Research Article

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Monitoring by Remote Sensing in Isolated Space Analog Missions Reveals Influence of Human Behaviour in Maintenance of Future Life Support Systems

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Abstract

Background: *The utilisation of remote sensing in isolated missions is associated with the safety of the crew and critical instruments on the base. However, there is a paucity of information regarding its application in existing habitats, particularly in the context of the development of future life support systems and non-invasive health monitoring of the crew.*

Objectives: *Select remote sensors and methods of environment and human health monitoring, implement them in the isolated environment and test functionalities regarding critical parameters for future life support systems such as food production vertical farms as well as air and water recycling bioreactors.*

Methods: *We organized seven isolated space analog missions: six missions with 6 person crews and one mission with 4 person crew, (40 people in total aged 20-27 years old), collected environmental and physiological data and visualized results. All presented data are real, not processed by any models.*

Results: *The observation of periodic fluctuations in power consumption, carbon dioxide concentration in the atmosphere, temperature and humidity levels, and water consumption has been demonstrated to correlate with the activity and sleep phases of human behaviour. It has been hypothesised that environmental oscillations evoked by human activity in isolation could facilitate the maintenance of health and the sustainable operation of life support systems, through the synchronisation of interspecies biological clocks.*

Keywords: Space Analog Missions, Isolation, Sensors Network, Biofeedback, Monitoring.

Introduction

The remote sensing of human life is applied in a variety of fields, including healthcare, safety, human-machine interface and survivability [1]. The selection of sensors and monitoring methods is contingent on environmental factors, communication infrastructure, and the specific conditions that necessitate surveillance. The analysis of real-time data offers the potential to gain valuable insights into health trends, resource requirements and patient behaviours, particularly among elderly individuals and those suffering from chronic diseases. The integration of remote monitoring of air pollution with wearable devices and garments facilitates efficient planning, decision-making and resource allocation in extreme situations such as wildfires, floods, mine collapses, earthquakes and life-saving interventions [1-4]. The most advanced remote monitoring systems are associated with the development of human spaceflight and the future colonisation of the Moon and Mars [5]. Technological advancements have currently reached a point where human life can be sustained in orbit. As of February 2024, 644 astronauts, cosmonauts and taikonauts have traversed the Karman line, which is defined as the boundary between space and the atmosphere at an altitude of 100 kilometres above mean sea level. Of these, 610 have been in Earth orbit and orbited the Earth [6]. The current record of 19 people in space at any one time (as of February

2024) on the International Space Station (ISS) demonstrates the potential for commercialisation of space tourism and expansion of human presence in extreme environments [7]. The private sector's growing interest in space tourism has given rise to new technological development needs. These needs are centred on the provision of safe and sustainable living conditions for individuals from diverse cultural and educational backgrounds, who, on average, generally exhibit poorer health compared to those who undertake space missions. In contrast to robotic missions, human missions demand life support systems that engender optimal physical and cognitive conditions for the crew, thereby enabling them to safely transition between Earth and space. The technologies required for this purpose encompass detailed monitoring of the life support system's environment, risk anticipation and mitigation, monitoring of limited resources, biocontamination, and human behaviour (Figure 1) [8].

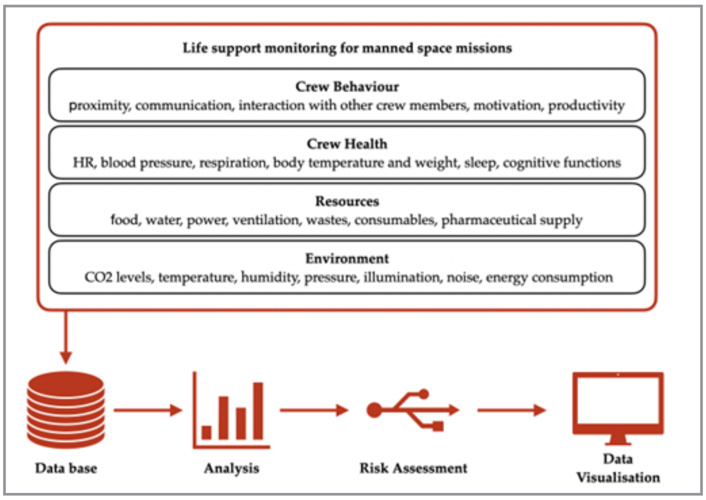

Figure 1

Figure 1: The remote monitoring of human life in space is imperative for ensuring the safety of space missions. In contrast to existing life monitoring systems, databases collect significantly more data at various temporal resolutions. The analysis of parameters is expanded by the available resources and the behaviour of the crew. The necessity for analytical processes to be automated and optimised arises from the limitations in resources aboard the base, including power supply and available hardware. The visualisation of results in a straightforward and accessible manner is paramount for effective communication both on board the station and with the Mission Control Centre.

The global interest in lunar and martian colonisation, in conjunction with the rapid commercialisation of the space sector, has given rise to the development of analogue environments on Earth for the purpose of conducting research and testing new technologies [9-11]. AATC is a facility created in 2018 in Rzepiennik Strzyżewski, the south of Poland [12]. Until April 2025, 95 one - week long standardized analog missions were successfully performed with more than 400 participants, analog astronauts, involved. Large database of multiple cross-linked parameters was established due to implemented multifunctional sensors.

Materials and Methods

AATC Habitat

The Analog Astronaut Training Center - AATC, is a 57m² human research laboratory (habitat) specialising in the conduction of analogue space missions in complete isolation from the external environment. This environment is defined by a lack of sunlight, time reference, privacy, connection with relatives and social media. The habitat is devoid of windows, thus precluding the possibility of determining the time of day by observing the Sun. Furthermore, three airlocks that facilitate communication between the habitat and the external environment are securely sealed throughout the mission and are subject to remote monitoring by the mission control centre in emergency situations. The principal components of the reconstructed analogue conditions in the AATC habitat were as follows:

Chronobiology Chamber

The hypothesis underpinning this initiative was that the perception of time is subject to variation in space, and in 2015, the Advanced Concepts Team in collaboration with the European Space Agency initiated a time architecture project [13, 14]. The experiment involved the induction of time illusions in test subjects through complete isolation from external sunlight and the utilisation of altered time references, such as the mission time starting everyday with hour zero. The Subjective Time Perception web application, accessible at www.stpa.astronaut.center, was utilised to monitor this parameter in volunteers on two occasions daily: in the morning and prior to bedtime.

Fully Controlled, Isolated Environment

Achieving full control and monitoring of the habitat environment was imperative to ensure safety, to facilitate the replication of conditions for human subject studies, and to ensure the efficient operation of the Mission Control Centre. The continuous collection of data was facilitated by the monitoring of habitat conditions, which also enabled the modification and alteration of specific parameters of the base, including temperature, light intensity, power consumption and internet band capacity. The implementation of multiple sensor arrays in each module at varying heights within the habitat ensured comprehensive 3D coverage and monitoring, facilitating enhanced data resolution.

Human-robot Interactions

The symbiotic interdependence between human and machine is one of the objectives of the analog simulations at the AATC. The habitat has been equipped with over 200 electronic devices that are commercially available and that accompany life in isolation. These include fans, bioreactors, air conditioners, heaters, hydroponic systems, an energy bike, a treadmill, mobile instrumentation, medical instruments, a vacuum chamber, 3D printers, microscopes, incubators, sterilisers, a microwave, an induction kitchen, an oven, random positioning machines, computers, small rovers and multiple sensors. The daily interaction with a wide range of electronic devices was intended to improve familiarity with the equipment. In addition, an intelligent ecological power saving strategy was employed to reduce the risk of short circuits. The utilisation of equipment was subject to variation, with certain components operating continuously throughout the mission, while others were employed for more limited periods. The Mission Control Center (MCC) facilitated the utilisation of electronic devices by proposing charging times for various sensors and smartwatches during the mission.

Limited Resources

The available living space, mobility, privacy, communication, power, clothing, food and water were all limited within the habitat. The crew communicated solely in written form with the MCC using a Signal communicator and an internal mission drive. Any contact with the outside world was kept to an absolute minimum. Any communication with the outside world was reported in a dedicated reporting system on the mission's internal drive. Electricity restrictions were based on data from solar power plants in the Egyptian desert and corresponded to 8 kWh per day per crew member [15]. Furthermore, analog astronauts were permitted a maximum of 3 kg of personal belongings, inclusive of clothing. The volume of private space in the habitat was 3 cubic metres per person in the sleeping module. The rest of living space was shared by the whole crew, growing plants and other experimental organisms. Crews were permitted to select one of three available diets: coeliac, vegetarian, or a control diet (which included meat). The menu was very strict and clearly determined based on specific shelf products. Water was allocated a maximum of 3 litres per person per day, in 1.5-litre PET bottles, and 5 litres of technical water per person per day, in 5-litre PET bottles. The water was stored in the same habitable space as the crew, which further restricted the living space.

Altered Atmosphere

Despite the absence of pressurization within the habitat, the atmospheric conditions therein deviated considerably from those of the natural environment. The principal driving parameter was CO_2, which was approximately four times higher than nominal values on Earth (2000 ppm). During emergency simulation trials, CO_2 levels escalated to 5000 ppm (the sensor's saturation value).

Mission Schedule

Mission plans were meticulously prepared in advance of the mission, ensuring that each activity was methodically planned. The overarching objective was to ensure the sustained motivation, productivity, focus and task orientation of the participants.

Emergency Simulations

The AATC Habitat is distinguished from analogous facilities worldwide by virtue of its capacity to simulate high-fidelity emergency scenarios in accordance with emergency procedures provided to the crew in advance during the pre-training phase. The range of simulations conducted included: micrometeor shower and impact, loss of communications, power failure, coolant leak, uncontrolled chemical reaction (fire) and rapid uncontrolled chemical reaction (explosion). These contingencies were typically simulated towards the conclusion of the mission, specifically on Day 6. It should be noted that certain contingencies were unplanned and related to real events; for example, coronal mass ejection simulations were synchronised with real-time space weather and solar activity, such as when an X-type solar flare was detected [46]. Furthermore, micrometeorite showers were synchronised with hail or rain outside the habitat, which was recorded by an external weather station. Despite the simulated emergencies, several real emergencies occurred inside the habitat, such as loss of communication with Starlink constellations, malfunction of critical equipment, power outages and depletion of limited resources such as technical water.

Sensors and Data Visualization

The controllable light in the habitat was characterised by spectral ranges including UVA, UVB, visual 5000K and IR. The crew had the capability to modify the lighting environment within each module as required. The ambient noise levels in the research station exhibited fluctuations around 50-60 dB, which is analogous to the International Space Station. The primary sources of noise were identified as the convection fans. The location and distribution of both fans and ventilation ducts have been determined based on CO_2 levels and diffusion monitored by a suite of atmospheric sensors (Figure 2).

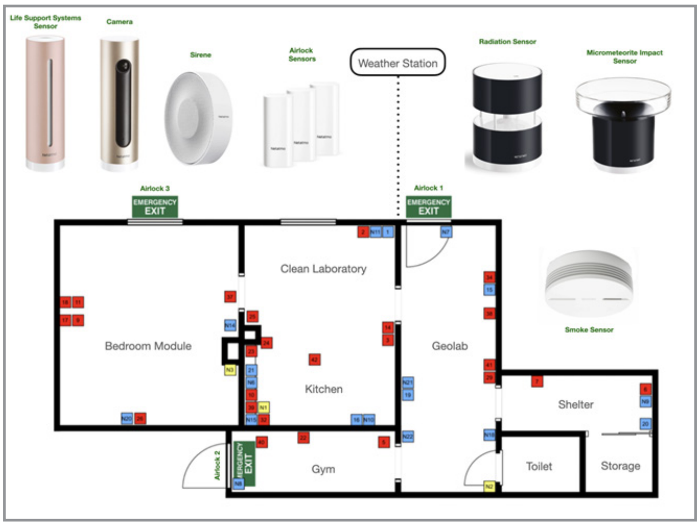

Figure 2

Figure 2: The implementation of numbered sensors within the AATC habitat has been undertaken to facilitate continuous and sustainable monitoring of the base. Cameras are indicated in yellow. Multi-sensor power switches are represented by the colour red. Single-purpose sensors are represented by the colour blue. Finally, the figure illustrates the deployment of additional Netatmo commercial sensors for isolated analog missions.

Parameters monitored in AATC habitat in real-time:
- Air Quality Index (5-grade scale AQI)
- Temperature (Celsius)
- Relative humidity (%)
- Carbon Dioxide level (ppm)
- UV Light intensity (11-grade scale)
- Carbon Monoxide level (ppm)
- Noise (dB)
- Atmospheric pressure (hPa)
- Motion detection
- Face recognition
- Light intensity - illuminance levels (Lux) - illumination inside habitat modules
- Door and window state (open/close)
- Eclectic energy current (Amper)
- Electric energy power consumption (Watt)
- Electric energy state (on/off)
- Electric energy usage (kW/h)
- Electric energy voltage (Volt)
- Light color (RGB)
- Wind gust direction and strength (degrees, meters per second) - outside the habitat
- Temperature, pressure, relative humidity (Celsius, hPa, %) - outside the habitat
- Precipitation type and intensity (type, mm) - outside the habitat
- Network speed and latency (bytes per second, seconds)
- Battery levels (V, %)
- Water level / flood / leakage detecting (mm)
- Main computer I/O load, CPU load, memory usage, network parameter (various metrics)

Visualisations of environmental parameters in the habitat were accessible to both the crew and the MCC. Furthermore, the MCC was granted the ability to manipulate these visualisations during emergency simulations, including decompression (loss of air) and blackouts. The crew's activities were meticulously documented in the form of daily reports, as well as activity reports from the Aeotec/Netatmo sensors mounted in the habitat and the telemedical devices worn by the crew.

The AATC habitat had been equipped with 143 commercially available sensors for real-time monitoring and control of environmental conditions within the laboratory. The sensor data was directed towards the InfluxDB time series database, and subsequently synchronised with a private cloud infrastructure. The integration of sensor data with an internal reporting and monitoring system enabled the creation of visual representations for the benefit of both MCC and analogue astronauts. This visualisation was facilitated by an open-source version of Grafana software (see Figure 3). The implementation of a colour scale was undertaken to facilitate data visualisation, with the scale demarcating nominal values and deviations from standard parameters. The Habitat sensors utilised two primary network types: Z-Wave protocol (Aeotec sensors) and regular Wi-Fi (Netatmo devices). Furthermore, certain sensors possessed the additional functionality of acting as actuators, thereby enabling the environment to be remotely controlled and operated by actuating lighting systems and appliances.

Figure 3

Figure 3: A customary perspective of the mission's data, accessible by analog astronauts and the Mission Control Centre. The integration of sensor data with an internal reporting and monitoring system, as well as the visualisation of results, was facilitated by an open-source version of Grafana software. The colour coding employed for environmental parameters enabled the determination of safety levels, with green denoting nominal values, blue indicating values below nominal, and yellow, orange, and red denoting values above nominal.

Results

Monitoring of the Environment

Aeotec sensors were utilised to assess technical characteristics such as power consumption and luminosity, while Netatmo sensors were employed to evaluate environmental factors including temperature, relative humidity, CO and CO_2 levels, noise, weather and barometric pressure. In order to create a three-dimensional distribution and visualisation, all sensors monitoring environmental parameters were placed at two heights (100 cm and 200 cm above the floor). The third additional level (0 cm

= ground, 50 cm and 150 cm) was currently being installed to create a dense network with a resolution of 50 cm (0, 50, 100, 150, 200 cm). Each sensor was capable of monitoring several different parameters per minute, generating a significant amount of data about the habitat environment (Figure 4). Oscillations between activity and rest phases of human behavior were not stable but increased toward the end of the mission from 150 Lx to 280 Lx. Day 2 of the mission was simulating a blackout situation in the habitat and usage of emergency power saving lighting system ranging 100 Lx.

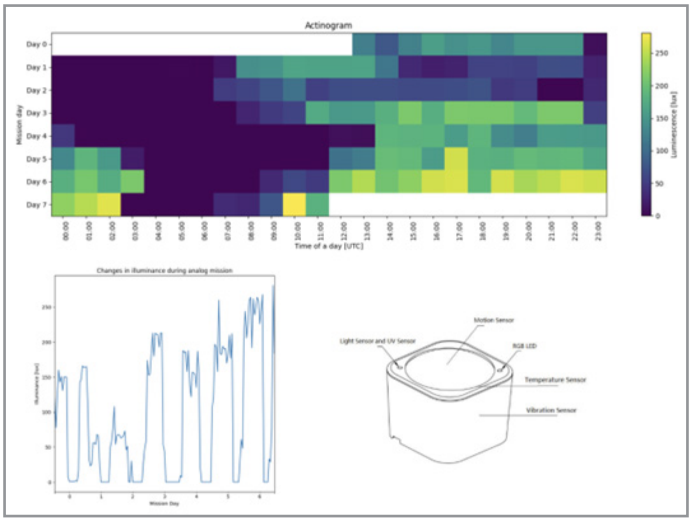

Figure 4

Figure 4: The actogram (up) and the diagram (down left) illustrate the activity of the analog astronauts obtained during a seven-day isolated mission with the Aeotec sensors (down right). It is a noteworthy and prevalent phenomenon that the illumination levels increased from the middle to the end of the mission. This is associated with enhanced team bonding and elevated crew motivation.

Monitoring of Crew

In order to collect relevant data, volunteers aged between 20 and 27 years were isolated for a period of one week in a habitat described in Section 2.1. The confines of the habitat ensured meticulous observation of human behaviour, with a particular focus on adaptation mechanisms and survival strategies. The knowledge gained could be used to optimize the design of highly tolerant life support systems in extreme environments, such as isolated human bases in polar regions, underwater and in developing technologies for space tourism. The life support systems considered in this work were identified as the critical factors for survival in isolation, i.e. healthy air, access to food and water, electricity, communication and waste management. The activity and sleep cycles of analog astronauts were meticulously recorded by a range of devices and applications, including blood pressure monitors, pulse oximeters, bioimpedance devices (Tanita scale), thermometers, mobile applications for cognitive analysis, Subjective Time Perception Test (STP), MiFit bands, Estimote proximity sensors (Estimote) and Movisens sensors [17, 18]. The collected measurements delivered daily screening of physiological parameters for each crew member, providing a unique insight into the individual health status and its dynamics during the seven days of adaptation to the extreme conditions. Figure 5 presents a sample report obtained for each participant of the analog mission.

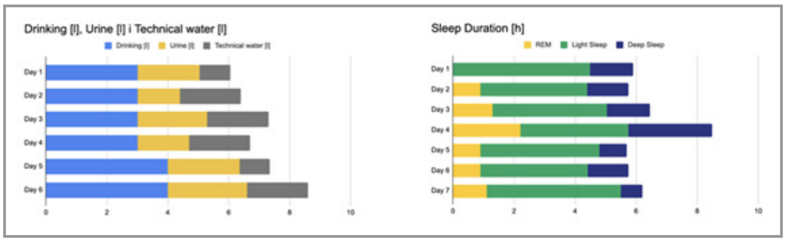

Figure 5

Figure 5: The utilisation of Moviesens sensor data for the purpose of visualising the data for a single analogue astronaut. The data set includes metrics such as the different types of activities undertaken, calories burned, step counts, metabolic levels, heart rate variations, heart rate variability, water balance and sleep quality dynamics. These metrics collectively reflect the level of adaptation to the simulated conditions in the habitat. The report is generated automatically using Movisens algorithms for all days of the mission. It is important to note that the maximum number of days for which data can be recorded is nine, and that each report is generated individually.

Monitoring of Adaptation to the Extreme Environment

Each day of the mission yielded data that facilitated the detection and analysis of adaptive changes in the behaviour of the crew. As early as the second day of the analog mission, the crew began to adapt to the novel environmental conditions. The participants adhered to the prescribed schedule without deviation, experienced adequate sleep and demonstrated proficiency in their designated tasks. The environmental parameters that remained stable included electromagnetic fields and noise, while parameters such as temperature, humidity and CO2 levels exhibited oscillatory trends. These fluctuations were found to be contingent on human activity, thereby rendering them a subject of particular interest in determining the minimal requirements for the future development of life support systems. It was observed that individuals exhibited distinct patterns in the production of carbon dioxide, the generation of waste, and the consumption of water, which varied according to factors such as time and individual differences. As demonstrated in Figure 6, the oscillating parameters are evident during isolated analog missions.

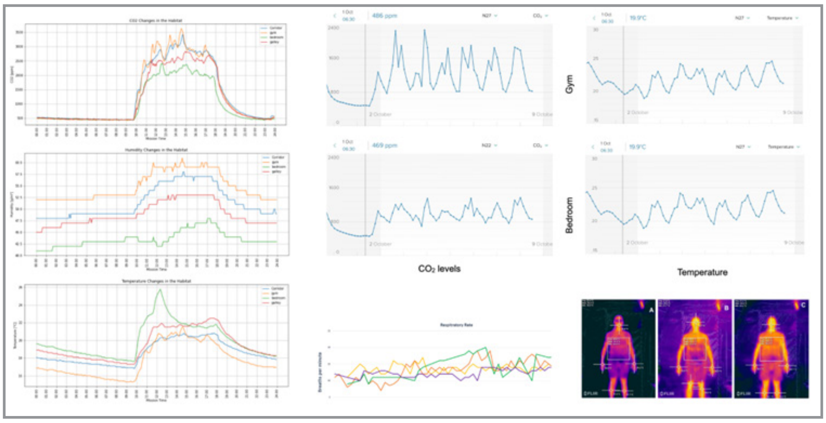

Figure 6

Figure 6: The oscillations of environmental parameters in isolated habitats are indicative of human activity. The graphs on the left illustrate the alterations in parameters in various habitat locations following the entry of a group of six analog astronauts for a duration of nine hours. It is evident from the graphs that parameters such as CO2 undergo a swift decline following the absence of human activity. A similar decline has been observed during nocturnal periods, particularly during sleep (as depicted in the graphs on the right, which utilise data from six days in the gym and bedroom modules). The thermal cameras (as shown in the exercise module) demonstrate that the temperature generated by the human body affects the habitat for longer periods and correlates with increased respiration. The respiratory rate graph reveals the respiration of four analog astronauts during the seven-day isolated mission. It is evident that humidity exerts the most significant inertia, underscoring the necessity for the development of future systems capable of removing water from the air.

Temperatures in excess of 32°C, carbon dioxide levels in excess of 2000 ppm, and humidity levels in excess of 70% have been demonstrated to result in a significant decline in mission morale and crew efficiency. Conversely, low temperatures, defined as those below 20°C, have been observed to have no adverse effects on humans in isolation. When comparing crews that have been kept in exactly the same conditions (environment, food, schedule), several parameters related to the human factor and crew dynamics have been found to fluctuate. These include motivation to physical training in the gym, water consumption and electricity generation on the energy bike. The data collected during six such missions is presented in Table 1.

Table 1: Parameters related with human factors in standardized analog missions in one week isolation expeditions 27, 28, 29, 36, 40 and 42.

Mission	Exp. 27	Exp. 28	Exp. 29	Exp. 36	Exp. 40	Exp. 42
Days	7	7	7	7	7	6
Crew	6	6	6	6	6	6
Water drunk [l]	59.4	109.55	97.47	57.55	69.6	57.7
Urine [l]	57.295	87.6	70.16	37.52	59.07	51.98
Cycling [km]	526.62	285.38	545.36	164.83	293	88
Running [km]	116.6	126.78	144.63	68.96	53.18	52.4
Avg. Sleep [h]	7	6	6.5	6.5	6.4	5.4

Monitoring of Limited Resources and Limited Space

The behaviour of the crew is significantly influenced by limited resources such as water, electricity and internet bandwidth. At the commencement of the mission, there is a propensity to accumulate resources; however, as the mission progresses, there is a shift towards a more relaxed attitude, as illustrated in Figure 7. Proximity tests with Estimote sensors have been shown to visualise crew dynamics and the distribution of analog astronauts within the base. The sensors can be programmed to measure various parameters and incorporate gamification into the process. The data obtained can be useful for non-invasive monitoring of crew mood and motivation. It is imperative to acknowledge the impact of these parameters on the environment within the habitat when formulating monitoring systems. An illustrative example is presented in Figure 8.

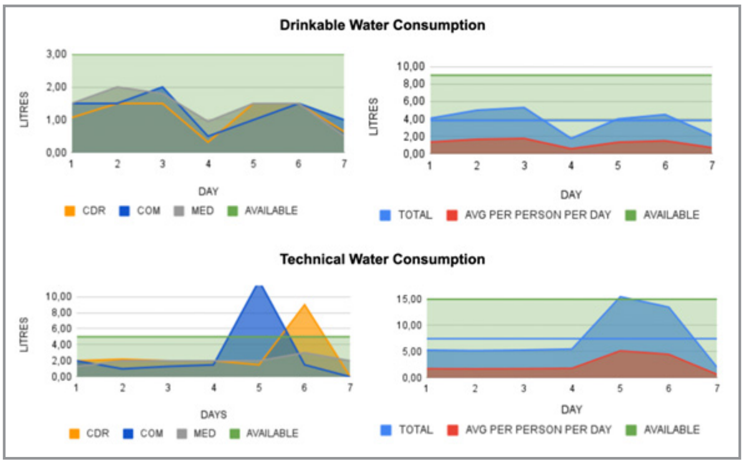

Figure 7: The data from Crew 62-Asteria provides an illustration of water consumption during a seven-day isolated analog mission for three analog astronauts (left). The data is also presented as a mean value per person per day (right). This pattern has been observed to occur in both large and small crews.

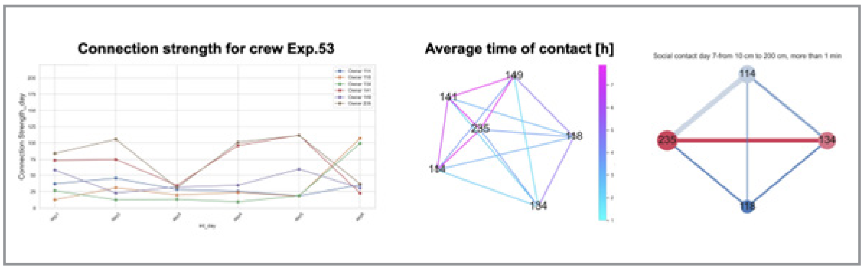

Figure 8: The following example illustrates data obtained from Estimote proximity sensors. The use of this hardware facilitates the straightforward measurement of levels of social contact. However, it is imperative to note that the interpretation of the data must be validated through additional monitoring from cameras installed within the habitat, as well as through supportive surveys from each crew member.

Summary

This article presented a case study of the implementation of commercially available sensors and monitoring systems in order to cover four components of life support monitoring for manned space missions: environment, resources, crew health and crew behaviour. Figure 9 provides a synopsis of the sensors employed in the system's design. It is acknowledged that there are numerous factors that require monitoring to obtain a comprehensive understanding of life in isolation, thereby ensuring the creation of a safe and sustainable environment [19-21].

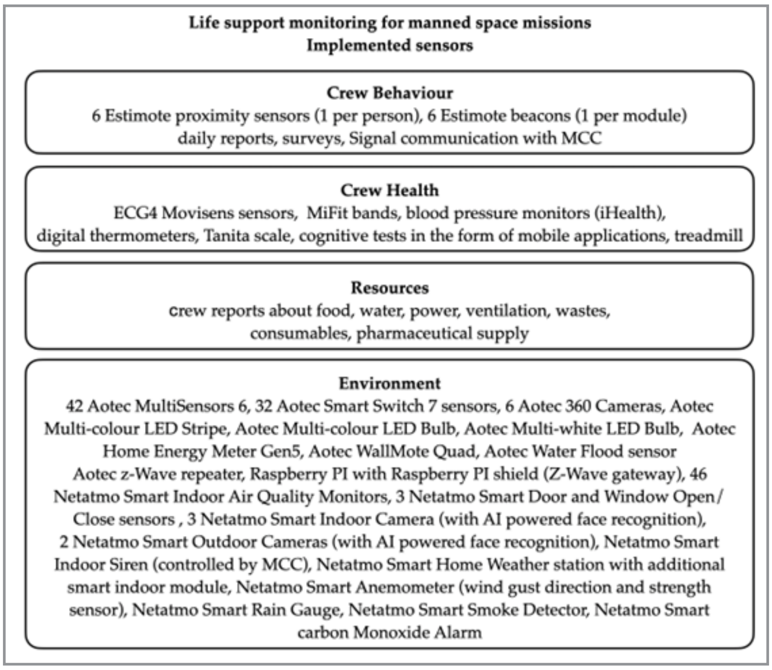

Figure 9: The implementation of sensors within the life support monitoring system for analog missions in the AATC habitat has been successfully executed. The sensors represent a variety of types and communication protocols. Consequently, the data are initially stored independently in the database, subsequently analysed at a metalevel, and visualised using Grafana software.

Crew activity within the habitat has been shown to reflect significant impact on environmental oscillations, which bear a striking resemblance to those observed in nature (high levels during the active phase, low levels during the resting phase). In the case of six-person crews, the amplitudes of these oscillations were found to be 1400 ppm of CO_2 levels, 4°C in temperature and 5% increased humidity due to respiration. This knowledge opens up the possibility of manipulating environmental factors and life support systems by controlling the activity levels of the crew. This could be achieved through the implementation of a specially adapted mission schedule, shift work and the provision of rapid feedback to anticipate maxima.The question that arises is whether it is preferable to maintain oscillations in a manner similar to natural phenomena occurring in the natural environment or to flatten oscillations in order to sustain control over recovery processes in real time.

Despite the existence of numerous solutions for the monitoring of environmental data, there is still a requirement for the development of methods for the monitoring of limited resources, crew health and behaviour. In particular, limited resources should be distributed in labelled portions capable of being detected by a counting system. The application of telemedical devices and garments for non-invasive monitoring could be expanded to collect data about circadian rhythms, metabolic activity, cortisol levels, glucose, vitamin D, serotonin and digestion [22]. The automatic monitoring of mood and behaviour, independent from subjective surveys and daily reports completed by the crew, may also be beneficial. The implementation of intelligent monitoring could contribute to the anticipation of potential conflicts and the promotion of the crew's wellbeing [23].

The safety of life in isolation necessitates the implementation of advanced monitoring technologies, at least until the point at which processes can be automated (machines) or trained (humans). The development of commercial launchers and space stations must take into account the results obtained in analogue environments, such as Earth-based habitats [24]. The observation of human adaptations and behaviours in a limited resource environment has the potential to yield novel solutions for the safety of future space exploration. Assuming that future life support systems in isolated spaces will include microorganisms to recycle air, water and waste in bioreactors, it would be easier to control them by tuning the environmental parameters. Oscillations of CO_2 content, water consumption, temperature and humidity levels related with human activity could support health growth of food and efficiency of bioreactors, because most living organisms evolved biological clocks driving their activity and resting phases [25-36]. In the future authors plan to develop a dedicated remote control system to monitor circadian rhythms of multiple organisms in the isolated environment. Synch oscillations could be a marker of health and sustainability of the isolated system.

Author's Contributions

AMK and MH designed the habitat, selected and applied sensors and organized analog missions. AMK wrote the main part of the manuscript including the presented ideas, figures and tables. MH analyzed the data presented in this paper, verified the text and the correctness of the described methods.

Competing Interests

no competing interests declared.

Funding

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Statement of Ethics Approval

The study was approved by the Bioethical Committee at Medical University in Poznań, approval number: 685/17. The research was carried out following the guidelines of the ethics committee listed in the ethics statement.

Informed Consent Statement and Consent to Publish
Informed consent was obtained from all subjects involved in the study prior to participation. No subjects below 20 years old were examined in this study.

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