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Lunar base design concept of DIANA Dedicated Infrastructure and Architecture for Near-Earth Astronautics

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The Dedicated Infrastructure and Architecture for Near-Earth Astronautics (DIANA) is a concept for a permanently crewed base on the lunar South pole with the objectives of furthering space exploration and achieving self-sustainability. The initial base will be autonomously deployed and robotically constructed near the de Gerlache crater ridge. DIANA's architecture and design address the challenges imposed by the lunar environment alongside structural, technical and habitability requirements. The construction of DIANA is divided into three phases. Upon reaching the lunar surface, the modules are autonomously deployed from their compressed state, expanding to a habitable volume. This initial base accommodates four astronauts and includes a common room with cooking facilities, sleeping quarters, a multipurpose lab, a window module, and a greenhouse. The first expansion sees the growth of the base to support eight astronauts. These first two phases rely on in-situ resource utilization of regolith to provide radiation shielding and construction materials. The goal of the final expansion is to create a sustainable base that provides better living conditions capable of accommodating tourists and astronauts alike. This is achieved by using enhanced in-situ 3D printing with regolith as material. DIANA's interior design has been directly informed by human factors promoting physical and mental well-being, optimal performance and safety. Its modules consist of multiple stories both above and below ground. The open layout and interior windows provide visual cues across both rooms and levels. Some unique features include the gym's placement within the greenhouse module, a dedicated window module with dining area, and crew quarters which double as a safe haven below ground. Providing a sense of nature and a connection to Earth are mainstays to DIANA and are achieved through private areas for confidential communication with Earth, customizable and personalized furniture and the use of both real and virtual windows.

I. Introduction

THE project presented in this paper was developed as part of the Space Station Design Workshop (SSDW) 2021 organized by the University of Stuttgart's Institute of Space Systems with the aim of engineering a lunar outpost. This paper focuses primarily on the architecture of the resulting habitat. The proposed design sees a basic surface base from Earth established on the lunar surface, following a preliminary, automated construction period. The innovative habitat design aims to optimize long-term performance and to act as a turning point for long-duration exploration and habitation on the Moon.

The lunar environment imparts challenging and unusual conditions for the creation of a human establishment. It is characterized by extremely low atmospheric pressure with no breathable air, partial gravity, extreme

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temperatures, micrometeoroid and orbital debris (MMOD) impacts, and permanent heavy energy radiation. These aspects must be addressed to design a functional habitat that can sustain a crewed mission.

One of the major constraints driving the design of an extraterrestrial habitat is its transportation. Therefore, the planned habitat modules must fit within the dimensions of the available transportation vehicle. Integrating heavy launch vehicle payload capabilities into the initial layout is crucial. Using a deployable habitat architecture composed of lightweight materials is a solution for dealing with the current launch vehicles' restricted dimensions. According to these guidelines, DIANA offers a design that is optimized for two different loading configurations: the launch configuration and the post-landing configuration on the lunar surface. In its final deployed state, the habitat will provide a pressurized environment which accommodates for all habitation needs. Dedicated work and communication spaces, private crew quarters, leisure-time areas, technical support systems and a greenhouse have all been incorporated. Additional shielding against radiation and lunar environmental conditions is provided by sintering regolith around the habitat, an effective alternative to transporting heavy shielding from Earth. This 3D printed regolith shell efficiently protects the habitat and its inhabitants from cosmic radiation, solar flares, MMOD, temperature variations, as well as increases the durability of the habitat modules and its associated components.

II. Mission Elements

A. Mission Requirements

Since this concept was developed during the SSDW, certain mission requirements were established as part of the challenge. The requirement was to develop a permanently inhabited platform on the lunar surface that accommodates at least four astronauts and enables both human and robotic exploration of the lunar environment. The mission should serve to help verify low technology-readiness-level capabilities and accelerate their development to sustain life beyond Earth.

Importantly, ensuring the base could achieve effective autonomy, gradually decreasing its reliance on terrestrial resources was emphasized. Therefore, in-situ resource utilization (ISRU) has been extensively implemented to meet habitability and construction requirements and to maintain launch and landing capabilities.

Beyond the engineering and technical means developed to ensure crew safety, human factors considerations were deemed essential for mission success. As such, ergonomics, comfort and psychology were all incorporated as mission requirements and are evident throughout the architectural and design choices.

B. Habitat Location

The DIANA base will be constructed within proximity to the de Gerlache crater located on the lunar South pole (88.71°S, 68.7°W)[1]. Sunlight is almost always present at this location ensuring consistent solar power generation. The temperature extremes range from 59.29 K during the winter night to 244.23 K during the summer day[1]. This is an acceptable range that thermal control can account for. Furthermore, despite the cratered region, this particular location is relatively flat (slope = 1.23º) allowing for safe landings and a solid foundation for construction. Importantly, the de Gerlache crater contains permanently shadowed regions from which ice can be extracted for ISRU purposes. The location characteristics are shown in Figure 1.

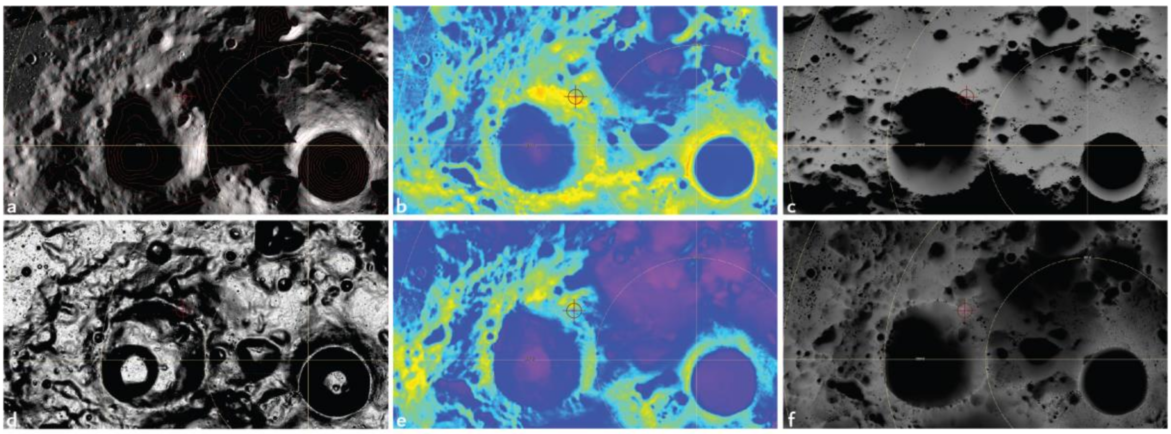

Figure 1. DIANA moon base location characteristics. *a) Moon base location terrain contour. b) Avg. Summer temp. = 180.7 K (min = 94.5 K and max = 227.3 K). c) Earth visibility = 0.60 (min = 0, max = 1). d) Moon base location terrain slope = 1.23º. e) Avg. Winter temp. = 103.0 K (min = 57.8 K and max = 208.9 K). (f) Sun visibility = 0.65 (min = 0, max = 1).*

C. Timeline & Mission Phases

For this mission concept, it is assumed that the following technologies will have all passed their development phase and be operational by mission start in 2027. The timeline can be divided into four phases: equipment arrival, base stabilization, nominal operations and expansion as shown in Figure 2. The expansion phase is further divided in two and will be described in the "Further Development" section.

Phase one is characterized by the arrival of necessary equipment, including the communications relay, rovers and power generators. The rovers will prepare the location for habitat construction. At the end of phase one, mission rovers and environmental control and life support systems (ECLSS) resources will arrive to support the first crew. This crew's arrival on the lunar surface pushes the mission to phase two, base stabilization.

During this second phase, the crews will continuously stabilize operations for long-term habitation. To ensure this, the ISRU refinery will be established. The radio telescope array modules will be autonomously deployed in this phase and rover-initiated scientific research will begin.

The nominal operations phase emphasizes scientific research and will see the continual expansion of the base with four additional modules.

The final phase, expansion, occurs once the base is deemed self-sustainable. ISRU resources will be exploited to aid in the expansion as resupply missions become less frequent. More mission rovers and radio telescope array modules will arrive. Scientific research will be continually conducted.

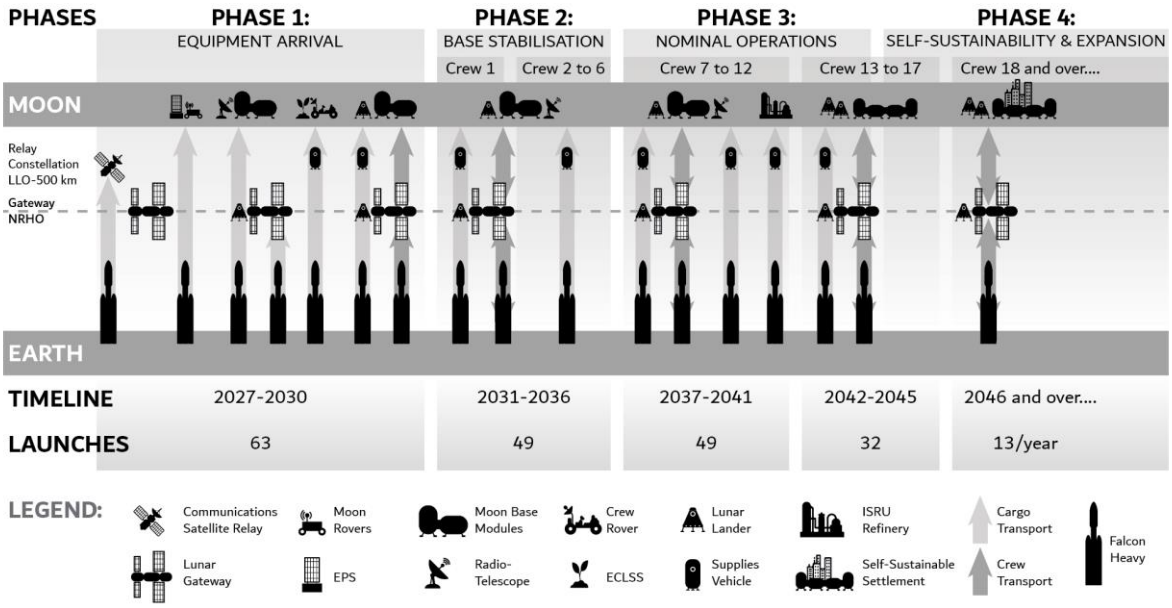

Figure 2. Bat chart for the mission DIANA

III. Design Method

Human factors considerations have been integrated into the habitat configuration to enable the most effective and efficient use of space that maximizes performance, well-being and self-reliance. To achieve these standards over the longevity of the base as well as the yearlong mission durations, sustainability, variation, and adaptability have been emphasized throughout the design. The modules have been laid out to optimize functionality, keeping in mind noise levels, sterility requirements and privacy. Sound proofing, smell containment and physical separation are all important functions of privacy[2] (Table 1). The promotion of physical and mental well-being, optimizing performance and prioritizing safety are all mainstays of the design.

A. Physical Well-being

The main physical challenges that could be dealt with through design are circadian rhythms, ergonomics, and lunar dust. Ergonomics solutions focus on providing adaptability to address lunar-gravity-imposed postural changes and to accommodate the variety of crew member sizes.

On the Moon, loping is the preferred form of locomotion[3,4] and therefore, ceiling heights must be taller than on Earth[5]. Benefits include making use of higher spaces, such as the elevated bed and lounge. Customizable furniture will allow for flexibility between crew members and adaptability to lunar gravity needs that may not yet be understood. An example would be having tables that not only fold to conserve space but are also adjustable to suit different heights.

Table 1. Habitability characteristics of DIANA modules

LAYOUT		FUNCTION				
Module	***Room***	***Privacy***	***Creates Contaminants***	***Sterility Required***	***Noise Requirement***	***Noise Production***
Multipurpose Lab Module	Science Lab	Shared/Semi-Private	Yes	Yes	None	Intermediate
	Med Bay	Semi-Private	Yes	Yes	Quiet	Quiet/Noisy
	Geology	Shared/Semi-Private	Yes	No	None	Intermediate
	Comm Room	Shared/Semi-Private	No	No	None	Intermediate
Greenhouse	Food Production	Semi-Private	Yes	Yes	None	Noisy
	Gym	Semi-Private	Yes	No	None	Noisy
	Hygiene Facility	Private	Yes	No	None	Noisy
	Stowage	Shared	No	No	None	Quiet
Social Module	Kitchen	Shared	Yes	Yes	None	Noisy
	Living Room	Shared	Yes	No	None	Intermediate
	Lounge	Semi-Private	No	No	Quiet/None	Intermediate
	Crew Quarters	Semi-Private	No	No	Quiet	Quiet
	Hygiene Facility	Private	Yes	No	None	Noisy
Window Module		Semi-Private	Yes	Yes	Quiet	Quiet

Exercise is a mandatory countermeasure to physiological degradation[2,6,7]. Initially, the International Space Station (ISS) regimen will be followed until more data about lunar gravity is collected. The co-location of the exercise module within the greenhouse will mimic as closely as realistically possible the perception of exercising outdoors. Additionally, virtual reality technology will be available to simulate a variety of running trails. It could even permit virtual racing with family members or friends which will improve their psychological health alongside their physical health[7,8].

Knowing that circadian rhythms will be disrupted[2], the crew quarters have been designed to provide the utmost comfort to each crew member. Privacy is a primary concern[2,6,9] and has been addressed through soundproofing, interior window covers and excellent ventilation. Lighting, ventilation and temperature will be controllable to allow for crew autonomy around their sleep and relaxation schedules.

Lunar dust is a major environmental stressor that requires provisions to prevent it from entering the habitat[2,10]. This is addressed by using suitports instead of hatches. Geology samples can only enter the habitat if they are sealed during extra-vehicular activities (EVAs) and can be tested within their secured tubes. Otherwise, a robotic arm will be used to collect the samples and place them within a sealed-off glove box accessible from the multipurpose lab.

B. Mental Well-being

NASA's Human Research Roadmap has determined that the likelihood of a cognitive or behavioral issue arising on a long-term lunar surface mission is high and requires mitigation[11]. Some of these are addressed in the design features.

The social module has been designed to combat feelings of isolation, confinement and conflict. The split-level open layout will provide both a social connection and the illusion of a larger space. Crew members can enjoy an individual activity, such as reading, while still seeing and interacting with their crewmates nearby. The proximity to the crew quarters will also allow crew members to retreat to their rooms. This easy access to privacy is an essential countermeasure for psychological health[2,6,9]. This includes soundproofing to ensure confidential conversations with loved ones and space for personal affects like photos, journals and books[2,9,10]. The open kitchen, dining and living spaces will allow the crew to congregate during meal preparation and dining. Those who are cooking can still socialize with the others in the living area. Incorporating group recreational time into daily tasks can promote crew cohesion and shared experiences[2,6,9].

The greenhouse is a mainstay of positive psychology in space. Maintaining the plants and watching them grow will provide the only true connection to the natural world that the crew will experience over the duration of their mission[9]. Initial missions will begin with simple, durable plants with proven growth in space. Future missions will incorporate more advanced greenhouse systems that can provide variety and fresh food to supplement the cargo. Considering the noise produced within this module, the exercise equipment and greenhouse machinery are co-located and separated from the quiet crew quarters and workspaces (Table 1).

Prior to the expansion phases, there will be a single window module (Figure 3). It is a semi-private zone for recreation, relaxation and dining. Astronauts in the window module will have views of the lunar surface. Due to the South pole location, Earth will always appear in the same location to the crews. Thus, the window placement will ensure astronauts always have a view of our home planet. Considering these are the only direct views of the outdoors, cameras and art supplies will be stored there to encourage photography and creativity. The vastness of the lunar surface can serve to counteract the feelings of confinement and sensory monotony from being indoors[6,9,12]. To supplement the lack of windows, there will be "virtual windows" dispersed throughout the habitat. These are customizable "windows" displaying a variety of scenes, including movement such as trees swaying in the wind. These are accompanied by sounds that can be turned off (e.g., the sound of birds chirping while looking out at the forest). Furthermore, the crew can upload their own images to be displayed. This could be an image of their garden or a favorite landscape. This will add a visual connection to their memories from Earth. This will also be beneficial for breaking social monotony and improving crew cohesion[2,9].

Figure 3. DIANA interior structure

Customizable furniture is another design feature that allows for the reconfiguration of the space. This can diminish sensory monotony and will allow for personal and cultural tastes to be respected[9]. Lunar gravity will enable the furniture to be easily moved allowing for changes throughout the mission. It will also provide multipurpose spaces where different activities can be conducted throughout the mission. For example, it could be beneficial to relocate and reconfigure furniture between the lounge and living room to create an open space to play a game.

For safety reasons, each module will be sealed with a hatch. However, each hatch will have a window allowing light to flow through the module, creating the impression of a larger space. Each module is designed with an open layout allowing for visual connections across levels. Beyond combatting the confinement, this open layout can allow crew members to work within the same space while having ample space to conduct tasks[9,12].

C. Safety

Safety features have also been embedded throughout the design. Each module can be sealed off in case of contamination or depressurization. Automated sensors will be present within each module to detect fire, smoke, radiation exposure, and chemical and biological contaminants. The alarms include sounds and visual cues and can be easily disabled. Translation paths will be large enough to accommodate the assisted transport of an incapacitated crew member and bulky equipment. Each module will contain access to an emergency airlock which is well lit even in low-light or smoke conditions. There is a medical suite within the multipurpose lab which will be readily equipped and compatible with telemedicine operations that may be required.

The lower level of the social module contains the crew quarters, a hygiene facility, and access to stowed food. It also includes a retractable ceiling that, when retracted, encloses the entire lower level. This will provide additional shielding, allowing the lower level to double as the safe haven. It meets all required habitability needs and is spacious enough for a solar event lasting up to ten days.

D. Performance

Addressing all of the previous issues will help mitigate performance issues throughout the mission. However, there are certain performance aspects that are met head-on for general workflow improvements and ergonomics.

Items will generally be stored in the module where they are most used. For example, food storage can be found in the kitchen and recreational equipment can be found in the lounge. Miscellaneous and large items will be kept in the storage area beneath the greenhouse. It is highly important that this area is organized logically and is constantly updated as consumables are used and as resupply missions arrive[2,12].

Workspaces must also be conducive to this unique isolated and confined environment. Creating open work areas, such as in the multipurpose lab, will allow crew members to focus on their individual work while keeping their visual connection to others[9,12]. Creating multiple workspaces throughout the habitat, such as the desk in the crew quarters or table in the living room, will help maintain variety. Rotating work tasks along with locations will help curb monotony and ensure work motivation remains optimal[2].

IV. Construction and Materials

The inhospitable lunar environment imposes extreme conditions for the establishment of a human-inhabited base and drives many of the design decisions for a surface habitat. Humans need a habitable living and working environment, and simply cannot survive without an additional protective layer. Some of the most severe conditions on the lunar South pole are the temperature variations from 59.29 K to 244.23 K, solar radiation of 1176 W/yd, and MMOD impacts. The uppermost layer of the lunar soil, or regolith, is an abrasive and statically charged substance that can cause severe damage to any unprotected material. However, the most life-threatening lunar condition is the lack of a breathable atmosphere. Therefore, the structure must be capable of supporting operational loading at 14 psi. At the same time, costs must be minimized, and transportation strategically planned. Under these terms, a pressurized habitat becomes an essential and valuable resource[5,13]. All these aspects must be addressed in order to design a functional base that sustains a successful mission. To achieve this, an interdisciplinary design approach is required to meet the technical, spatial and habitation requirements[14].

An integrated deployment mechanism is the foundation for DIANA's architecture. It satisfies lunar-specific mission and habitability requirements and bypasses transportation restrictions. To ensure the longevity of the base fulfills scientific research objectives and sustains long-term human habitation, four pressurized modules were designed: the social module, the multipurpose lab module, the greenhouse module and the window module (Figure 4).

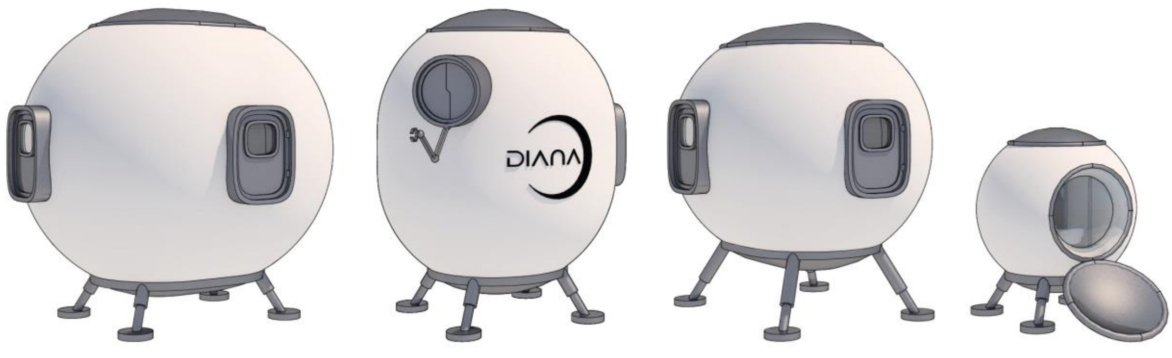

Figure 4. DIANA modules

Each module's shape and volume are based on their unique functions and were informed using NASA technical reports[2,10,12] and ESA's Moon Village concept[8] (Table 2 and Table 3).Each module will provide a habitable environment consisting of work, private, and social spaces. This feature is very important for crew social and interpersonal relationships, especially considering the long-duration confinement. The functional and physical separation of the social area, crew quarters, and work area creates a home-like design for the crew members, allows each function to remain permanently deployed for regular use, and is an absolutely necessary safety

Table 2. DIANA module dimensions

	Social module	Multipurpose Lab	Greenhouse	Window Module
Total volume	218.07 m3	141.36 m3	141.36 m3	33.51 m3
LWH dimensions	8 m x 7 m x 7 m	6 m x 6 m x 7 m	7 m x 6 m x 6 m	4 m x 4 m x 4 m
Packed volume	ca. 100 m3	ca. 70 m3	ca. 70 m3	ca. 20 m3
LWH packed	6.2 m x 4.6 m x 4.6 m	4.6 m x 4.6 m x 5.4 m	5.4 m x 4.6 m x 4.6 m	3.1 m x 3.9 m x 3.1 m
Habitable volume	141.36 m3	85.07 m3	85.07 m3	14.13 m3
Habitable area	44.4 m2	19.84 m2	21.71 m2	2.53 m2

Table 3. Habitable area per module and function

Social module	
Kitchen	6.13 m2
Living room	15.39 m2
Lounge	9.40 m2
Sleeping quarters x 4	4 x 0.82 m2
Toilet	0.52 m2
Bathroom	0.52 m2
Passage + Stowage	9.16 m2
Total habitable area:	**44.40 m2**

Greenhouse module	
Gym	9.16 m2
Storage	9.01 m2
Hygiene facility	1.25 m2
Passage	2.29 m2
Total habitable area:	**21.71 m2**
Food production	23.82 m2

Window module	
Dining room	2.53 m2
Total habitable area:	**2.53 m2**
Window area	4.81 m2

Multipurpose Lab module	
Science Lab	7.60 m2
Comm room + Med bay	7.34 m2
Passage	4.90 m2
Total habitable area:	**19.84 m2**

measure[15]. Although having differently-shaped and sized modules may seem counterintuitive at this original stage, it remains more beneficial in terms of habitation requirements and economies of scale as the base continues to expand and modules are repeatedly constructed.

The modules are arranged as a rectilinear grid with a cruciform scheme. Three nodes connect the modules, providing easy access to the entire base. The cruciform scheme offers a relatively small deployment footprint around the horizontal module, minimizing site preparation. Furthermore, although the scheme will begin as a cruciform, it can evolve into a closed-loop plan[16]. The nodes act as a transition space or vestibule between modules. Each node will have electronics, power equipment and three or four station-standard hatches for connections with airlocks or modules. The main utilities will be brought to the primary node bulkhead and will be transferred into DIANA's utility chaseways. Their function is to provide circulation between the modules and/or airlocks and to house critical equipment required during inflation. It will be the only pressurized volume in DIANA during launch. The main airlock is located on the primary node which connects the social, greenhouse and multipurpose lab modules. The other nodes have emergency exits as a safety precaution and strategically provide connections for the integration of future modules as the base expands. The tertiary node ensures easy and direct access from the window module to the main airlock, social module, emergency exit and future modules (Figure 5). Each airlock is equipped with suitports. These suitports replace the standard use of the airlock by providing two bulkhead openings (inner and outer), a capture mechanism and a sealing system. The latter will allow for ingress and egress of a spacesuit while keeping it outside of the pressurized volume of the habitat, yet protected from the lunar environmental conditions (e.g., dust, MMOD impacts) [17]. The airlock will provide a large enough space for spacesuit maintenance to be conducted.

The Bigelow Expandable Activity Module and TransHab inflatable habitation, that were originally designed as expandable station modules for the ISS, were the primary references used to carefully plan the development of DIANA's architecture and construction. Their composition of hybrid inflatables as deployable structures that combine a hard, skeletal structure with an inflatable outer pressure shell both optimizes load distribution for transit (as opposed to static phases of deployment) and perfectly suits the needs of DIANA and the crew[15,18]. DIANA uses a similar design, adapted to support crew operations in lunar gravity. Its modularity and hybrid inflatable structure will provide the required flexibility to support long-duration missions with varying crew needs. Furthermore, it will remain compressed during launch. Its deployment on the lunar surface will expand the habitable volume implementing unique architectural, technical and design approaches. Hybrid inflatables require significantly less mass than hard-shelled structures and have a high deployed-to-packed volume ratio. The reduction in metallic elements minimizes the risk of radiation exposure to crews. Since it will be deployed in-situ, the likelihood of depressurization during launch is low[18].

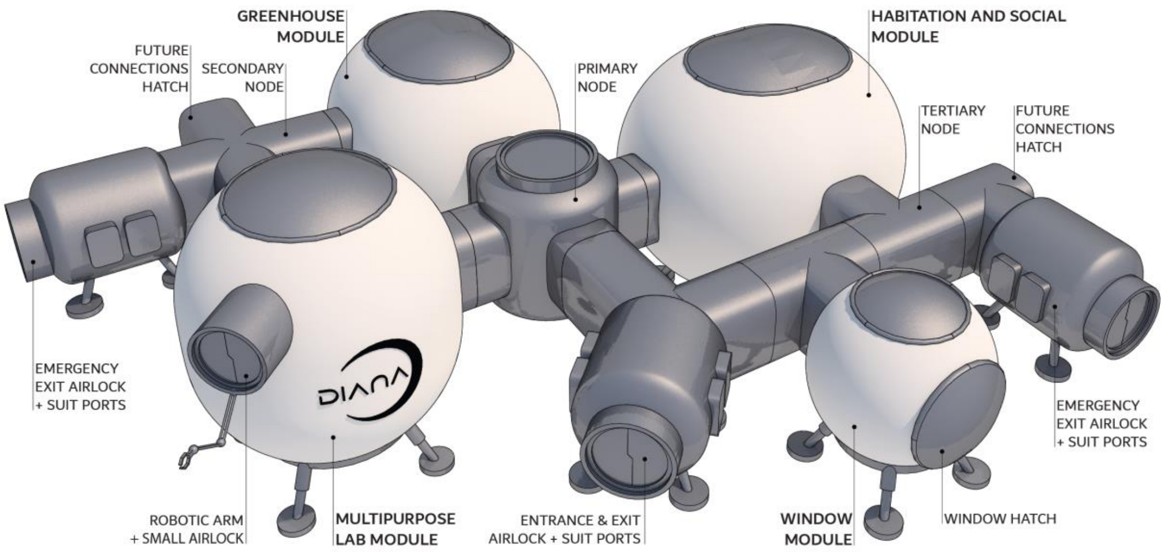

Figure 5. DIANA Phase I perspective view

A. Inflatable Shell

The inflatable shell provides a large multi-functional interior space. A special "pop-out" design concept enables floors and utility interfaces to be pre-integrated in a manner that avoids complex and time-consuming construction on the lunar surface. Transportation is possible in small launch vehicles, leading to a lighter payload and reduced launch costs. It offers substantial interior volumes, particularly suitable for living spaces that optimize crew comfort and performance during extended missions lasting months or even years. On such lengthy missions, the goal is to maximize habitability, crew safety, spatial efficiency, functional versatility, and EVA access to and return from the surface[16]. Because the inflatable shell is its own unique system, it can be optimized as a pressure shell. During launch, it will remain in its folded state until it is deployed and inflated after landing and final positioning on the lunar surface. It is composed of the following elements starting from the inside: inner scuff barrier and structural restraint layer (Kevlar layer 10 mm), pressure bladder (two vinyl polymer foam layers 230 mm each), and thermal protection blanket (two carbon layers 10/20 mm).

The inner scuff barrier provides fire retardant and abrasion protection from the inside of the habitat. The internal pressure (carrying pressure loads up to 14 psi) is resisted by woven straps of fiber material that form the structural restraint layer. Two bladder layers form redundant air seals to handle internal pressure loads and retain gas respectively while minimizing air loss. The multi-layer insulation with thermal protection blankets grants thermal and potentially radiation protection. All these materials need to be chemically and molecularly stable in a vacuum environment in order to minimize gas diffusion and provide an inner flame resistance. The flexibility of the cumulative laminate will enable the structure to be folded and packed multiple times[2]. MMOD and radiation shielding of the inflatable shell are incorporated into the layer of regolith shielding that will be described later.

B. Rigid core

The rigid expandable core is made of aluminum 7075-T6 alloy and can be expanded horizontally and vertically. The expandable core enlarges the deployable volume of the habitat and strategically enables the pre-integration of the equipment and utility systems[16]. Its four primary components are the crown, the bottom base with legs, the telescopic pillars, and the foldable beams. Movable modular panels and acoustic wall panels comprise the secondary components (Figure 6). The rigid core is optimized for the launch configuration and post-inflation loading conditions.

The crown and bottom base serve as connection points between the inflatable shell and the frame. They will be manufactured as single pieces of lay-up composites. Depending on module size, four or six telescopic pillars are built-in between the crown and bottom base. In the launch configuration, the telescopic pillars are in a compact state folded with the beams. The modular panels are packed between the pillars to provide lateral restraint. After the inflation of the shell, the telescopic pillars will be vertically extended and ultimately provide perpendicular reinforcement between the ceiling (the crown) and the floor (the base). Foldable beams will stretch out horizontally during the deployment process and can resist the gravitational loads of the occupants and the tension load of the internal pressure. Once the shell has been inflated, the secondary components can be detached and reconfigured. The movable modular panels will be used to form floors, ceilings, and walls. They help designate private and shared spaces as well as create a multi-level open layout. Mechanical connections are used to join the

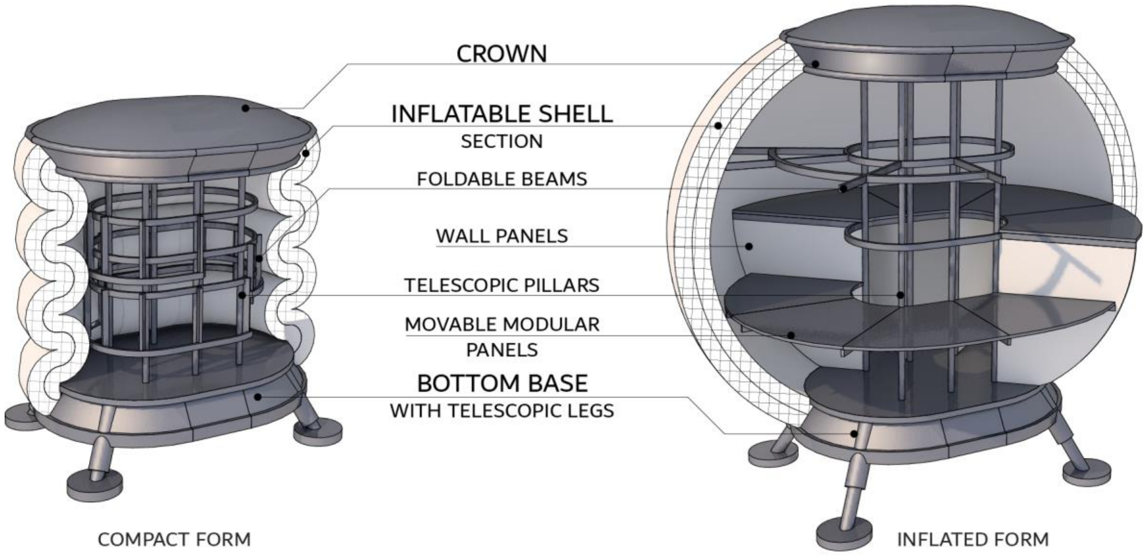

Figure 6. DIANA construction perspective view

rigid core structure with the woven pressure shell[18]. The acoustic wall panels are built out of a fabric sandwich of Nomex, felt, and Bisco (an acoustic abatement material). They are designed for cleanability and easy replacement to allow crew members to decorate their quarters according to personal taste. Studies and research on long-duration isolation and confinement have shown personalization, along with larger private crew quarters to have a positive impact on crew morale and productivity[15].

The provision of a regolith shield is an effective and efficient measure for radiation protection, minimizing mass requirements for launch. This shield will use 3D printed surface regolith collected in-situ. Beyond providing protection from cosmic radiation and solar flares, it is a successful thermal insulator and will increase the modules' durability[19] (Figure 7).

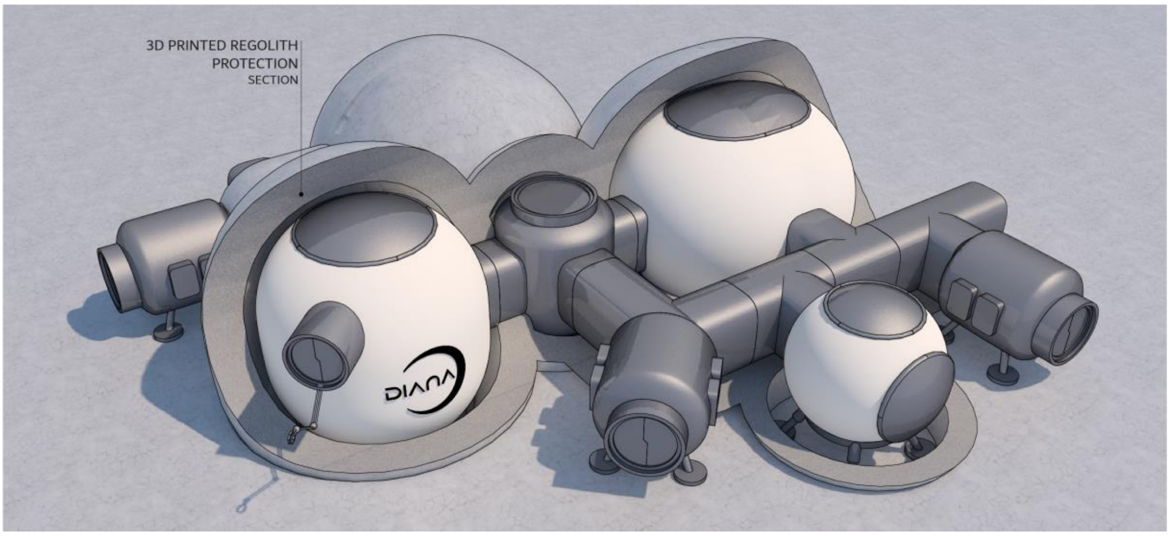

Figure 7. 3D printed regolith protective shield

C. Floor plans

Special emphasis has been placed on architectural design for comfort and safety which, in turn, promotes a high level of habitability for the crew members. The floor plans shown in Figure 8, Figure 9 and Figure 10 demonstrate how the modules are all mutually connected, offering smooth circulation between different spaces. All modules have access to emergency exits equipped with suitports and airlock hatch doors that correspond to the entrance of the lunar pressurized vehicle. In case of an emergency, modules can be sealed off from one another so that no other modules are compromised. If this were to arise, the layout ensures that the base will remain intact with no modules segregated from the rest of the habitat. To improve the crew's circulation through the base, each module (except the window module) has two passages connecting them to different nodes. Having only one passage per module would be considered a safety hazard, and having more than two passages per module would affect the interior configuration and usable area of the modules.

To minimize radiation exposure, the crew quarters will be located underground. Due to the curvature of the

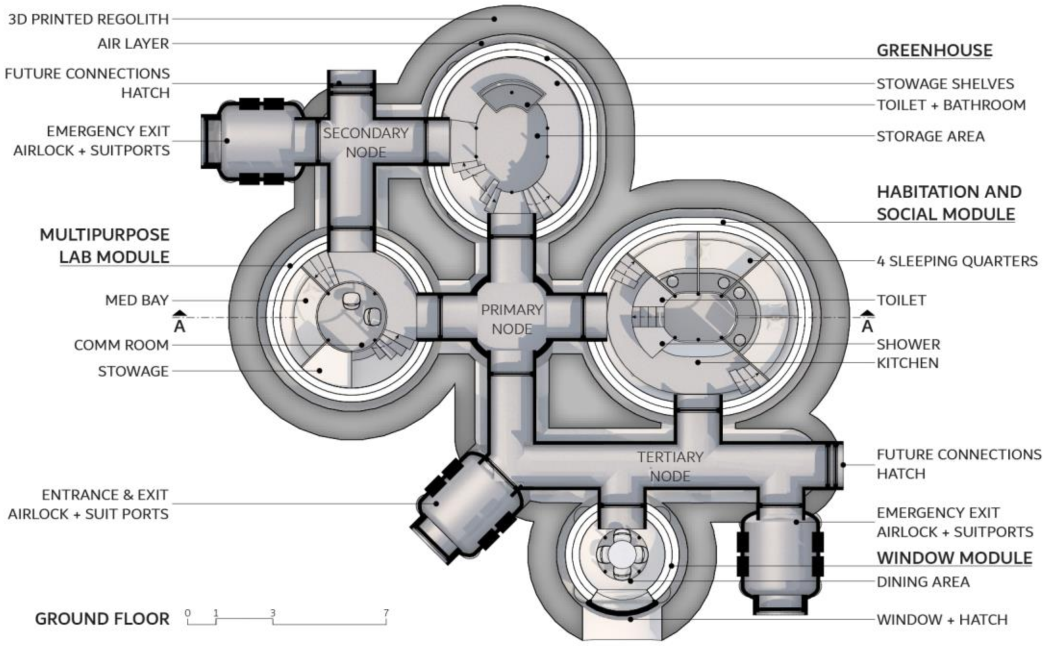

Figure 8. Ground Floor Plan

inflated shell, the sleeping quarters are small in area (0.82 m2), but make up for it in volume (8.5 m3). Each sleeping quarter will be equipped with a desk, a wardrobe, and a bed; the latter being strategically elevated and placed along the edge of the curved wall. Additional personal stowage will be provided beneath the floor panels.

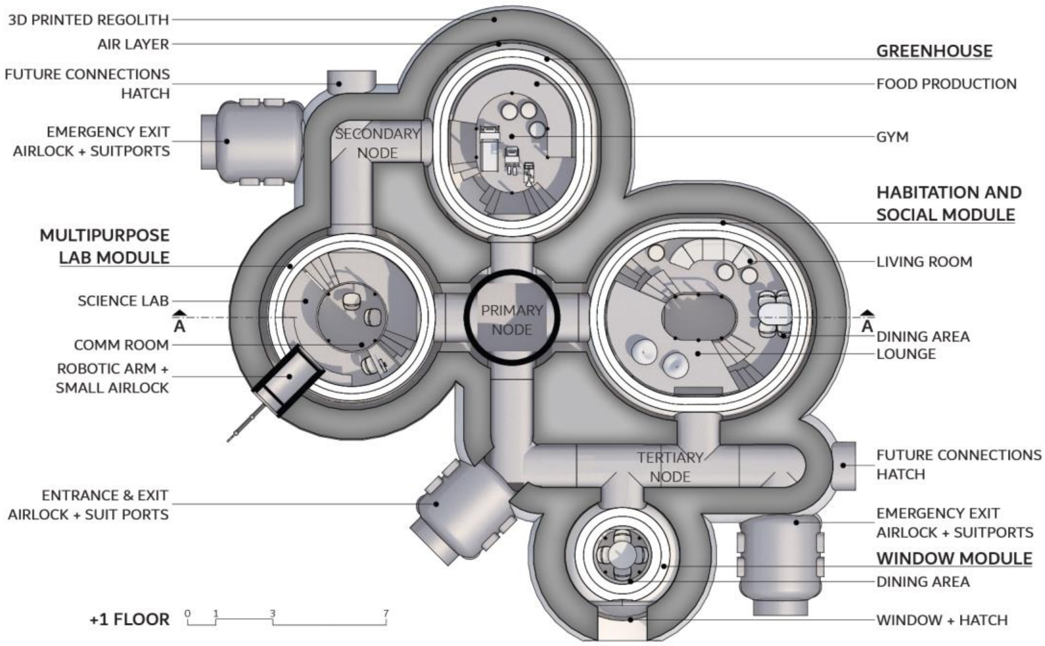

Figure 9. +1 Floor Plan

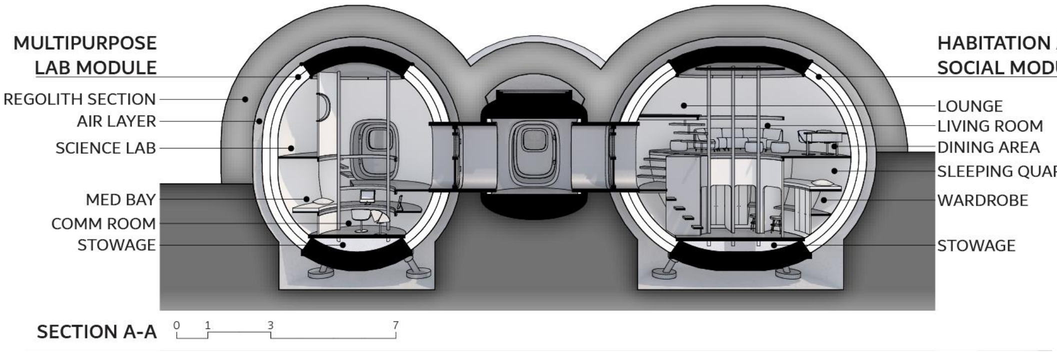

Figure 10. Section A-A

V. ISRU

The Moon provides plenty of raw materials required to establish a lasting, self-sufficient human station on its surface. Due to its vast distance from Earth, it is neither possible nor economically reasonable to provide permanent, interplanetary supply. ISRU will be necessary to minimize mission costs and launches from Earth and to provide a variety of construction material. For example, the 3D printed regolith shell will make use of in-situ resources for additional radiation protection.

Enabling the autonomous construction of the lunar base is of the utmost importance (Table 4). A specific set of rovers and construction machinery is required to access, excavate, and collect regolith for a 3D printing robot. Regolith excavation is one of the most important processes that enables the entire mission. Conventional mining methods are highly prone to pick wear, regolith abrasion, dust elevation, and electrostatic dust coating that may lead to mechanism failures and increased component wear over time[20]. The high vacuum environment also makes lubrication difficult[20]. To counter most of these issues, a pneumatic excavation rover, REG-X, designed by one of the authors will be employed. REG-X is powered by a radioisotope thermoelectric generator (RTG) and secondary batteries for a long-term independent operation. The system uses an isolated atmosphere in its forward compartment and will use the Venturi effect to excavate the regolith from the lunar surface. Short pulses of gas will be injected into the regolith using injector tubes leaving a vacuum in the tube. As a result, the nozzles at the end of the tube shall draw the adjacent regolith with the injected gas back into the delivery pipe leading to the collection container. To transport the regolith, an additional hauling module concept has been introduced. It has an electromagnetic couple that will allow it to integrate with the REG-X rover for the collection and efficient

Table 4. Robotic equipment for DIANA base construction

Image	Name of the component	Quantity	Mass per component [kg]	Power generation	Operation
	K-10	4	80	Li-Ion Batteries	Site monitoring, exploration and assistance
	Centaur 2 + Robonaut 2	2	500	Li-Ion Batteries	Assistance & Repair
	REG-X Pneumatic Traverse Mining Rover	10	2000	RTG + Secondary Batteries	Regolith Excavation
	Chariot	2	1000	Fuel Cells	Transportation between two sites
	Hauling Module (Chariot & Athlete&REG-X compatible)	2	200	-	Collect & Contain regolith for future transportation
	Athlete 2nd gen.	5	2340	RTG + Secondary Batteries	Platform for CCR&robotic arm for assistance in excavation
	Robotic arm	3	1000	-	Integrates drill, clamshell, excavating and gripping tools
	Contour Crafting Robot (CCR)	3	700	RTG + Secondary Batteries	3D printing regolith
	Lunar Electric Rover	2	4000	Fuel Cells	Pressurized transportation module for the crew
	Total	**33**	**48520**		

transport of the regolith. This module shall stay at the mining site as long as REG-X fills it to capacity. Then, it will be coupled with NASA's Chariot module[21], an independent unpressurized roving vehicle, to be taken to the regolith deposition site. The regolith will then be delivered to a 3D printing robot at the construction site.

There are several technology concepts that will be combined to execute the 3D printing task. The 3D printer technology, Deployable Contour Crafting Machine, is considered a viable option for regolith 3D printing[22]. This 3D printer has an integrated robotic arm that will enable the placement of extruded regolith into the desired form and size. This 3D printer module will be mounted on a mobile platform for increased operational feasibility. A NASA ATHLETE rover (2nd generation), powered with an RTG and secondary batteries, will be the platform for the 3D printer. It has a high reach (max. 15.5 m) and is highly flexible[23]. With this reach and the assumed 5 m length of the robotic arm attached to the module, the regolith shielding over the planned habitats (max. 7 m) shall easily be achievable and shielding for even higher structures is also a possibility[22]. In addition to the two ATHLETE rovers used for the 3D printing robot, three additional ATHLETE rovers, each integrated with a robotic arm, will be employed for drilling, clamshell, excavating and gripping-hand abilities[23].

VI. Further Development

Once the viability of the base and its production facilities are secured, the station will be expanded using lunar resources. Lunar concrete (processed regolith with a polymeric binder) will be used as the main in-situ construction material. To provide optimal living and working conditions, the base will continuously evolve by responding to the environment, to its population growth and to its residents' needs. Optimizing an adaptable interior configuration and a flexible layout will enable the crew to configure the space according to their needs and living preferences. The proposed design shows how an elementary surface base on the Moon could evolve into an established station and increasingly gain self-sufficiency by using local resources.

A. Expansion I

In the Expansion I phase, each module will be doubled to accommodate eight astronauts. The development is based on the already-existing components of the initial base, where the new modules will be attached by using the pre-existing connectors on the secondary and tertiary nodes. The modules are mutually connected with the intention of minimizing hazards, where most modules have at least two passages and all have quick access to an emergency airlock. This layout will ensure the separation and co-location of the original modules remain logical. The secondary window module will provide more access to Earth and lunar views. A second safe haven will also be incorporated in the new crew quarters, following the original design. Furthermore, the second greenhouse will be adjacent to the social module, allowing for easy access between the crops and kitchen as well as from the crew quarters to the exercise equipment and secondary toilet (Figure 11).

One important change to note is the separation of the science and medical laboratories (Figure 11). Initially, both will be contained within the multipurpose lab. However, when the additional module is added during the expansion I phase, the medical suite will be within its own unit. This allows for the inclusion of more equipment, more patients and better sterility. Furthermore, it creates more space for a wider variety of scientific experiments.

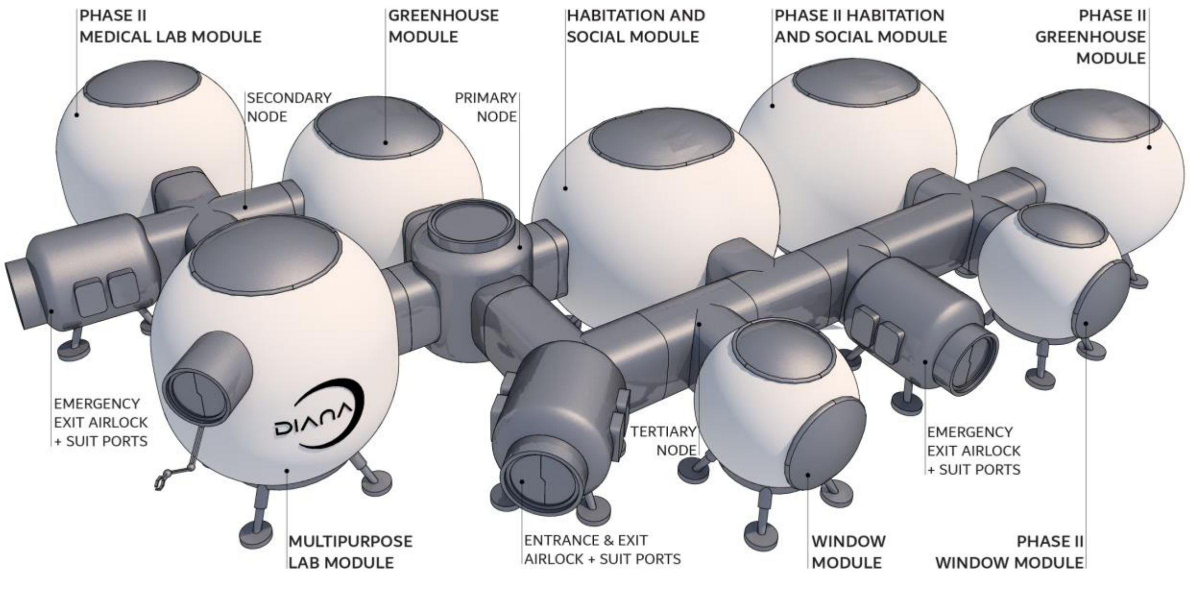

Figure 11. DIANA Station, expansion I

B. Expansion II

Expansion II is where the major expansion of the base arises (Figure 12). It moves from being solely a research station to a city-like structure, serving astronauts, tourists and residents. To meet the habitability requirements of this larger population, better living conditions are mandatory. As opposed to crew quarters, each individual, group or family will have their own self-enclosed apartment. Amenities required for lunar living will also be improved for this new group, including exercise facilities, recreational activities and research facilities. There will be a wider array of research being conducted, allowing visiting researchers to conduct their own work first-hand rather than relying on astronauts. Some innovative and lunar-specific recreational features will be included, such as stargazing facilities and activities on the lunar surface. The greenhouse will also be expanded and modified in this phase. The main greenhouse responsible for life support systems and food production for the entire base will be expanded and maintained by their respective experts. However, each section will have their own "garden" akin to a communal garden. Each "household" will have their own plot where they can grow whichever plants they desire from a selection of lunar-hardy plants. As with our astronauts, this will help maintain their psychological health, their connection to nature and create more opportunities for socializing.

Figure 12. DIANA Station, expansion II

VII. Conclusion

The lunar environment is not only a physically demanding environment, but a mentally and emotionally challenging one as well. It represents a physiological and psychological contradiction to the terrestrial environment in which humans have evolved. The optimal performance and welfare of the crew members will depend on their successful adaptation to the challenges of this extreme environment, which, in turn, will depend on the satisfaction of fundamental human needs. The human body is not made to survive in space, nor is the mind. Planning a habitat for the Moon is a tremendous challenge and requires combining the areas of design, engineering, and structural innovation to secure the deployment process and ensure habitability. It establishes a protective environment for the crew, ensuring a breathable and pressurized atmosphere and providing radiation and MMOD shielding. The modular configuration of the base offers spaces with different privacy aspects, as well as necessary functions, such as social and work spaces. With this project, we propose a long-duration lunar outpost that can be deployed and ready to be inhabited in a relatively short time. It is based on hybrid deployment construction and lower risk approaches for ISRU. Furthermore, the flexible and expandable modular design of the habitat allows it to be adapted as needed. The endoskeletal typology and deployment process should be further investigated and refined, and the choreography of the deployment dynamic simulated and tested in detail. Establishing a long-duration lunar outpost will be beneficial for further human space exploration with multiple applications for both Earth and beyond.

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