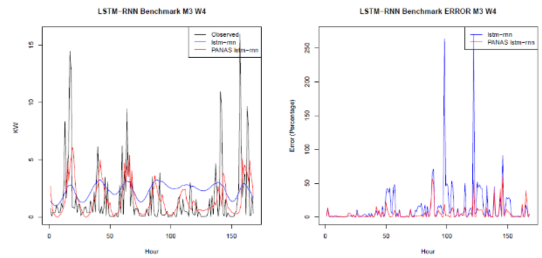

Fig. 11: *Forecast results using Neural Modulated LSTM-RNN method. The Observation data had a STD = 2.69, LSTM-RNN had an RMSE = 2.71, STD = 0.591, STD Error = 0.598, and a Mean Error = 14.13%. The Neural Modulated LSTM-RNN has a STD = 1.43, an RMSE = 2.57, with STD Error = 0.598, and a Mean Error of 5.39% [3]*

Altering the activation functions is done so it reflects the general changes seen in the probability distribution according t the activation function. A threshold value determines if the neuron will fire or not. To alter the probability density, we can alter the shape of the activation function. Here, the value of **k** has been added as the delta PANAS ratio value. Changing this value to be greater will slant the wall of the function in Figure 9, causing a different probability distribution to occur.

4. Improving simulation fidelity

Using the knowledge that the crew energy consumption is influenced by emotions and external events, it should be possible to increase the fidelity of the simulation by making modifications. Taking into account that the crew consumption is heavily influenced by water resupplies, which are not realistic on a real mission, it is proposed to create a virtual water tank that the crew will monitor. Additionally, crews have adapted their behaviours for power consumption based on the available power from the solar panels. Efforts to reduce power consumption during various levels of power productions have been created by the crew. However, this is done without a full knowledge of what the power production is actually like, and knowledge of what appliances will have an overall negative effect on energy resources. Two modifications to the simulation are proposed to improve fidelity.

4.1 Virtual water tank

Data from previous crew has shown a very strong correlation with a change in crew behavior with water resupply. Leading up to the resupply the crew will begin to conserve water usage. Upon water delivery there is a explosion in activity with crew doing laundry and taking showers etc. The water resupply creates an inadvertent out-of-sim situation that should be rectified to increase fidelity of HI-SEAS. Here we propose present future crews with a virtual water tank which they will monitor and use without any indication of resupplies. Meanwhile, mission support will monitor the real water tanks and schedule refills.

The virtual tank will be much smaller, 1.5 times the average daily water usage by the crew. The crew will be told the virtual tank has a water generator with a variable water generating rate. Say 1 gallon per hour which can be varied as required. The level of the real water tanks and the virtual tank are interlinked in a way that the virtual generation rate will slow down as the real water tank levels get lower, ensuring that the crew will not drain the tanks before resupply can arrive. The virtual tank is 50 gallons. The rate is governed by the estimated number of days left in the real tanks, such that it will never drop below one day supply of water. The water in the virtual tank can be calculated in Equations 1, 2, and 3.

$$W_h(l) = l/1000 * W_{ave} \qquad (1)$$

$$W_{rate} = (W_{hours} - 24)/24 \qquad (2)$$

$$V_l(h) = V_{(l-1)} + W_{rate} * h <= 50 \qquad (3)$$

Here, in Eq.1 W_h is the number of water hours given by the current level, l, divided by the average gallons per day used. In Eq.2, the water production rate, W_{rate}, is set by the results of Eq.1 subtracting the number of water hours by one day and dividing by 24-hours. This ensures that the water production rate will slow down as the water level approaches the average of one day waters usages, ensuring that the virtual tank will not have water when the real water tanks are empty. The water hours of the virtual tank are then calculated by Eq.3 by taking the previous virtual tank level, $V_{(l-1)}$, and adding the water production rate over the number of hours.

4.2 Modelling crew individually

The crew schedule and personal activities are uploaded to the simulation on a daily basis. This allows the simulation to adapt for changes in activities. The crew consumption simulation model, system will be implemented in the habitat to log the crew activities. Crew will be able to change and inform the computer of their intensions with ease. The crew simulation model will be combined with methods of monitoring and identifying appliances. The combination of these two models will be the foundation of the forecasting model, which will be the next stage of development.

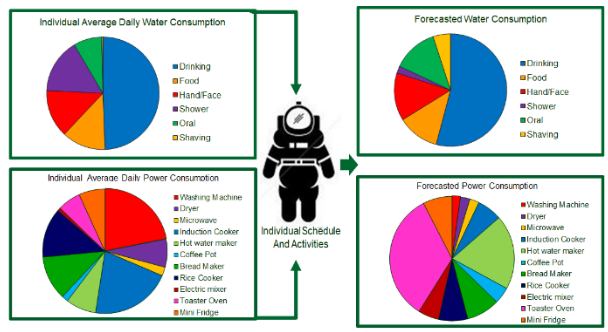

***Fig. 12**: Diagram depicting the variety of activities that crew members can plan ahead of time and the impact the activities will have on resources. [3]*

5. Discussion and conclusion

The approach in this document looks at electrical consumption in the kitchen and incorporates psychological data for the crew as a whole. The next steps will be to incorporate all consumption areas of the habitat, including water. Body sensors can provide data indicating the level of activity of each crew member which can be incorporated into predicting the daily needs of the crew. The neural modulation method is an analogy for emotion by using the PANAS score as neural enhancer/inhibitor with some encouraging results. The neural modulation method does not show that the results are directly simulating emotional response. Once the system has been expanded into the entire habitat, it could be expanded to all of the habitat and planetary colony systems. A large scale intelligent control system could be developed to monitor, guide the crew activities, and forecast resource requirements over the course of a mission.

Acknowledgements

This work is made possible through NASA HFBP grants NNX11AE53G, NNX13AM78G, and NNX15ANO5G, ICS department of the University of Hawaii, ground support from Blue Planet Research Inc., and the HI-SEAS mission support volunteers.

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