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Habot Mobile Lunar Base Configuration Analysis

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[Abstract] This study presents an architectural analysis of the base configuration concepts and options for the Habot Mobile Lunar Base. "Habot" is a contraction of Habitat and Robot. The analytical technique consists of a systematic comparison of the various configurations at several scales. These scales include the overall configuration of the base cluster; the architectural plan and sections of the Habot modules; the pairing and adjacency relationships among modules; the implications for structural details of the module pressure vessels; and the thermal control/heat rejection system. The evaluation criteria include complexity; mass of redundant overhead hardware; efficient use of floor area; useful allocation of equipment volume; and effectiveness of the circulation pattern. A major consideration is that the functional purposes of each Habot unit pose different demands and implications for the design. The minimum set of Habot unit functional types are: living/habitat unit, laboratory unit, logistics unit, EVA access/ airlock/ excursion port, and excursion Habot. The key finding of the study is that a simple linear arrangement of Habot units, with the EVA Access/ excursion port units at either end, is the most efficient. It is the most efficient at nearly all levels of the analysis, but most especially in the advantages for useable floor area, equipment volume, and avoidance of excessive circulation area and unnecessary design complications.

Nomenclature

ATHLETE = All terrain hex-legged extraterrestrial explorer.
CEV = Crew Exploration Vehicle
EVA = Extravehicular Activity
EOR = Earth Orbit Rendezvous
Habot = Habitat Robot
HARMONY = Human and Robotic Modular Infrastructures/Systems
HMVDM = Habitat Multivariate Design Model
KW = Kilowatt
LEM = Lunar Excursion Module, Apollo Program
LEO = Low Earth Orbit
LZ = Landing Zone
MMOD = Micrometeoroid and orbital debris
mT = Metric Tonne
Robonaut = An anthropometric, master-slave telerobot developed at NASA Johnson Space Center
RTG = Radioisotope thermal-electric generator
SE&I = System Engineering and Integration

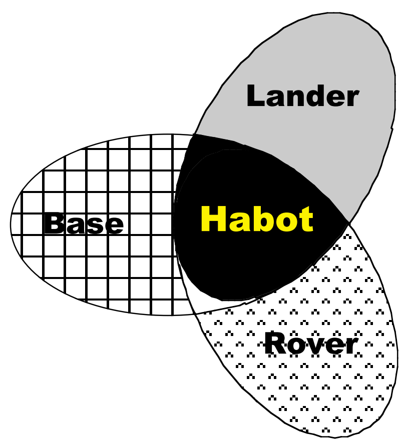

Figure 0. Diagram of the Habot Mobile Lunar Base Concept.

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I. Introduction

Habot is a contraction of Habitat and Robot. It constitutes an innovative approach to combine human and robotic exploration capabilities. (Mankins, 2000, 2001; Cohen 2003, STAIF 2004). The Habot concept consists of a self-mobile habitat that lands autonomously at a specific landing zone on the Moon. It moves under its own power to a lunar base site. More Habots follow, landing at the LZ and then moving to the base site. The Habots launch to the Moon over a period of one to two years. After verification of the first Habot mobile base, the first crew arrives. The nominal mission timeline is 100 days, allocated to a primary mission of two lunar day/night cycles (56 Earth days). There are eight Earth days planned margin for lift-off from the Moon and 36 Earth days reserve capability. The planned initial crew size is four astronauts. The baseline number of crew missions is 10, for a total planned crew time of 560 Earth days, with a total capability for 1000 crew days on the Moon during those 10 missions. Figure 0 expresses the Habot concept with its three aspects of lander, base, and rover; the rover and base are not fully contiguous because the rover units have a quasi-separate functionality from the base.

A. Crew Piloting Exclusion

The Habot is not intended to serve as a crewed spacecraft in LEO, in cislunar space, or in lunar orbit. It is intended for crew use only on the lunar surface. The crew would travel to the moon in a separate conveyance: the Crew Exploration Vehicle (CEV) that takes the crew to lunar orbit and then a crew descent/ascent lander. This vehicle or system of vehicles could derive from the Apollo architecture, but make common use of the nominal six-legged lander for the lunar descent stage and the surface mobility system. The proposed Crew Exploration Vehicle shall provide this cislunar crew transportation and so is not part of the Habot study.

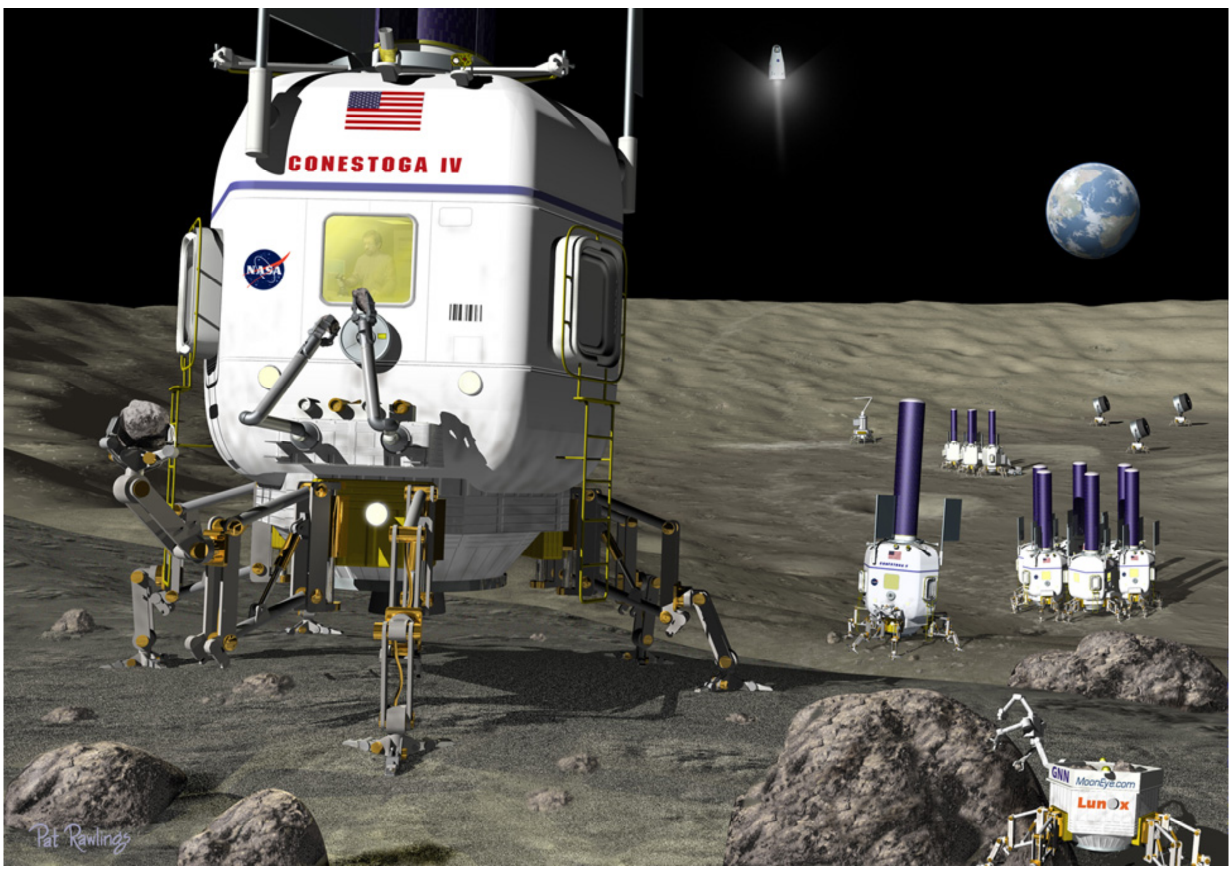

Figure 1. Pat Rawling's rendering of John Mankins' Habot concept.

B. Mission Activities

After landing successfully, the lander drops its terminal descent engine and moves a safe distance five to ten km away from the LZ to a pre-selected base site. These mobile modules can operate in an autonomous or teleoperated mode to navigate the lunar surface. At the site of the base, the modules can combine autonomously or telerobotically into the base cluster; make pressure port connections among themselves, to create a multi-module pressurized lunar base. Once enough Habots arrive to form the lunar base, they assemble at a site of scientific or technical interest, and make the vital connections for pressurized access, communications, data, life support, etc. After the Habots form the lunar base and verify it as safe for the crew, the first lunar expedition crew may launch from Earth in the CEV. The crew lands in the separate Apollo LEM-like lander and transfers to the Habot base, where they set up housekeeping and begin their work. When the crew completes their mission, they launch from the lunar surface in an Apollo LEM-like ascent stage, rendezvous with the CEV in lunar orbit, to return to the Earth. In the following weeks or months, the Habots may separate from one another, and move across the lunar surface to a new location of scientific interest, and a second crew arrives.

During the lunar day, the crew would conduct the exploration portion of the mission, working from the base. In addition to the base cluster, the concept includes two or three Excursion Habots. The crew would use the Excursion Habots as rovers, meeting and docking as necessary for various crew operations and procedures. As the lunar day approaches its end, the excursion Habots would return to the base cluster, where they remain except for contingency or emergency operations. During the lunar night, the crew stays primarily in this united lunar base, and pursue work that they can perform in the laboratories with minimal need for EVA or rover excursions. They conduct scientific work in the laboratory unit and prepare scientific and technical publications. This arrangement constitutes the baseline configuration for the Habot cluster.

It is also possible for the crew to drive or travel with the Habots in a traverse in an individual Excursion Habot or with some or the entire base, although their presence is not required for this migration. The crewmembers also use individual Habot units as pressurized rovers to explore the lunar environment. In Figure 1, the articulated legs carry manipulator devices that can pick up rocks. A hexagonal "benzene ring" cluster appears in the middle ground at the right.

Table 1. Advantages and Disadvantages of a Stationary Lunar Base versus the Habot Mobile Lunar Base

	Stationary Lunar Base	**Mobile Lunar Base**
Advantages	• Accumulation of assets in one location / economy of agglomeration. • Economies of scale in one location. • Potential for larger, permanently situated habitats (e.g. inflatables). • Potential to use regolith as ISRU radiation & micrometeoroid shielding. • Ability to situate power supply permanently (i.e. nuclear reactor) in a crater near the base, and to fill in the crater with regolith for final burial and disposal. * Less Complexity – no need to make everything mobile.	• Greater mobility of assets affords superior exploration opportunities and operations. • Makes best advantage of commonality and economy of scale through mass production. • Ability to easily modularize the Habot modules to match launch vehicle capacity. • Greater systemic redundancy • Ability to bring the science lab to multiple sites of interest – excursions are not "just picking up rocks." • Single type of EVA access module for both excursion rovers and base. • Can establish a Landing Zone at each new location and moving Habot units from the Landing Zone is not a burden.
Disadvantages	• Program RISK of putting the fixed base in the "wrong" location and needing to support distant science field operations. • Necessity for dissimilar heavy equipment movers and pressurized rovers. • Cost and burden of moving all modules and equipment from the Landing Zone. • Risk of stranding a rover excursion crew far from the base. • Ability to satisfy only a small subset of the scientific constituencies.	• Risk of a roving base not returning to the ascent vehicle. • Risk of reconnecting modules at new base location. • Increased complexity. • Must carry its own radiation shielding** ** See Cohen (2004, July) Carbon Shielding for the Habot Mobile Lunar Base. SAE 2004-01-2323

C. Mobility and Speed

The speed at which the Habots move is secondary to safe navigation and movement over varied and rough terrain. The acceptable top speed may be only 1km per hour. In difficult terrain, 10m per hour may be an acceptable speed. *The point is* that without the crew present to consume precious life support and other consumables and supplies (and with a limited radiation exposure window) THE SPEED DOES NOT MATTER so much as predictable, reliable, and safe operations. The crew waits safely on Earth until the Habots arrive at the new base location, before they launch to the Moon. Moving at low speed not only reduces risk, but the need for power for acceleration, with its attendant mass penalties.

D. The Habot Base

The Habots cluster together to form a base-habitat complex. They dock together, form pressure seals, and pressurize the complete living environment. After verifying that the Habot base is ready, the crew arrives on the Moon to occupy the Habot base. After carrying out their mission, the crew returns to Earth. The Habots disconnect the base and migrate across the lunar surface to the next mobile lunar base site. There, they cluster together again, reconnect to form the base, and verify readiness. A new Habot logistics module may land at the second base site to resupply consumables and bring new equipment. The second crew arrives to carry out the next mission.

E. Design Parti: Habot Advantages and Disadvantages

The design parti (point of departure) for the Habot begins from the analysis of advantages of a mobile base versus a stationary base, as presented in Table 1. This table leads to the question: ***So, why not make the entire base mobile?*** Then all the resources, reliability, and redundancy of the lunar mission move with the exploration crew. This approach means that the laboratory facility would travel with the explorers, affording them the capability to conduct complex and sophisticated scientific assays and analyses on site, without a need to "return to the base." Wherever the crew may roam, they are at home at the base.

Figure 2. Brian Wilcox with the full scale ATHLETE Rover prototype. Courtesy of NASA-JPL

II. Mobility System

The Mobile Lunar base allows the explorers to bring the base to the sites of scientific interest to make the most complete investigation, without the severe constraints and limitations to traverses and EVA sortie time. A further advantage of the Mobile Base system is that it is possible to land new mobile modules with new equipment, supplies or logistical support in the path of the moving ensemble. These new units could then join the "wagon train" to continue on the journey, or simply provide a cache of supplies for the crew to pick up along the way. The mobility system is a critical part of the Habot System. It is a challenging problem because it requires a durable and reliable transportation system to carry a 10 mT mass across the rough lunar surface without danger of overturning or losing control. Although the early Habot concept in Figure 1 incorporated a hexapod walker with the leg mounts in a hexagonal configuration, such a system has not yet been proven to carry the payload of the pressure vessel and all its associated systems. Therefore, it is necessary to consider better proven and tested — although perhaps more conventional — alternatives.

The closest embodiment to the original Habot image is the *all terrain hex-legged extraterrestrial explorer*. (ATHELETE) rover from NASA-JPL. A team at NASA—JPL led by Brian Wilcox and Jaret Matthews is developing the ATHJLETE, also known as the "wheels on legs" or "wheels on strut" concept that can make dual use of the legs for a lander and a rolling mobile unit that can lift its body over obstacles. Although the suspension design to support a large habitat payload (5 to 10 mTons) will be a challenge in terms of resisting the overturning moment, while maintaining ground clearance, and assuring dynamic stability, it lies in the domain of conventional mechanical and automotive engineering. Figure 2 shows Brian with the full scale ATHLETE prototype.

The mobility system interacts with the base configuration in profound ways. However, this scheme does not really address the full intent of the Habot concept, which requires that each Habot be mobile as an integrated "System of Systems." The difficulty in making this integration succeed lies in matching the base geometry to a mobility system that can align and place Habot modules correctly within the configuration plan. This question encompasses how to combine the modules and how to physically place them into the configuration. Small units are easier to make mobile, both for short, one-time traverses and for repeated long hauls.

Table 2. Comparison of Automobile and Aircraft Industries to Space Station Considered as an Industry.

■ **Automobile Production**	■ **Aircraft Production**	■ **ISS Module Production**
■ $1-3Billion in R&D, tooling, & facilities per vehicle type (e.g. cars & light trucks).	■ $6-8 Billion in R&D, tooling, & facilities per aircraft type (e.g. 7E7).	■ $15-20 Billion in R&D, tooling, & facilities, for 5 Modules (each is unique).
■ 1 Production facility	■ 1 Production facility	■ 5 Production facilities.
■ Production Rate: 50 cars/ hour -- ~160,000/year.	■ Production Rate: 100 to 200 planes per year.	■ Production Rate: 5 modules + 3 Nodes in ~10 years
■ Standardized operation and maintenance. Small service stations can maintain & repair any vehicle.	■ Standardized operation and maintenance. Regular Airport Service Depots can maintain & repair the aircraft	■ Operations & monitoring for each module is unique.
		■ Differences in modules create vast complexities in integration and maintenance that require huge ground support.

A. HABOT Mass Production

A fundamental driver behind the Habot concept is that—aside from the conventional methods of reducing launch mass and mission scope—the only certain way that NASA or other space agencies know to control or reduce costs as a large percentage of a mission or program is mass production of common elements. The key question that the Habot design answers is this economic basis for building them.

Despite the various tools to chip away at cost such as value engineering, earned value management, and life cycle cost analysis, ***there is no miracle*** waiting in the shadows to reduce launch costs, development costs, or fabrication costs by half or more. The only way to reduce fabrication and operating costs over the long term is to make a vehicle that is simple, reliable, and produced in significant numbers to achieve an economy of scale.

To understand the importance of mass production and the economies that it affords, it is useful to compare space module production to other industries. Table 2 presents a comparison of three industrial production models: The automobile industry, the commercial aircraft industry, and the International Space Station (ISS) viewed as an industry. There are two comparisons to consider. The first comparison is commonality: Table 2 describes how the Space Station ensemble consists of one-of-a-kind, dissimilar modules. The second comparison concerns the number and size of modules, whether they are similar or dissimilar, common or non-common. There are two arguments. The *Integration Argument* and the *Modularization Argument.*

B. Integration Argument

The *Integration argument* states that it is most cost-efficient in terms of System Engineering and Integration (SE&I) to combine all functions into a single large module that can be built, integrated, and transported in one unit. In this way, there is just one type of module or unit, and the SE&I costs are not duplicated or "wasted" on a second module type. The estimates of SE&I as a total cost of an International Space Station module type may run as high as 75%. In the end, there will be five different modules on the ISS, not counting the nodes.

C. Modularization Argument

The *Modularization Argument* states that it is more economical, reliable, and safe to spread the risk of a human lunar mission among multiple modules with very strong commonality. In this view, the ability to mass-produce common modules can reduce the cost and simplify the process of SE&I, despite some variation in the functions assigned to each module. Given a true common module that can be adapted to house a variety of functions, a lunar exploration program would become much more manageable. A small common module in the range of five to ten metric tonnes (mT) would be a candidate for launch on the Energia to Saturn V class of vehicle for a "direct to the moon" mission without earth orbit rendezvous (EOR) of separate launches or vehicle assembly. The Habot stands firmly for modularization.

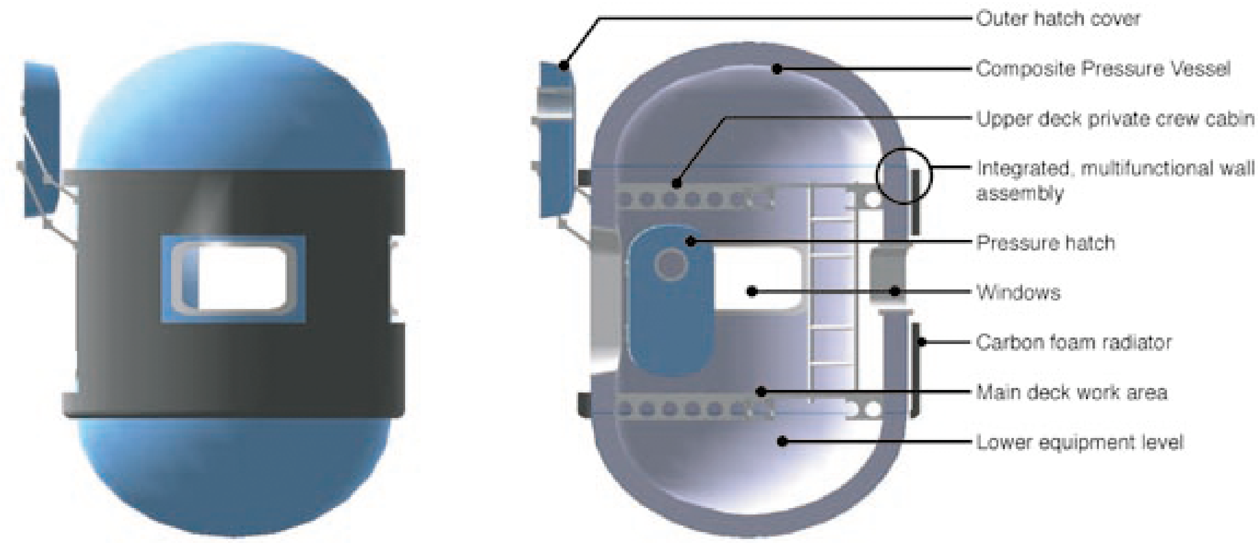

Figure 3. Concept for a Habot module (Drawn by Ross A. Tisdale).

IV. The Habot Base

The core of the base consists of the Habot modules and the ways in which their design is customized but still common to support the crew's living and working activities. The configuration grows from the module types, and conversely informs the module type designs to facilitate configuration-specific arrangements.

A. Habot Module Types

In his 2000 and 2001 articles, Mankins proposes six Habot modules that form the Modular Integrated Lunar Outpost "MILO" cluster. The Habot Base would consist of more module types, deriving from the same basic pressure vessel, platform, and chassis. Together, these modules comprise the complete living and working environment: Figure 3 shows a Habot "basic module" that can adapt to support each of these functions:

1. EVA Access Facility, including Suitport "airlockless airlock," the NASA "Robonaut" anthropomorphic master-slave, tele-robot and EVA suit Stowage and maintenance.
2. Ward Room (back-up Command and Communications Center).
3. Crew "Cabin" (Sleeping Quarters) in two or more modules.
4. Life Sciences Laboratory #1.
5. Physical Sciences Laboratory (Cupola and Observatory) #2.
6. Bio-regenerative Life Support Laboratory # 3.
7. Physical/Chemical Life Support Laboratory # 4.

8. Two or more Excursion Habots (rovers) for Local Exploration.
9. Fuel and Logistics Depot.
10. Powerbot mobile energy unit w/reactor or other source.

B. Base Plan Configurations
Figure 4 present John Mankins' early concepts for the Habot lunar base cluster. In both diagrams, a detached Habot Rover unit (Excursion Habot) appears in proximity to the airlock / docking module. Mankins chose the hexagonal plan geometry as a deterministic way to evolve a hexagonal grid, three-axis plan. However, when imposed upon pressure vessel design, it poses serious technical problems. Thickening and reinforcing the 120° corners add considerable structural mass. Flat surfaces are not natural for a pressure vessel, so the six faces require stiffening, which means more mass. These differentially strengthened areas may tend to reduce the ability of the structure to expand and contract in a consistent manner; thereby possibly creating unwanted stress concentrations between the reinforced corners and the stiffened flat panels. In subsequent module plan designs, the floor plans are circular to represent an upright cylinder, consistent with Figure 4.

C. Open-Ended Plan
Figure 4/DIAGRAM 1 shows the relatively open-ended "HARMONY" configuration that Mankins presented in the original 2000 paper on the Habot. The module labels correspond to the designations in the original concept. This plan has the potential advantage of being able to "grow organically" on-axis within the constraints of the 60°/120°/180° geometry. It would allow replacement Habot units to be attached at almost any open port, and for adaptability as the plan expands or contracts.

D. Closed-Loop Plan
Figure 4/DIAGRAM 2 presents the closed-loop "CONESTOGA" (benzene ring) configuration that appears in the artist's rendering shown in Figure 2. The labels in DIAGRAM 2 show the authors' interpretation of those modules into the ring configuration. The benzene ring affords the surest means of achieving dual access and dual remote egress from all the core modules. However, the benzene ring concept poses the additional challenge of the "last module docked" between two pressure ports angled at a 120° apart. Although US Patent 4,728,060 on the Triangular-Tetrahedral Space Station claims the lateral docking of a module between two nodes, the alignment of all pressure ports occurs along one axis, not at an obtuse angle as in Figure 4.

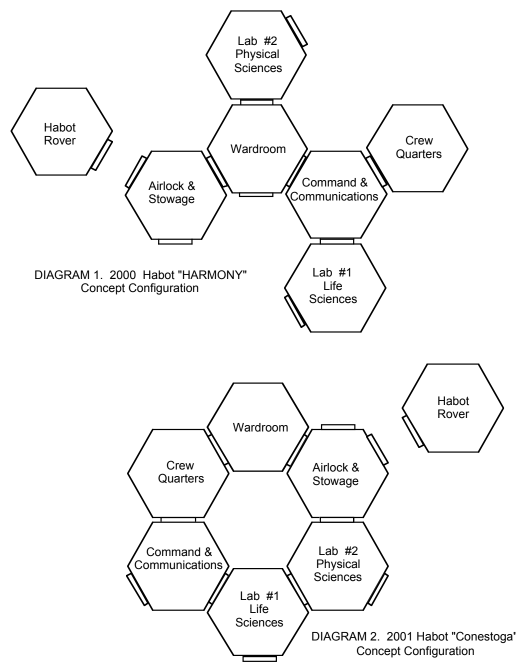

Figure 4. John Mankins' configuration concepts for the Habot Base cluster. (2000, 2001).

V. Configuration Analysis
The following series of diagrams and sketches conveys a first order architectural design analysis of Habot base configuration. This analysis addresses both the clustering of modules to form a base, and the "internal configuration" – the plans and sections that describe a building architecturally. The geometry of the Habot modules and base must be rigorous to make the best use of limited area and volume. Yet, the individual Habot modules are so small that the interaction of the module-scale and the base geometry becomes critical to what would constitute a successful Habot "System of Systems" design for these configurations.

A. Configuration Criteria
In developing this analysis, the study established these nine criteria for the Habot Base Configuration:
1. Provide circulation access to all parts of the base. Dual access is preferable.

2. Provide egress from all parts of the base; ideally, the configuration will provide dual remote means of egress for fire safety and escape in emergencies.

3. Provide an efficient and utilitarian amount of equipment functional areas and volumes; the shapes of these areas and volumes must be compatible with the circulation.

4. Provide the ability to create suitable workspaces and social areas within the base.

5. Provide ease of mobility for assembly and disassembly of the base.

6. Provide efficient thermal view angles for body-mounted radiators.

7. Provide docking modules for Excursion Habots, including accommodation for EVA access.

8. Minimal number of pressure port angle variations.

9. Docking port efficiency.

B. Habot Floor Plans

As shown in Figure 3, the exterior wall thickness would be approximately 20cm to 25cm thick to accommodate radiation shielding, thermal insulation, body-mounted thermal radiators, and micrometeoroid and orbital debris (MMOD) protection. This wall thickness would enclose a floor plan in the range of 3.5 to 4.5 m interior diameter. This dimension would allow the Habot module to fit comfortably within the 5m-diameter shroud of the Delta IV Heavy or Atlas V launch vehicles, or on top of a larger Saturn V/Energia class of rocket.

1. Circulation Area

The subtractive quality of circulation area becomes very powerful as the number pressure ports for docking/berthing/circulation increases. Even with the minimum number of two ports shown in plans A, B, and D, the circulation area severely diminishes the equipment solid packaging area. For Plan F, with four pressure ports at 90°, the area available to install equipment is almost purely residual between the pressure ports. This preliminary result suggests strongly that an interior diameter of 4m or less poses a serious challenge to allow a feasible design for a Habot.

Circulation is neither a negative phenomenon nor a complete liability. It provides a variety of useful functions besides allowing people and hardware to move around in the module or the base configuration. In a spacecraft, the circulation area and volume provides working room in front of equipment racks. It provides a de facto social environment. The circulation areas also provide a very important factor of perceived spaciousness, that researchers can model quantitatively (Wise, 1988).

2. Floor Area Analysis

Figure 5 shows an analytical exercise to examine the circulation/ equipment—figure/ground phenomenon of the Habot plans. For this exercise, the interior diameter of the Habot module was set at 3.75m, based upon the findings of the earlier HMVDM for a constant volume Habot module of $50m^3$ total pressurized volume (Cohen, SAE 2004-01-2466, p. 17). This diameter gives an interior floor area of $11.04m^2$ (exclusive of outer wall thickness). This decrease from the 4m diameter's $12.5m^2$ makes the architectural layout more challenging, but also suggests that it is possible to hold to volume and mass constraints.

The essential dimensions for the 3.75m diameter Habot Plan types appear in Figure 5. The plan composition rules are as follows:

1. Each plan type has a center circulation area, 1750mm in diameter.

2. This center circle connects to at least one passage, 1500mm wide, leading to a pressure port (standard ISS 1250mm wide). The total circulation area equals the center circle plus the area of all the passages.

3. The "Usable" solid equipment area equals the total floor area minus the circulation area.

4. For each additional pressure port in the outer wall of

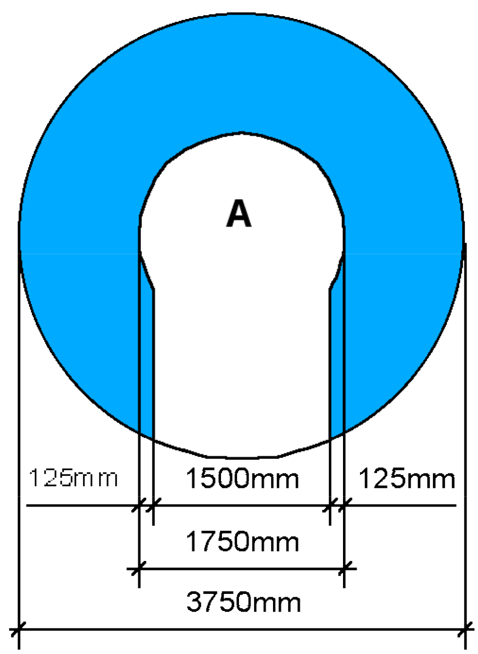

Figure 5. The basic interior plan dimensions for the Habot Floor Area Analysis Exercise, illustrated using Habot Plan Type A.

the Habot module, a dedicated passageway is required.

In the upper left quadrant of Figure 6 are nine Habot Plan Variations. Table 3 explicates the area properties of each of the nine Plan Variations. It documents the inverse relationship between the number of pressure ports (with their associated circulation aisles) and the usable equipment area. With two ports each, Plans B, C, and J afford the highest ratio of usable equipment area to circulation area.

C. Habot Plan Types and Areas

Table 3 presents the area and volume properties of the nine Habot module plans. The diameter for this exercise is the 3.75 m result. The most obvious observation is that the inverse relationship between circulation area and solid equipment area. The more circulation area required, the less area and volume would be available for equipment or other functions. The following plan briefs refer to the Habot Plans in Figure 6.

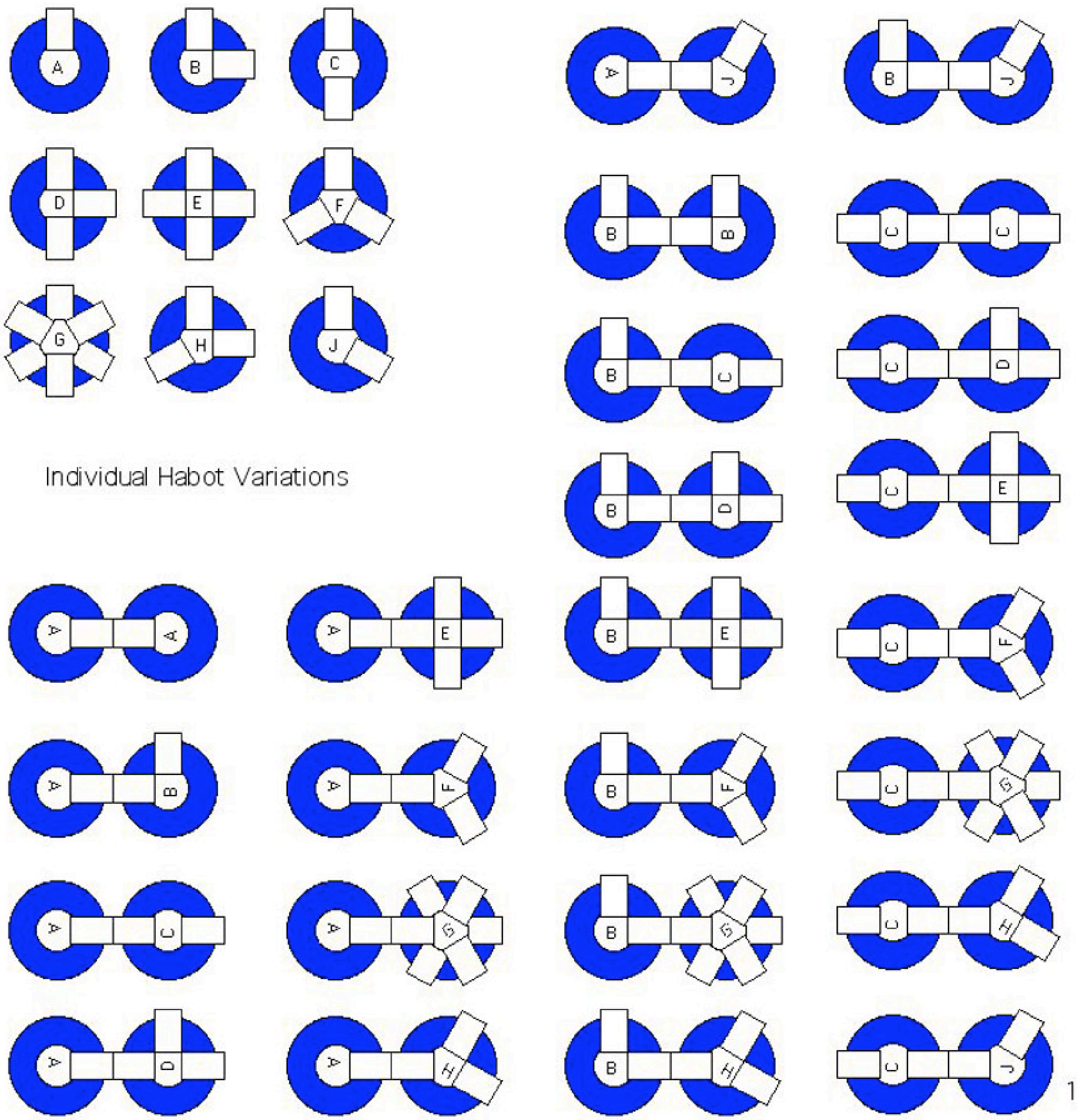

Figure 5. Individual Habot Module Variations and Pairing Patterns of the Module Variations.

Habot Plan Type A

Plan A represents the minimal circulation arrangement with one pressure port entry and one passage to the center circle. The practical application of Plan A *as a living and working environment* would be limited to an Excursion Habot or rover in which the second means of egress is the EVA airlock. As in Diagram 4, Plan A may also be applicable for a logistics module that would dock to one spare pressure port on the Habot base cluster.

Habot Plan Type B

The "L"-shaped Plan B divides the equipment area into a major "three quarters"-area and a minor "quarter"-area. However, please note that 3*quarter area ≠ 1 three-quarter area because of the tremendous impact of the circulation. In this plan, the ratio of circulation to equipment area is essentially 1:1. Plan B represents the minimal arrangement for a base assembly pattern based upon 90° bends in the circulation pattern. It would come into play in an orthogonal scheme.

Table 3. Properties of Nine Habot Floor Plan Variations for a 3.75m Diameter Module

Plan Type	Name	Circulation Area	"Usable" Equipment Solid Area	Percent Circulation Area	Percent "Usable" Equipment Solid Area	Ratio of "Usable" Area to Circulation Area	Remarks
A	Single	4.04	7.00	36.6%	63.4%	1.73	Occurs only as Habot Rover w/ airlock.
B	Double 90° "L"	5.60	5.44	50.7%	49.3%	0.97	Equivalent to Plans C & J
C	Double 180° "Fat I"	5.64	5.40	51.1%	48.9%	0.96	Equivalent to Plans B & J
D	Triple 90° "T"	7.16	3.88	64.9%	35.1%	0.54	
E	Quad 90° "+"	8.71	2.33	78.9%	21.1%	0.27	Node for cruciform plan
F	Triple 120°	7.27	3.77	65.9%	34.1%	0.52	Essential node for "HARMONY"
G	Hex 60°	10.64	0.40	96.4%	3.6%	0.04	Not Feasible, except for a non-equipment area.
H	Triple "Y" 90°/135°	7.19	3.85	65.1%	34.9%	0.54	Occurs only in Hybrid Plan
J	Double 120°	5.63	5.41	50.7%	49.3%	0.97	Key unit for "Benzene Ring," Equivalent to Plans B & C.

Habot Plan Type C

The straight passage with a widening in the middle of the "Fat I" in Plan C represents the simplest connecting unit that affords dual access and dual remote egress. This plan divides the equipment area into two bilaterally symmetric and equal sides. . In this plan, the ratio of circulation to equipment area is essentially 1:1.

Habot Plan Type D

The “T”-shaped layout of Plan D attaches a module to the side of a linear arrangement of Habot units. This plan creates two smaller “quarter-areas” and one larger “half-area.”

Habot Plan Type E

The orthogonal cross-axis in Plan E divides the floor into four equal “quarter-areas.” Plan E allows two linear arrangements of Habots to “cross” at the center. This cruciform plan would afford four end units at which to connect Excursion Habots or airlock units, compared to the two available in a single linear arrangement.

Habot Plan Type F

Plan F conveys the omni-directionally symmetric arrangement of three pressure ports 120° apart. The three passages divide the equipment area into three equal third-portions. The ratio of usable equipment area to circulation area is approximately 1:2. This plan reflects the nodes in Mankins’ HARMONY Habot base cluster. They would also play a role in a “benzene ring” plan to allow the attachment of Excursion Habots to the third port that is not forming part of the ring.

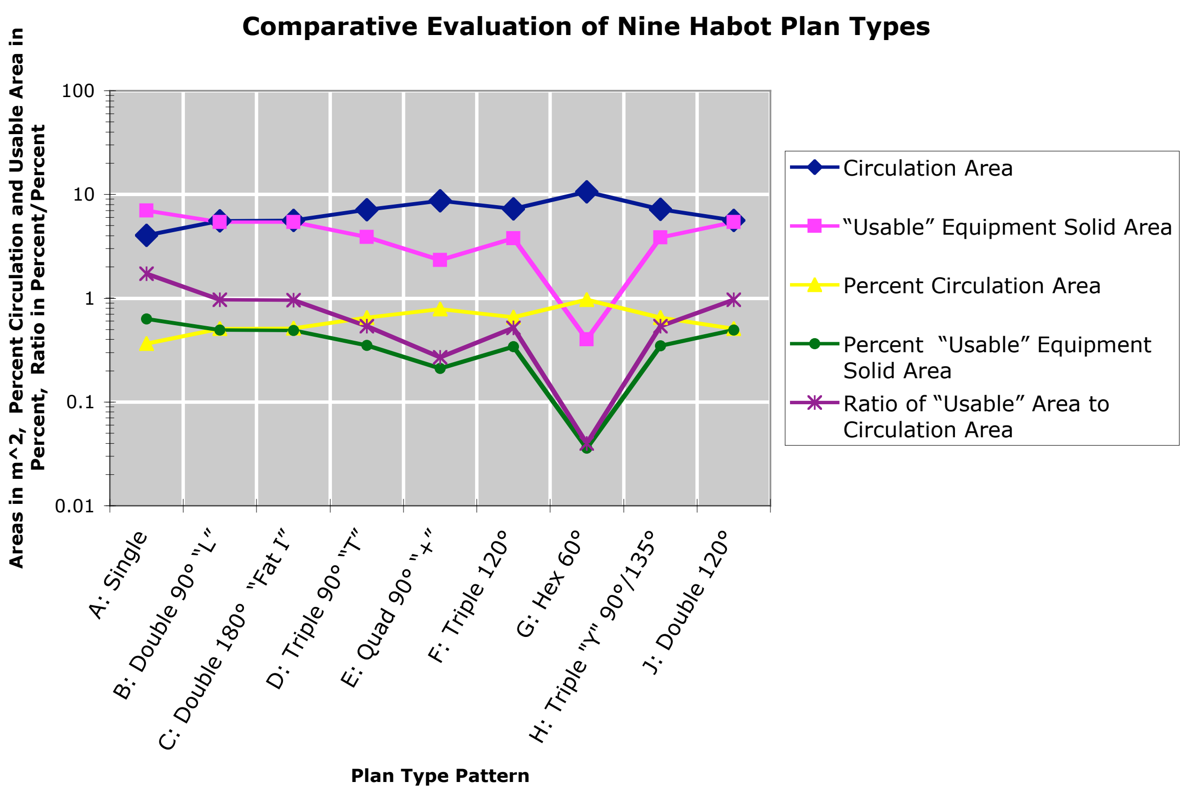

Figure 7. Comparative Evaluation Chart for the Nine Habot Plan Types.

Habot Plan Type G

Plan G displays the maximum circulation area possible, with six pressure ports and six passages at 60° apart, around the circumference. At less than 5%, the floor area available for equipment packaging is nearly non-existent. However, this geometry may be appropriate for a central circulation hub, exercise, or recreation area, as a social area that could include demountable furnishings and equipment.

Habot Plan Type H

Plan H presents the unusual option of combining a 90° bend with an obtuse angle. In this case, the angles mark symmetrical 135° rotations from the vertical axis. This plan would play a role as a node in a so-called “Hybrid” scheme that combined two or more of the prominent angles (60°, 90°, 120°). The Hybrid plan circulation pattern results in one quarter-area and two bilaterally symmetric 135° oblique areas, slightly larger than the 120° oblique third-areas.

Habot Plan Type J

Plan J represents the benzene ring equivalent straight-through passageway. The 120° angle between the pressure ports actually makes no significant difference from the straight passage Plan C. In this plan, the ratio of circulation to equipment area is also essentially 1:1. The two floor areas at 120° and 240° suggest a use for a galley and dining area, with the galley and food storage in the larger part and the wardroom table against the wall in the smaller part.

Figure 7 presents a chart of the five evaluation metrics in Table 3. These results are not additive. Each data point has meaning only in comparison to the other points on the same line. Figure 7 suggests that the plan types that score consistently highest will perform best. These plan types include most notable Plan A Single, Plan B Double 90° L, Plan C Double 180° T, and Plan J Double 120°. The plan that scores dramatically the worst is G Hex 60°.

D. Habot Pairings

Since the better scoring plan variations shown in Figure 5—and more—appear feasible, the next step is to look at the possible permutations or combinations. Since the total number of linear permutations (excluding changes in plan orientation) is 9 Factorial = 362,880, it not practical to enumerate them all. Neither is it possible to *start* with a ***deductive*** approach. Instead, this analysis takes an ***inductive*** approach of postulating a range of plan types and the ways in which pairs of them may combine. In this manner, the remaining three quadrants of Figure 5 illustrate selected pairings of the Habot Plan Variations. These pairings stand irrespective of the larger Habot configurations of which they may form a part. Two modules would not make a lunar base, but they might comprise an "outpost." After pairing, a lunar base might be the next step. The value of this paired plan approach is to look at a "molecular" level at how these building blocks of the base cluster can join. This pairing exercise demonstrates several architectural design precepts:

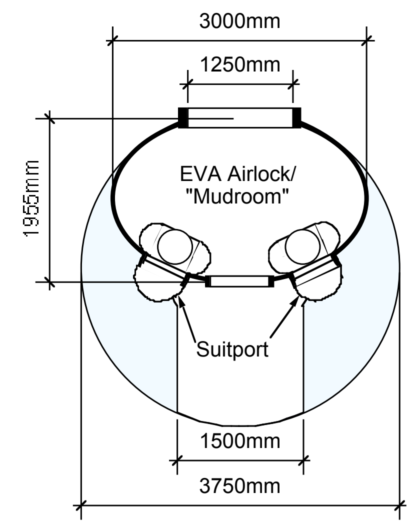

Figure 8. Plan of a Habot EVA Access Module, showing details of the airlock with two Suiports.

- The net architectural building area (per American Institute of Architects, D101, 1994 or later edition) can be defined as the gross building area minus circulation, service and utility areas.
- Paired Habot modules would function as adjacent rooms with a more diversified geometry.
- The pairings of Habot Plans show that a complex pattern of solid and open areas can develop in a geometrically diverse configuration.
- The 90° modules suggest an orthogonal pattern of development and the 120° modules suggest a hexagonal pattern.
- Joining unlike modules can create a visually stimulating arrangement, introducing much-needed variety into the confined and isolated lunar base interior.

E. Suitport EVA Access Facility

The EVA spacesuit, airlock and support system is part of the plan for the Habot crew to perform their scientific and engineering missions successfully. In, the NASA Exploration Systems Architecture Study (December, 2005, pp. 126-127) portrayed the Suitport as an alternative to the conventional pumpdown airlock for a lunar base or habitat. This "airlockless airlock" provides an efficient functional concept for space suit egress and ingress (US Patent no. 4,842,224). This EVA Access Facility is a key component of the Habot EVA module and the Excursion Habot. Figure 8 shows a schematic plan view of a Habot EVA Access module. The Excursion Habot or Habot-Rover would be similar insofar as it would include the airlock and Suitports.

F. Thermal View Angles

In addition to the architectural plan and mobility system analyses, thermal view angles emerge as an important consideration. Figure 3 shows the Habot module. Wrapped around this module is a body-mounted radiator to reject heat from the thermal and environmental control systems for the living environment. These systems collect heat from the life support system the electronics, people, plants, lights, other equipment, and sources of heat. While passing through the air revitalization process, the heat passes through a heat exchanger to a coolant loop that carries the heat to the radiators, which then reject it into space. The red "wavy" hatched segments of the external radiators indicate that they have active coolant flowing through them to reject heat.

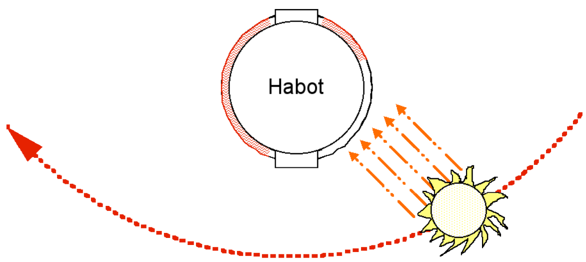

Figure 9a. Lunar Morning. Body-mounted radiators reject heat orthogonal to the sun's insolation and away from it.

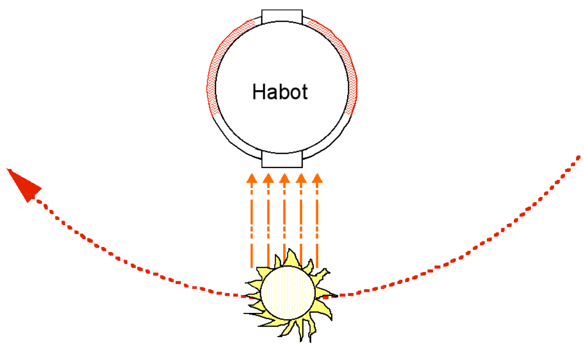

Figure 9b. Lunar Noon. Radiators shift active surfaces around to reject heat away from the sun.

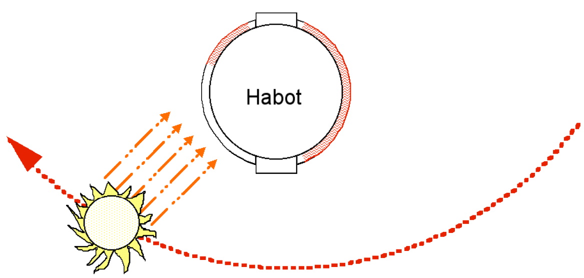

Figure 9c. Lunar Afternoon. Radiators shift active surfaces further around, away from the sun.

1. Incident Sun Angle

As the moon rotates, the sun appears to move through the sky much as it appears from earth, rising in the east and setting in the west. By providing omnidirectional heat rejection, the Habot modules and base configuration would be less constrained by thermal orientation than if the radiator view angles were restricted. The external radiator plumbing would be zoned into sections of 45° circumferentially, allowing heat rejection to occur selectively in directions that did not face the sun.

Figures 9a, 9b, and 9c illustrate this approach. During the lunar morning, when the sun rises in the East and shines in direct normal on the east radiators, they would absorb more heat than they could reject, so they are not used for cooling a that time. The west and north radiators that do not receive direct sunlight provide this cooling. Then, as the sun moves across the sky throughout the lunar day, the radiators reject heat from the radiators least exposed to solar radiation. As the sun rises higher in the sky, so that the direct solar radiation on the east radiators gradually diminishes, the Habot begins rejecting heat from the East, while continuing on the West. At Lunar Noon, the Habot rejects heat equally east and west. In the Lunar afternoon, the west radiators gradually diminish as a fraction of total heat rejection, while the east radiators become primary.

2. *Heat Rejection View Angle*

In addition to the incident sun angle, a second consideration is the *thermal view angle* for heat rejection. Ideally, the heat rejection system should not radiate toward a warm object – particularly another radiator –, which would diminish the efficiency of both. Figure 9 shows two thirds of the body-mounted radiators active at one time to reject heat as the sun moves through the lunar sky.

G. Habot Module Connection Patterns

Figure 10 presents a graphical exploration of how these plan types may combine into Habot base configurations, as a systematic matrix of Habot module connection patterns. It draws upon previous work by Sherwood and Capps (1990) on module cluster topology analysis. It identifies four fundamental connection angles: straight (could be considered 180°), 60°, 90°, and 120°. Figure 10 tests these four angles against four configuration types: Open Configuration, Closed Loop Configuration, Expanded Loop Configuration, and Hybrid Configuration, revealing several fascinating relationships:

• The Open Configurations for Straight and 90° angles are quite similar to each other, and so are Open Loop Configurations for the 60° and 120° angles.

• The Minimum Closed Loop Configurations for all 60°, 90°, and 120° angles are all simple polygons: triangle, square, and hexagon, respectively.

• The Expanded Full Loop for all four angles develops from adding 180° Plan C units.

• The Hybrid Configurations combine loops and multiple angles with additional C Plans.

• The Suitport oval appears as the white arc-segment in units at the end of the axes. These units represent the EVA Access modules or Excursion Habots that may be nearly identical in plan.

VI. Configuration Evaluation

TABLE 4 presents an evaluation matrix of the four fundamental patterns presented in Figure 10 against the nine configuration criteria. The success in fulfilling each criterion is scored for each of the four basic patterns. This evaluation is intended to be as fundamental as possible insofar as it addresses the generic pattern rather than a single specific configuration within a pattern.

The assumption for the number of modules is a minimum of six units, exclusive of Excursion Habots. Although docking modules were included as Criteria 7, they turned out to be not a discriminator as it was possible to include them equally in all the patterns. In a similar view, the dual remote egress was *almost* equally feasible for all module patterns, if an Excursion Habot is always available at each distal docking port. However, for the Straight/Linear pattern, it is not possible to guarantee that an Excursion Habot would always be present there, so that pattern scores slightly lower to reflect this uncertainty.

A. CONFIGURATION Evaluation Criteria

At the beginning of this paper, the authors stated the Habot base configuration evaluation criteria. Here is a restatement of them, with an explanation of the derivation of the numerical ratings in Table 4.

1. Circulation Access

Afford circulation access to all parts of the base. Dual access is preferable, especially in the case of loss of safe access through one of the hatchways. This criterion measures the number of the six core modules that enjoy dual pressurized access at all times from another permanently attached core module. This criterion is where the loop plans show an advantage over the open plans. An Excursion Habot docked to a pressure port does not afford this kind of permanent pressurized access, although it may do so in an emergency. This provision requires that the crew can embark in the Excursion Habot at a different pressure port and then drive it around the configuration to the module they are trying to reach. For example, in the case of the straight configuration as an open plan, the two core modules on the ends do not have permanent pressurized access. Therefore, only four of six modules meet this criterion, for a rating of .66.

2. Dual Remote Egress

Facilitate egress from all parts of the base; ideally, the configuration will provide dual remote means of egress for fire safety and escape in emergencies. For this criterion, unlike Access, the Excursion Habot units can afford a means of egress. However, where this arrangement is necessary, the evaluation credits only half of the total number of Excursion Habot egresses, penalizing the Straight/Linear configuration in particular. The importance of this criterion is that it directly affects safety in case of evacuation of any module because of fire, decompression, contamination, or other such hazards (Raasch, Peercy, Rockoff, 1985; Cohen, 2001, pp. 28-31)

3. Efficient Equipment Areas

Provide an efficient and utilitarian amount of equipment functional areas and volumes; the shapes of these areas and volumes must be compatible with the circulation. This number comes directly from Table 2 as the ratio of the equipment area to circulation area in the core modules. It is a measure of how useful the overall floor plan is at providing equipment area in relation to circulation area.

4. Work Spaces/Social Areas

Provide *the ability to create suitable workspaces and social areas within the base.* This criterion assumes that the best module for a group work and social area DOES NOT serve as a circulation hub. Although a circulation hub with three, four, or more hatches may seem like a logical meeting place, the problem is that excessive through circulation may be disruptive to work – especially group work or team activities. In addition, for a group habitability social setting such as a wardroom and galley, with such a small floor area, there might not be sufficient space for the wardroom table and food preparation areas. The Habot modules are, however, large enough to set the wardroom table to one side of a Type B, C, or J plan from Figure 5 and Table 3.

5. Ease of Assembly

Provide ease of mobility for assembly and disassembly of the base. This criterion looks at the sequence of assembling Habot units into the base cluster. It evaluates the "puzzle-making" aspect of each configuration—what does it take to insert the last piece? The ideal configuration allows a relatively unconstrained single-fit, rather than being compelled to align the module between to other modules, especially if those docking ports occur at differing angles. This criterion assesses the relative difficulty of achieving this alignment and docking.

6. Qualitative Thermal View Angles

Ensure efficient thermal view angles for body-mounted radiators. The simplest Habot base configuration that can achieve the self-sufficient thermal requirement is the Straight or Linear Configuration shown in Figure 5. The body-mounted radiators point orthogonally to the axis of circulation, and look away from the cluster. The other configurations are all compromised in this respect. Although all have a number of radiators pointed away from the cluster, making effective use of them throughout the lunar day would mean pumping coolant around the entire circulation pattern.

7. Docking Modules

Give the ability to provide docking for four Excursion Habots or EVA Access Units. Maximum score is for providing four available docking ports for Excursion Habots, including accommodation for EVA access.

8. Minimal Pressure Port Variations

Minimize the number of pressure port arrangement variations. This criterion measures the number of different port angles * the number of modules at each different angle.

9. Docking Port Efficiency

*Gives the ratio of number modules*two ideal ports/number of actual ports.* This criterion rates the fraction docking ports that are necessary to achieve the configuration, against an ideal average allotment of two ports per module.

B. Evaluation Summary

Table 4 presents a summary of results from the evaluation in Figure 10 as the multiplied products of the ratings. Each of these two results reveals different but important aspects of the configurations. In both these scorings, the data is *unweighted* because there is not yet sufficient evidence to determine, say, that it is safety related, the criterion *"2. Dual Remote Egress"* should be weighted three times heavier than another criterion. This evaluation also shows valuable qualitative lessons about the treatment of differing module types.

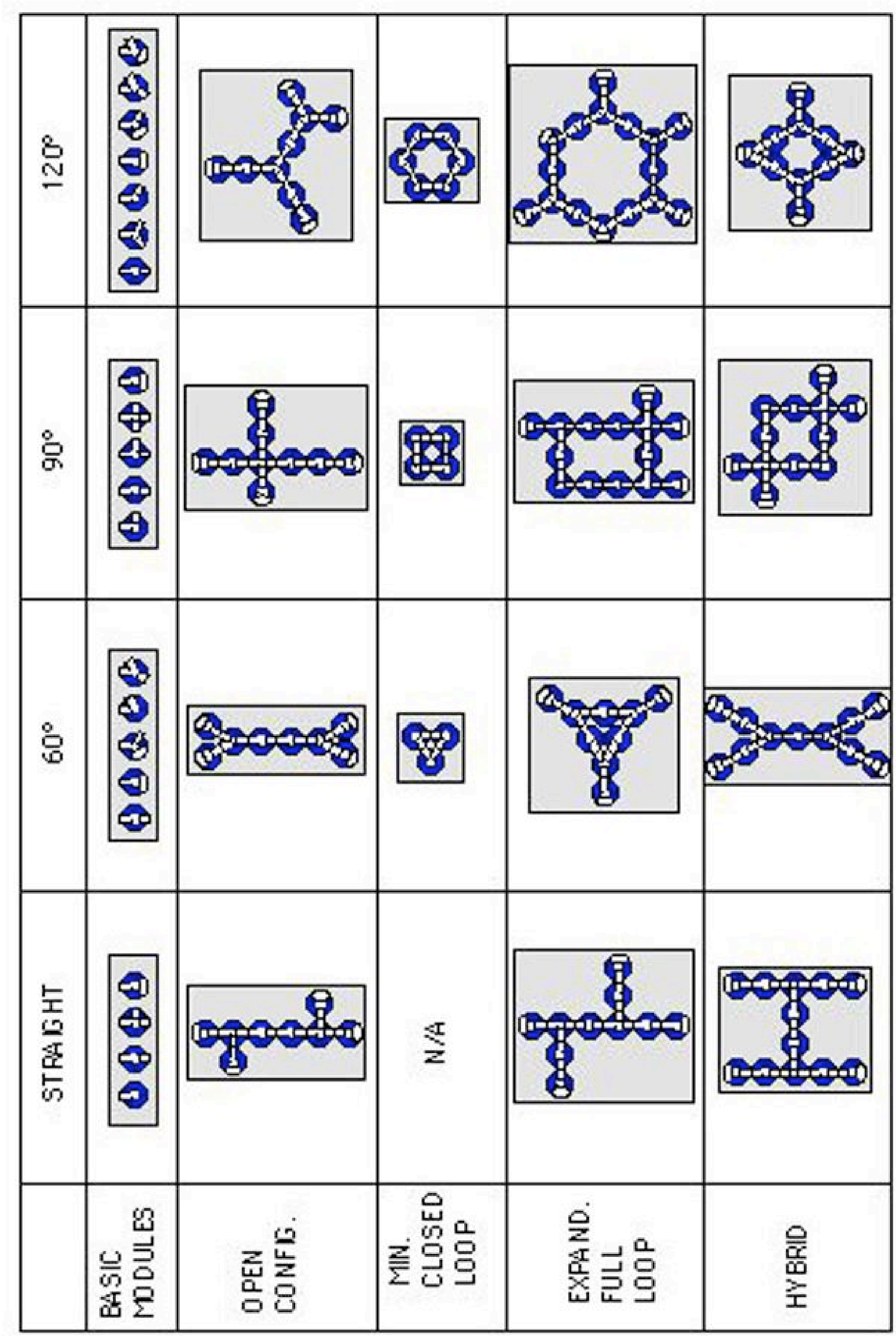

Figure 10. Habot Base Configuration Analysis Matrix (Drawn by Ross A. Tisdale).

Table 4. Evaluation of the Four Major Configuration Patterns Against the Nine Configuration Criteria

Configuration Criteria	STRAIGHT LINEAR PATTERN	60° PATTERN (TRIANGLE)	90° PATTERN (SQUARE BOX)	120° PATTERN (HEX)	REMARKS
1. Circulation Access/ Dual Access	0.67	1.00	1.00	1.00	Gives the percentage of core modules with permanent, pressurized dual access.
2. Dual Remote Egress	0.80	1.00	1.00	1.00	Gives the percentage of core modules with pressurized dual remote access, allowing 50% of end modules to use Excursion Habots.
3. Efficient Equipment Functional Areas	0.82	0.75	0.77	0.82	Gives the ratio of equipment area/ circulation area * the number of Plan Types from Table 2.
4. Work Spaces/ Social Areas	0.67	0.50	0.60	0.50	Gives the ratio of core modules with ONLY 2 ports/total number of modules.
5. Ease of Assembly	1.00	0.33	0.80	0.66	Gives the proportion of modules that can make a 0° linear connection to other modules.
6. Qualitative thermal View Angles	1.00	0.30	0.50	0.70	Gives the ratio of core modules that have clear, unobstructed thermal view angles for body-mounted radiators
7. Docking Modules	1.00	.75	1.00	1.00	Gives the ability to provide docking for 4 Excursion Habots or EVA Access Units.
8. Minimal Pressure Port Variations	0.50	0.33	0.50	0.50	Gives the variation in number of different angles of Pressure Ports.
9. Docking Port Efficiency	0.86	0.80	0.83	0.86	Gives the ratio of number modules*2 ideal ports/number of actual ports.
SUM	7.32	6.01	7.03	7.01	= a + b . . . + n
PRODUCT	0.13	0.01	0.08	0.08	= a*b . . .*n
ARITHMETIC MEAN	0.81	0.65	0.77	0.77	= (a + b . . . + n)/n
HARMONIC MEAN	**0.16**	**0.02**	**0.10**	**0.10**	= Product/arithmetic mean

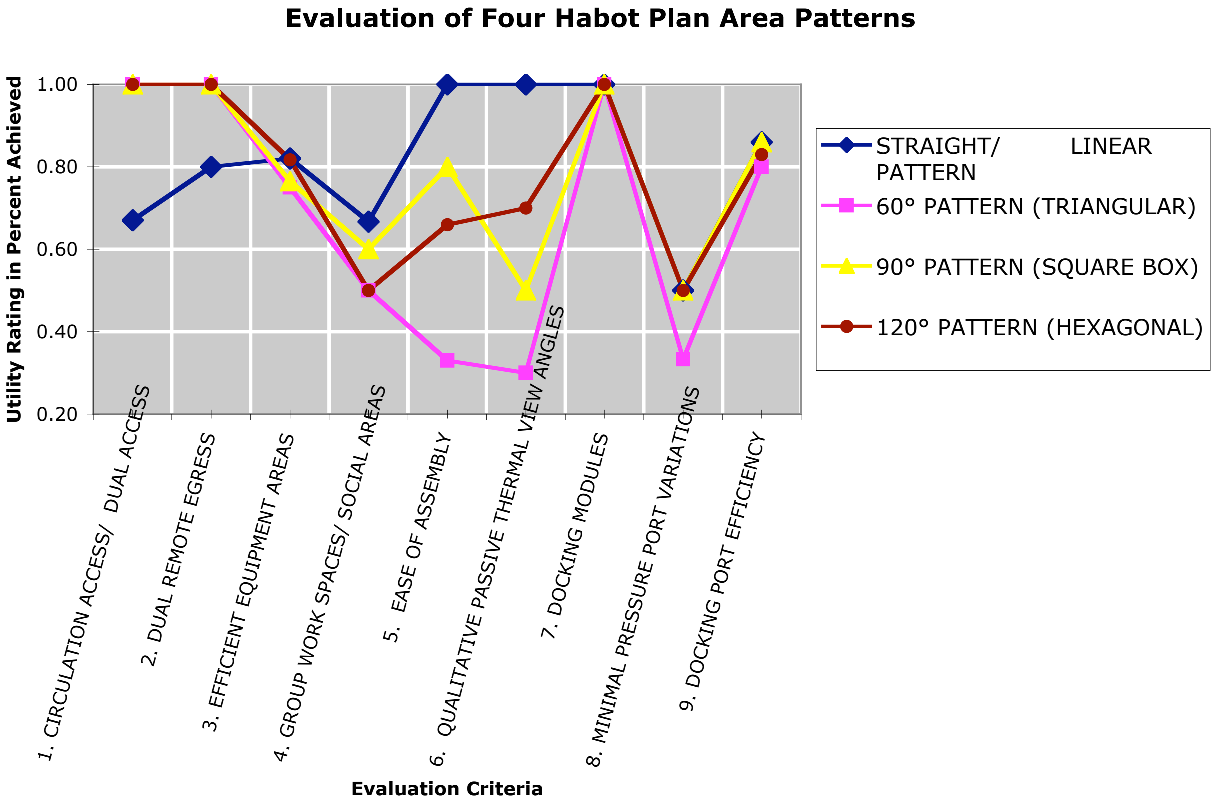

Figure 11. Line chart of the evaluation results for four Habot plan area connection patterns.

The method of evaluation that appears at the bottom of Table 4 is the harmonic mean, which combines the sum and product of a set of values in a way that reduces the effect of criteria with very similar scores, for example the docking modules that are "a wash" between patterns. Stepping through the rating section, the first row shows the sum of each pattern, and the scores are very close. However, when treating the rating fractions as multipliers on the *multiplied products* line a very different picture emerges. Multiplying performance fractions in this manner is the foundation of reliability calculations. Because the maximum value is one, any deviation from the "perfect value" will be a fraction that when multiplied in the chain of values, must reduce the total score.

The products range from 0.01 to 0.13 a ratio of 13:1. The average product is 0.075. Perhaps not surprisingly, the hexagonal and rectangular configurations score close the average: 0.08. The straight configuration performs much better than its nearest competitors, which in turn do vastly better than the triangular configuration. The next step is to take the arithmetic mean. Finally, the harmonic mean divides the product by the arithmetic mean.

The results of this evaluation are striking. The Straight/Linear pattern scored highest, with a harmonic mean of 0.16. The 90° pattern (square box) and the 120° Hexagonal pattern are tied for second place with a harmonic mean of 0.10, compared to which the Straight/linear pattern scores 60% higher. Finally, with a harmonic mean of 0.02, the 60° Triangular pattern scored only 20 percent of the middle two patterns.

Figure 11 is a line chart that presents another perspective on the variance among the four patterns. The highest scoring pattern, Straight/Linear plot tends to connect points nearest the top of the chart. The Square and Hexagonal patterns occupy at least part the middle range. Finally, the lowest scoring Triangular pattern produces a line that dips deeply toward the bottom of the chart.

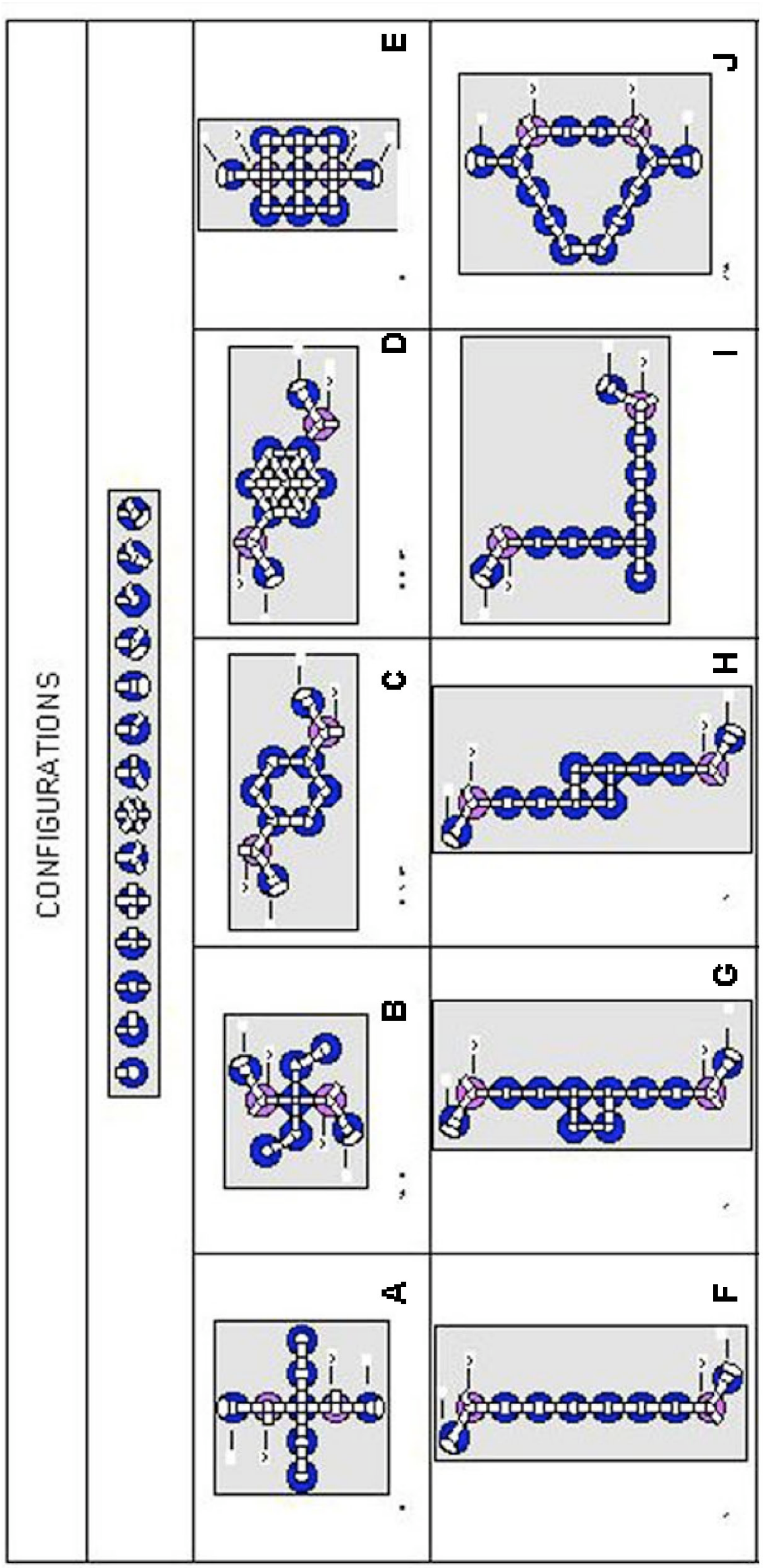

Figure 12. Habot Base Configurations.

The results of Table 4 and Figures 10 and 11 lead to the elimination of the 60° triangular pattern. Figure 12 presents a selection of expanded Habot base geometries based upon the three highest scoring patterns. The evaluation summary in Figure 12 shows a selection of 10 complex base configurations from the many that the authors created. These configurations employ a considerable variety of module floor plans to achieve the diverse layouts. The upper row 12a to 12e shows five experiments with "dense pack" clusters of modules base upon the two assumptions that there may be an advantage to maximizing access ports, and, that clear thermal view angles would not be an issue if the base relied primarily upon gimbaled, pointable radiators. Figures 12a, 12b, and 12e show a comparison of three short Straight/Linear pattern configurations, with the docking modules offset to the sides for form a sort of cruciform plan. 12a and 12b are exercises in the "short arm" straight/cruciform configuration. They explore the treatment of the end module in the straight series of modules, and how the 90° hub compares to the 120° hub. The lower row 12f to 12j shows four experiments in the straight/linear configuration and one attempt to redeem the triangle configuration.

The module plans appear in two colors: dark blue for the "standard" modules, and purple for "docking" modules to which an Excursion Habot would dock. Each of the docking modules has three pressure ports, arranged either at 90° or 120° around the circumference. Rather than use them primarily for internal circulation, these end hubs may serve as the external circulation nodes for docking accommodations of Excursion Habots/rovers and EVA Access Facilities. As these experiments developed, the triple 120° Plan Type F emerged as the favorite Excursion/Rover docking hub and is colored purple. These Excursion Habots/Rovers incorporate the Suitport as the arc-segment oval.

Figure 12e takes the short cruciform pattern in the hybrid direction of combining it with a rectangular (square) loop. This pattern creates a classic square circulation grid among the Habot modules.

Figures 12c and 12d show a comparison of two 120° Hexagonal configurations, one a "hollow" benzene ring of six modules and the other with a seventh module in the center as a hub with multiple radial ports. Although this center module could have up to six radial ports, it would have no significant area for equipment because this G plan affords only 4% equipment area. It raises the questions that if all the crewmembers are attending a group activity in this central module, why worry about through traffic? Given this caveat, this module could probably fulfill the hub function and serve as a Wardroom module and social center with just three ports, although the galley might need to be in an adjacent module.

Figures 12f to 12i show a series of experiments with the straight/linear configuration. 12f is the most pure – a straight series with the 120° hubs at each end, providing four mobile unit docking ports. 12g shows a small hybridization of the straight configuration with the addition of two units to one side, forming a small square. This hybridization responds to the precept that a denser concentration of modules at the center may offer operational advantages over stringing out all the modules in a long line. . In 12g, the box forms off to one side. In 12h, the box forms from offsetting two halves of the linear pattern, which overlap one another by two modules. The distinctions between 12g and 12h are subtle but powerful. 12g admits of the potential to add extra modules mid-series, without having to remove and relocate the end hub. 12h takes the approach that each of these halves can be essentially symmetrical and identical, offering a way to achieve complexity and richness while maintaining a higher standard of reproducibility and reducing SE&I costs.

Figure 12j shows an attempt to modify and salvage the triangular configuration that faired so poorly in the configuration evaluation. In this case, two 120° hubs form each 60° corner (this version uses four 120° Plan F triples and two 120° Plan J doubles. All together, 12j has six 120° modules and six straight "Fat I" core modules If the two Plan J doubles became two Plan F triples, there would be an equal number of hubs and core modules. This scheme would afford six external docking ports for Excursion/rovers. However, as drawn, the two Plan J doubles may serve as core modules, for a total of eight core modules.

A lesson from this evaluation is the need for a deeper level of analysis of the module types, especially the role they can play as multiport (three or more) hubs to connect other diverse modules.

Conclusion

This design research examined a variety of approaches and considerations to the Habot Mobile Lunar Base configuration. It evaluated both a series of the most likely Habot Module plans and the combinations of these plan types into base cluster configurations. The key considerations to emerge included the efficiency of the Habot module floor plan, the variability of pressure port angles, the ability of the mobility system to place the Habot into the base configuration, and the thermal view angles for body mounted radiators. The EVA Access Facility and Excursion Habot/rover design did not present a key discriminator among the module plans or base configurations.

The conclusion at both levels of analysis – module plan and base configuration -- is that ***the simplest solution is best.*** For the module analysis and the configuration evaluation, the straight "Fat I" passage Plan C and its logical extension to the Straight/Linear Configuration scored as the best approach. Certain additions or variations can add value, such as the docking modules with pressure ports at 120°, and a simple offset in the line of modules to create a higher circulation area for the crew.

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