PIUME™: In space as on earth, on earth as in space

G. Cecchini[1], C. Lobascio[2]
Thales Alenia Space, Turin, TO, 10146, Italy

P. Vidal-Peiró [3]
Universitat Politècnica de Catalunya, Terrassa, Barcelona, 08222, Spain

When humans live and work in extreme conditions, vital resources must be managed with extreme care. The International Space Station (ISS) today, and the Moon and Mars surface outposts of tomorrow, provide an inspiring approach for new solutions on earth. PIUME™ (Portable Independent Utilities and Modules for Extreme conditions) stems from industrial experience and heritage in human spaceflight systems and technologies now flying on the ISS, including pressurized habitats, systems, and utilities necessary to sustain life. PIUME™ intends to be the next-generation product line for habitability and affordable management of all necessary resources to accommodate living in remote areas and inhospitable environments. Concepts and solutions currently utilized for in-space human living inspire terrestrial applications, and vice versa. This paper introduces the key features of PIUME™ including its concept, the preliminary design of its functional building blocks, an analysis of the functional analogies between Space and terrestrial applications, and its applicability in different contexts on ground. PIUME™, now in its design phase, aims at providing life support capabilities in extreme conditions through a multi-functional system based on six (6) primary building blocks ("utilities"): water management and recycling, thermal control, air control and regeneration, power management and distribution, telecommunications, and system monitoring. These functional blocks are made into modules with standard size, shape, and interfaces, conceived for easy integration and fast deployment. Selected functional blocks would be combined into a single integrated system responding to the specific user needs and environmental conditions, to guarantee autonomy and reusability. PIUME™, with its integrated product approach, aims at offering an innovative habitability solution for terrestrial markets with a focus on safety, reliability, connectivity and sustainability, via the adoption of renewable energy, and water recycling. Thanks to its scalability, PIUME™ not only suits applications with size similar to the equivalent space exploration concepts but also features a growing capability towards applications on larger platforms. Terrestrial applications currently under study include Oil and Gas exploration and prospecting campaigns, Maritime and Mining activities, and Social Emergency events, as well as other potential use cases such as space analogue missions, sub-sea exploration, or scientific research stations in extreme climates. In return, the authors believe that the deployment of PIUME™ in a terrestrial context will generate returns for developing habitats, integrated solutions and technologies for managing resources in space exploration applications, particularly for future planetary surface missions.

[1] System Engineer, PIUME™ Project, Strada Antica di Collegno 253.

[2] Innovation Lead, Exploration & Science, Strada Antica di Collegno 253.

[3] Aerospace Engineering Graduate Student, Department of Project and Construction Engineering, C\ de Colom 11.

Nomenclature

ATV	=	Automatic Transfer Vehicle
COTS	=	Commercial Off-The-Shelf
HVAC	=	Heating, Ventilation, and Air Conditioning
ISS	=	International Space Station
MPLM	=	Multi-Purpose Logistic Module
MVP	=	Minimum Viable Product
NASA	=	National Aeronautics and Space Administration
PCM	=	Pressurized Cargo Modules
PIUME™	=	Portable Independent Utilities and Modules for Extreme Conditions
PoC	=	Proof of Concept
R&D	=	Research and Development
SHEE	=	Self-deployable Habitat for Extreme Environments
TAS	=	Thales Alenia Space
TASI	=	Thales Alenia Space in Italia
TRL	=	Technology Readiness Level
USA	=	United States of America
USSR	=	Union of Soviet Socialist Republics
VR	=	Virtual Reality
WHO	=	World Health Organization

I. Introduction

Since the beginning of the space era, one of the biggest challenges for humans has been to survive in the harsh environment outside of the atmosphere. As a result of many years of efforts in the development of orbital habitats such as Skylab (USA), Mir (USSR/Russia) and the currently operative International Space Station, humans have reached the milestone of being able to sustain life in low earth orbits for long periods of time[1]. Such efforts have brought an incredible amount of leading space technology and knowledge, with the potential to be transferred to earth applications.

Planet Earth presents regions that share significant similarities with the space and planetary environment: the Arctic and the Antarctic, deserts such as the Sahara or the Gobi, or the depths of our oceans are well-known examples. These regions have been historically used as testbeds for many demonstrators and space analogues for microgravity, Moon and Mars missions. Examples include the Mars Society Mars Desert Research Station[2] in the Utah desert, the Flashline Mars Arctic Research Station[3] in the Canadian tundra, or the NASA Extreme Environment Mission Operations[4] located on the ocean floor next to the coast of Florida, among many others.

Moreover, throughout history, humans have explored, settled, and eventually exploited these extreme regions, learning how to sustain life in those conditions. The best examples are polar regions, with research stations such as the Amundsen-Scott Station[5], the Halley VI station[5, 6], or the Neumayer III station[7, 8].

Previous attempts to transfer habitability technologies from space to terrestrial applications range from the Grumman Corporation's Integrated Household System from the 1970s, having the goal of transferring technologies used in the life support systems of the Apollo Lunar Module to Earth homes[9]; to the innovative Self-deployable Habitat for Extreme Environments (SHEE)[10] that not only aims to fulfil the needs of a space analogue, but also aims to have various applications in terrestrial extreme environments.

The PIUME™ (Portable Independent Utilities and Modules for Extreme conditions) project, the topic of this paper, focuses on dealing with the challenges of life support in extreme environments. The driving idea is that humans on the ISS, as in any other extreme condition on Earth, have basic needs to be satisfied. Like in space, where each subsystem provides functions to support human life, on Earth each function can be allocated to a functional block, designed to support it. Each functional block, that we also name "utility", is designed for integration with in-situ systems, exploiting available local resources.

PIUME™ intends to be the next generation product line for habitability and affordable management of all necessary resources to accommodate living in remote areas and inhospitable environments.

This paper introduces the key features of PIUME™ including its concept, the preliminary design of its utilities, an analysis of the functional analogies between Space and terrestrial applications, and its applicability in different Earth markets.

II. From Space to Earth

PIUME™ stems from the industrial experience and heritage of Thales Alenia Space on about 40% of the habitable volume of the International Space Station (ISS).

On the ISS, as for every human system designed for space exploration, there is the necessity to satisfy vital needs, providing the crew with physical and psychological support in line with international standards.

Figure II-1 shows the key critical functions and typical accommodations and associated TRLs for the space application, that Thales Alenia Space has designed and integrated into several different habitats launched to the ISS, including the MPLM, Nodes, ATV and Cygnus PCM.

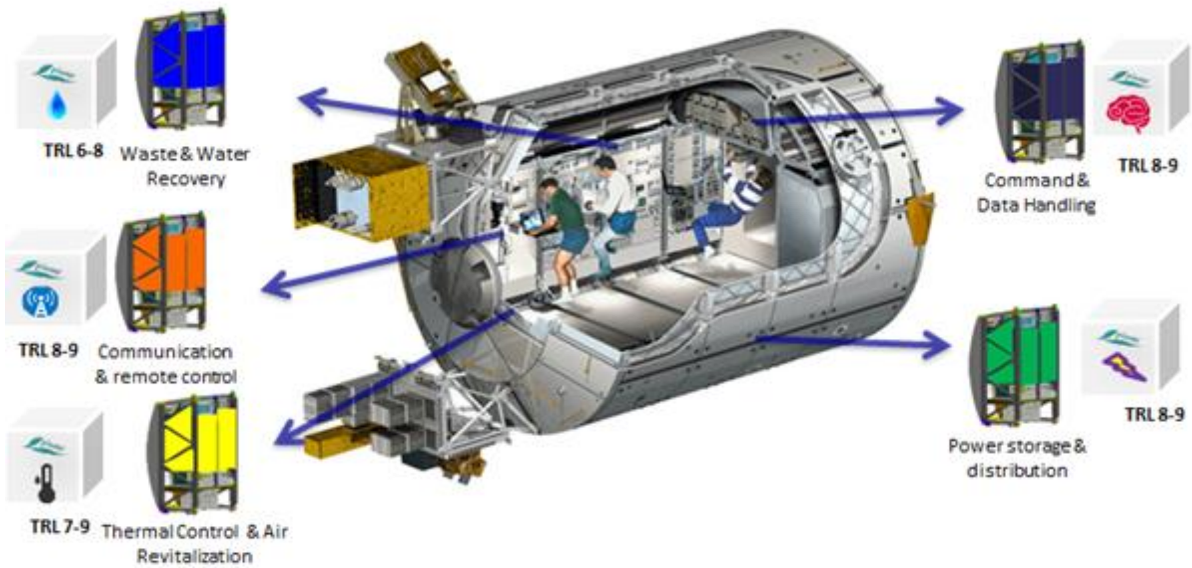

Figure II-1: Key functions supporting human life in space habitats

The solution and methodology that we propose to transfer from Space to Earth refer to the use of interconnected systems, providing primary resources through standardized blocks, which on the ISS are implemented via the standard "rack" concept, and are developed at TRL9. These blocks are modular, with standard size, shape and interfaces, designed for easy integration and portability. Different blocks can be combined into a single integrated and tailored system according to the specific user needs.

The PIUME™ team has identified a set of functional blocks, answering the basic question: "how could we provide primary services to people living and working in extreme or critical conditions?". On Earth as in space, human habitats need to implement:

- Water management (including regeneration, under specific conditions),
- Thermal control,
- Air management (including regeneration, under specific conditions),
- Power management and distribution,
- Telecommunications/connectivity,
- System monitoring and data processing.

The transfer of such a modular approach to ground habitats in extreme conditions enables the provision of a fully integrated turn-key solution for terrestrial markets, where we believe it may represent a differentiator compared to existing ad-hoc solutions.

In turn, the technology transfer from ground to space could push towards innovative COTS-based solutions for space exploration systems, generating benefits in terms of more agile and affordable approaches, in line with a rapidly evolving commercial space market.

III. PIUME™ Concept

When humans need to live and work in extreme conditions, space exploration can inspire a sustainable approach: every vital resource must be managed with extreme care. PIUME™ provides a transportable and scalable solution for resource management with a plug & play approach, based on six (6) primary functional blocks, or "utilities" for:

- Water Processing,
- Temperature Control,
- Air Revitalization and Control,
- Power Distribution, Storage, and Conditioning,
- Communications,
- Command, Data and Control.

Each functional block is standardized in size, shape, and interfaces, making it possible to combine different modules into a single integrated and tailored system according to the specific user needs. In addition, in order to have a solution independent from the external infrastructure, the utilities are designed for integration with in-situ energy production systems exploiting renewable resources and others (e.g. water extraction systems, greenhouses for food production, …).

The PIUME™ mission statement is in fact: "*To develop utilities which provide basic services to de-located workers in harsh environments within an integrated system.*"

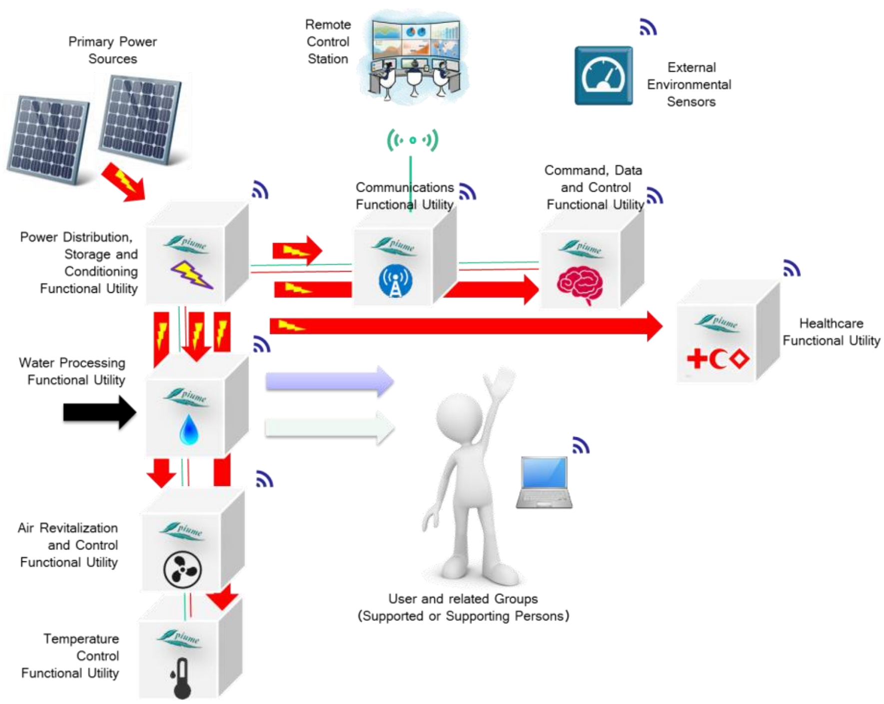

Figure III-1: PIUME™ functional blocks ("utilities") and interfacing elements ("plug-ins")

The initial concept of functional blocks ("utilities") has been complemented by considering how such blocks may be provided in habitats and connected with existing systems. For this reason, the concepts of Plugins, Habitats and Network have been defined, as described in the following table.

Components of the PIUME™ Systems	Definition	Examples	Application
piume Utility	A configurable hi-tech integrated system performing a specific function, with defined standard interfaces	The PIUME™ functional utilities	Transversal to all the applications
piume Plugin	Existing application-specific device which can be integrated with a PIUME™ Functional Utility to enhance its capabilities (easy integration)	Solar Panels, External Units for Temperature Control, Drones, Env. Sensors, 3D Printing devices, Storages, Waste management	Application specific
piume Habitat	An integrated system comprising external shell and needed piping, electrical and data networks, with utilities and plugins	Containers, Tents, Vans, Shelters, Pressurized Modules, Inflatable modules	Domain Specific
piume Network	Integrated networks of habitats, telecommunication systems and remote-control stations	Emergency Camps, Moon base, Space Station	Mission Specific

Table III-1: PIUME™ - definitions of key constitutive elements.

As in a "game of Chinese boxes", PIUME™ solutions range:

- from the single self-standing utility (satisfying a given, specific primary need);
- to the integration of multiple utilities within a shelter and interfacing plug-ins to obtain a habitat;
- to the integration and simultaneous operations of several habitats, connected into a network.

The customer can select, mix and match what is needed from the PIUME™ catalogue, sizing and tailoring the solution according to the number of users to be served and the specific environmental constraints.

IV. PIUME™'s Roadmap

The business development process identified for PIUME™ is based on different steps. A preliminary step is represented by a Proof of Concept (PoC), to perform first test activities in an in-situ application in order to apply, deploy, and demonstrate the basic design solution.

The second step entails the industrialization process set-up and Minimum Viable Product (MVP) sale on the markets identified during PIUME™ incubation phase, with a value proposition based on reliability, safety, modularity, and scalability.

The next evolution of PIUME™ will be based on feedback and data collection on utilities. This will enable to further understand operative constraints, perform trend analyses, and carry out failure prediction studies. The ultimate aim is to set up a: build, measure, learn loop which will eventually lead to product refinement, to bring PIUME™ to a wider Earth market.

When consolidating the system, there will be the possibility to include in PIUME™'s catalogue additional utilities or functional sub-blocks, which are already under investigation, such as:

- MediPod: a remote crew health check system;
- Warmkit: a urine recycling system, for those applications where we determine that a highly closed loop for water is convenient;
- Biowyse: a system for the prevention, monitoring and control of biocontamination risk in water and wet systems.

V. Functional Analysis

An analysis between Earth and Space characteristics and needs has been performed in order to assess the functional cross-over capability of each space system (or PIUME™ utility) and to better understand the functional overlaps existing between space and terrestrial extreme environments.

Initially, a comparison between the characteristics of the space environment and those of Earth extreme environments interesting for PIUME™ has been carried out to study the main differences and similarities between these domains.

	Space (ISS)	**Artic/ Tundra**	**Desert**	**Subaquatic**	**Sub-terranean**	**Social Emergency**
Crew Size	Small crews of 2-6	From small teams of 6 to bases of 50	From small teams of 6 to bases of 50	Small crews of 2-6	Teams up to 20 people	From teams of 10 to camps of 5000
Activity Areas	Exploration, Research	Exploration, Research, Defence, Tourism	Exploration, Research, Defence, Tourism	Exploration, Research, Tourism	Mining, Exploration, Tourism	Search and Rescue, Emergency Relief
Temperature	From -157ºC to +121 ºC	From -80ºC to +20 ºC	From -15ºC to +45 ºC	From +4ºC to +20 ºC	From 10ºC to 55 ºC	From -15ºC to +40ºC
Climate	Not suitable for human life	Strong winds, low humidity	Strong winds, low humidity, high temp. variation	Currents, reduced visibility	High humidity, lack of fresh air	Variable depending on geography
Degree of accessibility	Very low	Very low	Low	Low	Low	Medium (Location dependant)
Degree of isolation	Very high	Very high	High	Very high	High	Medium (Location dependant)
Resource availability	Very low	Low	Low	Low	Low	Medium (Location dependant)
Deployment Speed	Low	Low	Low	Low	Low	High
Other relevant characteristics	Microgravity, Vacuum	Polar days and nights	Sandstorms	High pressures	Build-up of hazardous gasses	Characteristics dependant on geography

Table IV-1: Comparison of characteristics between space and terrestrial extreme environments

As seen in Table V-1, many similarities exist between space and terrestrial domains: extreme temperatures and climates that make human life impossible or very difficult, very low levels of accessibility, high degree of isolation, and limited access to external resources. Among these, the similarities of special interest to PIUME™ are the degree of isolation and accessibility, which are highly related to the resupply difficulty/cost, a crucial metric for Earth markets, and the type of climate, which has a direct impact on the specific requirements of the habitat and its utilities.

On the other hand, the most significant differences encountered between the two domains are the microgravity environment and the vacuum which are peculiar of space. These characteristics clearly make space habitability constraints much more stringent than those for terrestrial environments. This arises the question of up to what extent there can be synergies between such space and earth systems. Table V-2 and the subsequent analysis attempts to provide an answer to this question.

Environments	Space	Artic/ Tundra	Desert	Subaquatic	Sub-terranean	Social Emergency
Water management and recycling						
Wastewater collection	E	E	E	E	E	E
Wastewater recycling	E	A	A	A	A	A
Potable and wastewater storage	E	E	E	E	E	E
Distribution	E	E	E	E	E	E
Power management and distribution						
Independent power generation	E	A	A	U	A	U
Conditioning & Distribution	E	E	E	E	E	E
Storage	E	A	A	A	A	A
Communications & Monitoring						
Automatic systems monitoring	E	A	A	A	A	A
Telemetry	E	A	A	A	A	A
Tele-command	E	A	A	A	A	U
Air revitalization						
Atmospheric Collection	N	E	E	N	E	E
Active Revitalization	E	A	A	A	A	A
Distribution	E	E	E	E	E	E
Storage	E	N	N	E	N	A
Thermal control						
Detect thermal conditions	E	E	E	E	E	E
Respond actively	E	E	E	A	E	A
Respond passively	E	E	E	E	E	E
Use control logic	E	U	U	U	U	U

Table IV-2: Functional comparison between space and Earth extreme environments

For each Earth environment identified as interesting for the PIUME™ concept, an evaluation of the different functions to be provided has been performed with the intention to provide the following classification:

- Essential (E): if the function is essential to support life in the habitat;
- Advantageous (A): if the function provides a clear advantage to traditional solutions;
- Useful (U): if the function is considered to be potentially useful but does not provide a significant advantage;
- Negligible (N): if the function does not provide any advantage whatsoever.

The objective of this assessment is to evaluate the functional overlapping of the main space habitability functions in terrestrial environments. Following, a short discussion on the transfer and cross-over potential of each space utility is presented.

Water management and recycling - Through the collection of wastewater, recycling, and redistribution of clean water, space water management systems, as on board the ISS, have proven to be an excellent way to greatly reduce the amount of water carried on board and have consequently lowered drastically the resupply costs and frequency. A very similar issue is encountered in numerous Earth applications; from oil and gas prospecting campaigns in the isolated tundra to military encampments in the desert face huge operational costs related to water and fuel resupply. Therefore, we consider that a water recycling function similar to that found in space could generate great value within this type of activities, by lowering the amount of water to be carried and to be resupplied.

Additionally, the emergency relief sector, usually characterized by having to cover the basic needs of a large number of people in a very short period of time, could not only benefit from PIUME™'s water recycling technology to reduce operational costs, but could also benefit from its quick and easy deployment, an essential feature in this sort of situations where every second counts.

Power management and distribution – The provision of power in any habitat is crucial to enable the most basic living conditions, from illuminating a room to powering appliances and other systems. While most terrestrial habitats are connected to the power grid, those in isolated places must rely on other power sources. Traditionally, diesel generators have been the most viable option in these applications, despite their need for frequent fuel resupply. Space power management and distribution technology, already designed for self-sufficiency and independent operation, can provide huge added value to this domain. The use of renewable energies, such as wind or solar, in combination with storage methods like batteries or fuel cells, could significantly reduce the resupply needs and operation costs. Currently, however, these benefits still fall short in front of the advantages that traditional diesel solutions present in terms of lower equipment cost and high availability.

Operations in extreme environments are also usually characterized by their elevated risk and by the fact that any sort of power loss or system failure could be life-threatening. For this reason, transferring the representative reliability and safety of space systems into these applications by means of emergency modes and fail-safe designs would be a significant differentiator.

Additionally, being able to easily scale-up the power supply using the "space rack philosophy" would allow for faster and more efficient habitat modifications to quickly adapt to operational needs.

Communications and Monitoring – Uninterrupted connectivity and monitoring are a basic need for both space and terrestrial remote locations. Our market studies determined that a key differentiator in remote habitats is quality connectivity because of its huge benefits in terms of operations and crew morale. This would carry benefits such as higher control on systems performance, more efficient resource management, and lower maintenance costs, which is especially relevant in those environments where the climate has a significant impact on systems deterioration.

Additionally, remote-control technologies would allow the habitat to be uncrewed for long periods of time and would enable a reduction in crew size by allowing operational and maintenance activities to be performed remotely.

Air revitalization – In comparison to space, on Earth fresh air can be generally collected directly from the atmosphere. However, some terrestrial applications, especially those that take place in highly confined spaces, such as in emergencies during mining activities, environmental contaminations or in underwater operations, lack this direct access to a source of fresh air. For this reason, space air revitalization technologies could benefit these areas.

Additionally, more traditional methods for air revitalization, such as HVACs, are of utmost importance in other terrestrial applications where, although atmospheric air is accessible, its regeneration is not easy (think for example of spaces with tight envelope construction). According to the WHO, indoor air quality in social emergency environments where people cook with cooking gas is of great importance.[11] Air revitalization functions in this type of applications are therefore essential.

Thermal control – The very stringent thermal control requirements found in space due to vacuum and microgravity drive space thermal control technologies to have little functional overlap with terrestrial needs. In addition, terrestrial HVAC and insulation technologies are very mature and cover the thermal control needs of even the harshest environments fairly well. This means that thermal control technologies from the space domain have a difficult transfer to Earth applications. As of now, the only habitability-related application found for such technologies on Earth is that of suborbital touristic flights, where the exterior environment resembles more that of space than the one on Earth. Still, the Earth domain could benefit from automatic control and remote monitoring technologies to improve the performance of thermal control systems, increase crew comfort, and reduce energy usage. Additionally, it could benefit from modular solutions to scale operations fast and easily.

This analysis has shown that there exist many similarities between space and terrestrial extreme environments. It has also shown how these similarities drive numerous functional overlaps that offer an opportunity potential for technology transfer. Moreover, although every Earth extreme environment presents particular characteristics, many have shown to share similar needs and would benefit from the same technology. Among the analysed functions, the most relevant ones for PIUME™ are water recycling, independent power generation and storage, quality communications, remote monitoring, and active air revitalization. Additionally, characteristics such as modularity, reliability, safety, and deployment speed have shown to be key features in all applications.

VI. PIUME™ Utilities preliminary design

Following the findings of the Functional Analysis, we carried out the preliminary design of PIUME™'s four most relevant utilities: the Water Processing Utility, the Power Distribution, Storage and Conditioning Utility, the Communications Utility, and the Command, Data and Control Utility. This section provides an overview of the key functional blocks of these utilities.

The design of each habitable module is driven by a set of input conditions and constraints, including:

- Service Duration (range of time and frequency of re-use of the utility);
- Number of users to be supported;
- Target customer (including available budget);
- Constraints (mass, logistics).

These inputs drive the definition of the selected utilities as follows:

Water Processing Utility – Dedicated to the provision of fresh water and the treatment and recycling of grey and black water, this utility is composed of:

- Water storage (potable, treated, grey, black);
- Potable water dispenser;
- Water pre-treatment unit;
- Grey water recovery and treatment unit;
- I/O standard interfaces (power, wired data, thermal control) with other utilities.

System specifics vary accordingly with variables such as the source of freshwater (tank, spring, groundwater, marine, etc…) or the desired degree of closure (grey water recycling, freshwater treatment, etc…).

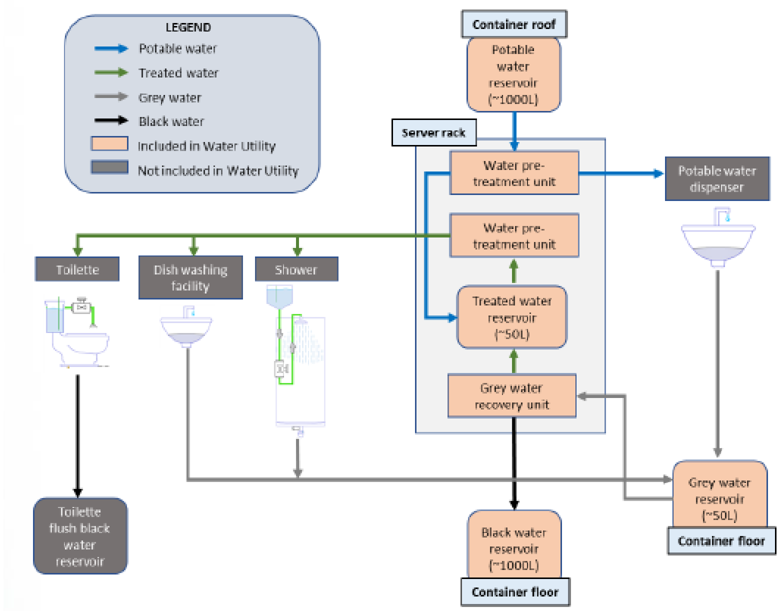

Figure V-1: Functional diagram of the Water Processing Utility

Power Distribution, Storage and Conditioning Utility – In charge of the distribution, conditioning, and storage of power, this utility consists of:

- Standard I/F to allow interaction with different PIUME™ power generation or external power distribution systems (identified Plugins, application dependent);
- Energy storage section, based on batteries or fuel cells (e.g. regenerative fuel cells H2-O2);
- Power conversion and distribution unit providing:
  - Standard User Interface;
  - Communication interface for the Command, Data and Control utility;
  - Power bus for other utilities.

Communications Utility – Aimed at providing the habitat with local and global communications, this utility comprises:

- Global Comms I/F to allow transmission and reception of signals from satellite communications for voice and data traffic, remote control and maintenance;
- Area Comms interfaces to allow communications within existing networks available on the zone;
- Local Comms interfaces to allow communications with the local users (e.g. explorers, sensors, wireless connected utilities moving around the central habitat);
- I/O standard interfaces (power, wired data, thermal control) with other utilities.

Command, Data and Control Utility – Dedicated to handling the habitat's data and controlling the operation of the systems, this utility is composed of:

- Processing HW and SW to:
    - Monitor and control other utilities;
    - Acquire and process data from sensor network;
    - Handle and Distribute Commands to other utilities;
- A dedicated User-Machine Interface to:
    - Allow user interaction with the other utilities;
    - Allow user communications with other networks;
    - Allow remote support from remote segments;
- Data interfaces through the Communications utility or dedicated wired I/F;
- I/O standard interfaces (power, thermal control) with other utilities.

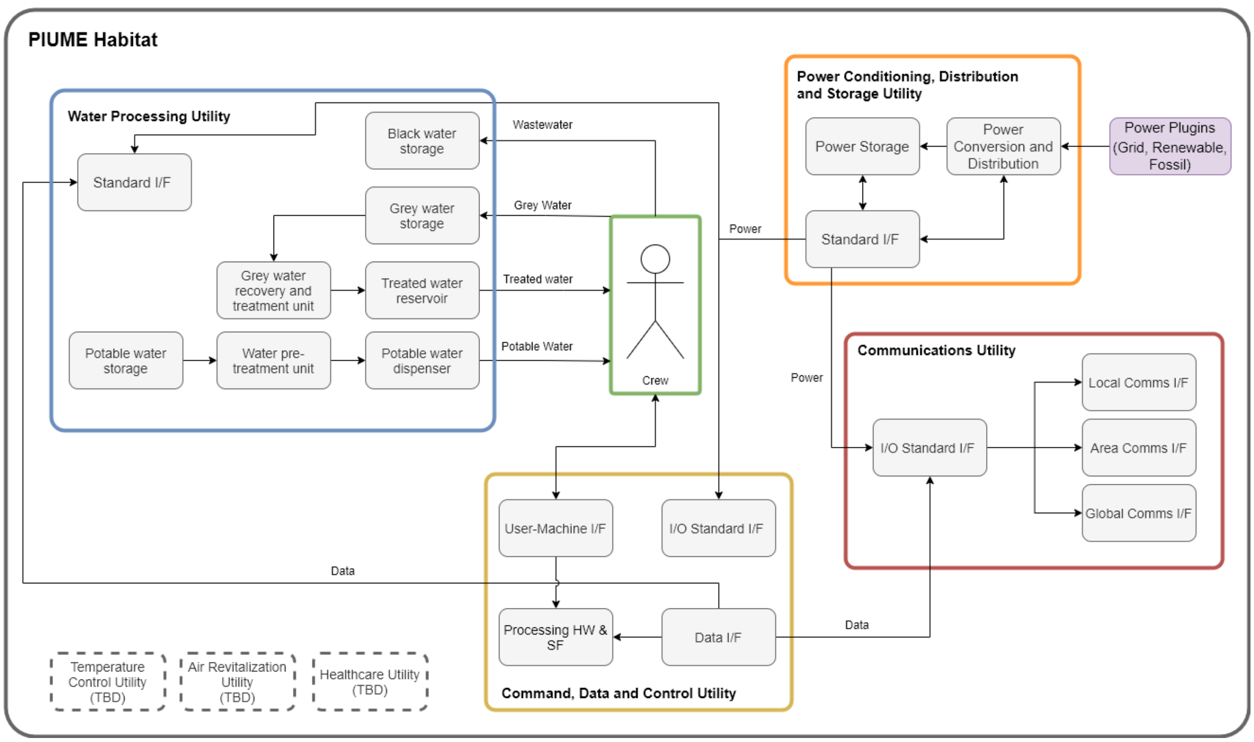

Figure V-2: High-level functional diagram of the PIUME™ architecture

VII. Earth Applications and PIUME™ Configurator

On the basis of the Functional Analysis and conceptual design of the key Utilities, a market survey was carried out to identify:

- to which extent the PIUME™ offer is already covered by existing solutions;
- if and to which extent existing solutions are already satisfying the stakeholder needs;
- if there are potential stakeholder needs uncovered by any solutions, which could be satisfied by the PIUME™ functional utilities or by integrated habitats/networks solutions.

The following market segments were surveyed:

- Humanitarian;
- Oil and gas;
- Mining and construction;
- Extreme exploration and marine.

Upon consultation of users for the different segments, PIUME™, with its customizable solution for resource management, resulted to be a differentiator in the areas of safety, reliability, connectivity, adoption of renewable energy, and water recycling.

In order to provide users with a clear idea of the proposed solution for their specific conditions, and gather their feedback, we developed a PIUME™ configurator in the frame of ESA's Technology Transfer Program.

The configurator has also the objective to collect data from terrestrial users, generating a database of real-world use cases, with the goal of developing a market-pulled solution.

The following utilities were identified as the most suitable for this first iteration:

- Water Processing;
- Power Distribution, Storage and Conditioning;
- Communications;
- Command, Data and Control Utility.

The configurator is tailored to provide an estimation in terms of costs and resources needed as a function of the user mission, environmental conditions, and resources available, among other parameters.

The tool is based on a specific logic identified for each PIUME™ utility. Using the inputs provided by potential terrestrial users of the system (such as mission time, crew size, crew turnover rate, climate characteristics, and remoteness level) the configurator is able to select the most suitable solution for the user.

The application provides in output the volumes occupied by the overall system, represented by the number of racks needed to contain each utility and the number of clean and wastewater tanks to support the mission, as well as different metrics regarding power and water consumption, mass, and cost.

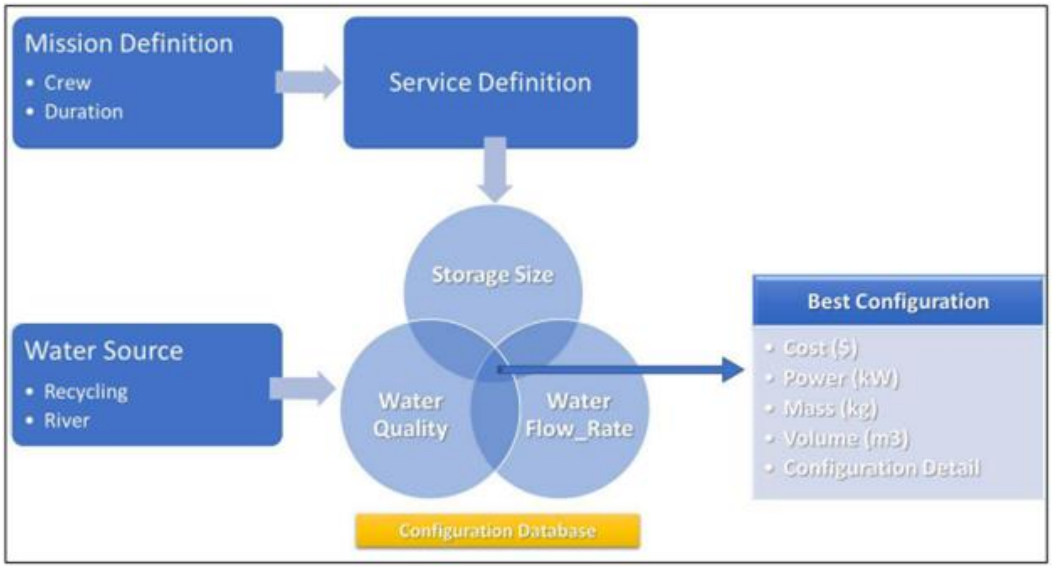

Figure VI-1: PIUME™ configurator concept and logic

Figure VI-2 shows an example of results produced by the configurator. In this case we obtain the number of required racks, defined as a volume with a base of 80x60 [cm] and height of 100 [cm], to support a crew of 5 members during a mission of 45 days in a temperate region. The columns reported in the lower part of the image provide a comparison between clean and wastewater of a traditional mission (without recycling) and a PIUME™ solution implementing a recycling solution for greywater.

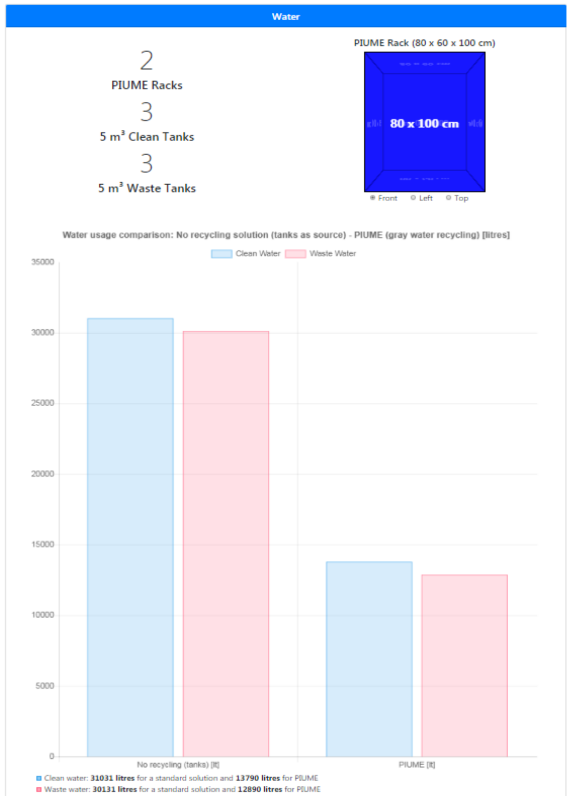

Figure VI-2: PIUME™ configurator output for a crew of 5 members during a mission of 45 days

The output of the configurator is then represented within a VR environment, providing an immersive experience to possible stakeholders, users, and developers.

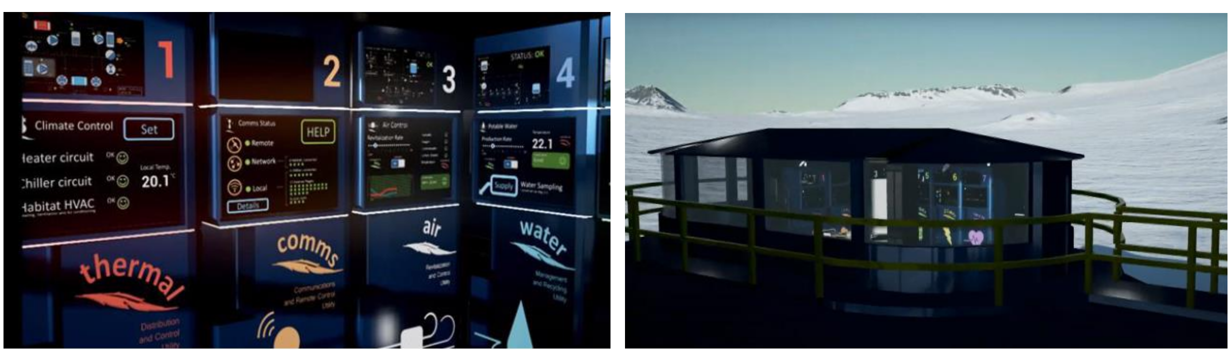

Figure VI-3: PIUME™ physical accommodation represented in the Virtual Reality environment

VIII. Conclusions

PIUME™ represents the transfer from space to ground habitats of a modular approach towards the provision of vital resources in extreme conditions, providing a fully integrated turn-key solution for terrestrial markets, where we believe it may represent a differentiator compared to existing ad-hoc solutions.

PIUME™ will provide a transportable and scalable solution based on its six primary utility functional blocks.

The identified market areas include the oil & gas, mining, maritime, humanitarian and emergency relief fields, where PIUME™ has been appreciated by potential users as an interesting solution due to increased safety, reliability, and sustainability, providing savings in fuel, energy, and water consumption.

In order to demonstrate PIUME™'s capabilities, and gather user feedback, a configurator was developed. Given a set of inputs and constraints from the users, the configurator provides an estimation of the dimensions and components of the system and quantifies the expected savings with respect to traditional solutions. At the same time, it allows the designers to generate a database of real-world use cases, to be considered for enhancing the proposed solution.

The output of the configurator is then represented within a VR environment, providing an immersive experience to possible stakeholders, users, and developers, very helpful to gather further feedback for product development.

The next steps include the development and construction of a physical Proof of Concept, represented by a small "service module" including key utilities, i.e. the water and power management and data / connectivity functional blocks, to be tested first at industrial premises, than in the field at a remote location. The evolution of this demonstrator will be an enhanced Minimum Viable Product (MVP), usable by a crew of "early adopters" in the field at a remote location. If such steps will be successful, the industrialization phase for a small series production will follow.

References

[1]Häuplik-Meusburger, S. and Bannova, O., *Space Architecture Education of Engineers and Architects*, Springer, 2016, pp. 193-196.

[2]Allner, M., Bishop, S., Gushin, V. and Rygalov, V., "Crew Performance Analysis of a Simulated Mars Mission at the Mars Desert Research Station (MDRS) in Utah, USA," *International Astronautical Federation - 59th International Astronautical Congress 2008*, 2008, pp. 11-23.

[3]Ferrone, K., Cusack., S. L., Garvin, Ch., Kramer, W. V., Palaia, J. E. and Shiro, B. F., "Flashline Mars Arctic Research Station (FMARS) 2009 Crew Perspectives," *American Institute of Aeronautics and Astronautics*, 2010-2258, SpaceOps Conference, Huntsville, AL, USA, 25–30 April 2010.

[4]Todd, B. and Reagan, M., 2004. "The NEEMO Project: A Report on How NASA Utilizes the 'Aquarius' 'Undersea Habitat as an Analog for Long-Duration Space Flight," *Engineering, Construction, and Operations in Challenging Environments: Earth and Space 2004*, pp. 751-758.

[5]Bannova, O., "Architectural approach to planning in the extreme arctic environment," *ArchiDOCT: Transformable Architecture*, 4(1), 2016, pp. 53–67.

[6]Bannova, O. and Jorgensen, J., "Can We Test Design for Coming Interplanetary Expeditions in the Arctic? Arctic Research Stations as test bed for simulations of future long-term space environments," *Collection of Technical Papers - Space 2006 Conference*, Sept. 2006.

[7]Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, "Neumayer III and Kohnen Station in Antarctica operated by the Alfred Wegener Institute," *Journal oflarge-scale research facilities*, 2, A85, 2016.

[8]Imhof, B., Schlacht, I., Waclavicea, R., Schubert, D., Zeidler, C., Vrakking, V. et al., "Eden Iss: A Simulation Testbed to an Advanced Exploration Design Concept for a Greenhouse for Moon and Mars," *69th International Astronautical Congress (IAC)*, Bremen, Germany, 1-5 October 2018.

[9]Terranova, C. and Tromble, M., *The Routledge Companion to Biology in Art and Architecture*, Taylor & Francis, 2016, pp. 121-122.

[10]Doule, O., Imhof, B., Hoheneder, W., Ransom, S., Waclavicek, R., Kull, P., Aabloo, A., Weiss, P., Taillebot, V., Gardette, B., Gobert, T., Gancet, J., Letier, P., Rodriguez, G., Salini, J., Nelson, J., Welch, C., Gajdoš, P., and Ševčík, D., "Self-deployable habitat for extreme environments-universal platform for analog research," *AIAA SPACE 2014 Conference and Exposition*, Aug. 2014, pp. 1–16.

[11]*WHO Guidelines for indoor air quality. Household Fuel Combustion*, World Health Organization, 2014.