Space Architecture
The Role, Work and Aptitude

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Space architecture has been an emerging discipline for at least 40 years. Has it arrived? Is space architecture a legitimate vocation or an avocation? If it leads to a job, what do employers want? In 2002, NASA Headquarters created a management position for a space architect whose job was to "lead the development of strategic architectures and identify high-level requirements for systems that will accomplish the Nation's space exploration vision." This is a good job description with responsibility at the right level in NASA, but unfortunately, the office was discontinued two years later. Even though there is no professional licensing for space architecture, there is a community of practitioners. They are civil servants, contractors, and academicians supporting International Space Station and space exploration programs. Space architects currently contribute to human space flight, but there is a way for the discipline to be more effective in developing solutions to large-scale complex problems. This paper organizes contributions from engineers, architects and psychologists into recommendations on the role of space architects in the organization, the process of creating and selecting options, and intrinsic personality traits including why they must have a high tolerance for ambiguity.

Nomenclature

ISS	=	International Space Station
LEM	=	Lunar Excursion Module
LEO	=	Low Earth Orbit
MIT	=	Massachusetts Institute of Technology
MEL	=	Master Equipment List
RLM	=	*Reichsluftfahrtministerium*

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I. Introduction

MUCH of the material in this paper has been better reasoned and much better written by others. Eberhardt Rechtin's Systems Architecting provides source material for the section on the Role; Brent Sherwood's contribution to the "International Space University's 1993 Space Architecture Curriculum Notes" is used to structure the section on Work; and the Attribute section relies on the work of Professor Mark Chignell who describes the personality traits of successful, creative system architects. Because this material is presented in summary, it is strongly encouraged to read the original writings for a more thorough understanding of each of these topics.

II. The Role

A. Architectural vs. Engineering Approach

Babies are born pretty much alike, but some grow up to be engineers and others architects. Because engineers are understandable--architects "get" engineers but the reverse is not true. Engineers think architects make things prettier, difficult to build and more expensive. Some can, but space architects are different. They analyze like an engineer and synthesize like an architect. This is not an identity problem, but an asset more like being ambidextrous rather than schizophrenic. Figure 1 provides some insight into the different approaches of engineers and architects.

Engineering Approach	Architectural Approach
There is a single, ideal solution	There are many solutions
I must start at the beginning of the process	Start anywhere, then adjust
A good process will yield a good solution	Inspiration before process
Most decisions are quantifiable	Some decisions are quantifiable
You can't do that	Why not?

Figure 1. Engineers and architects approach problems differently

Today's penchant for classification and labeling has influenced the perception that personal attributes are either complementary or mutually exclusive. Thus, one is either engineer or artist; not both. Most authors writing about system architecture are engineers yet they acknowledge that the role requires a combination of deductive (engineer) and abductive (architect) reasoning.

Because space flight started and remains within the engineering domain, space architects have had to sneak under the engineering tent masquerading as system engineers or configurators (engineering for vehicle designer). Engineering managers suspect there must be a role for architects but do not know where to place them within their organization. Part of the problem is job title. This paper uses "space architect" which can easily include system architect, space system architect, configurator, subject matter expert, and sometimes systems engineer. MIT professor Ed Crawley offers the following comprehensive definition for system architecture: "the embodiment of concept, and the allocation of physical/informational functions to elements of form, and definition of interfaces among the elements and with the surrounding context." It is no wonder space architects have not found a home in the engineering organization.

Another issue is that not all space architects call themselves space architects. There is no single job title for the "space architects" scattered across organizational trees and geographically distributed around the world. Practicing space architects currently contribute to mission planning, vehicle integration, habitat design and human factors, but are particularly attracted to the areas of design integration and concept development.

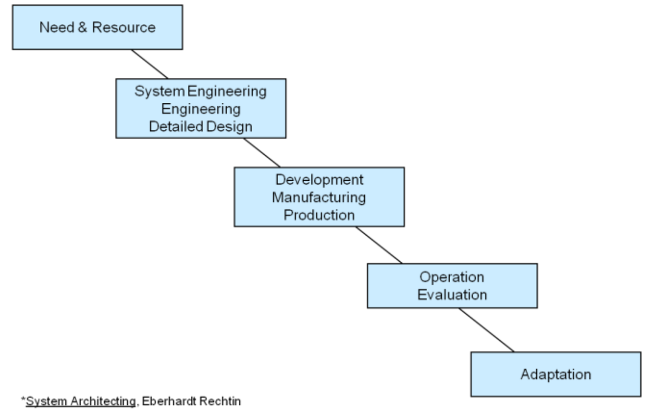

Figure 2. Waterfall of major programmatic steps

B. Waterfall

In his book Systems Architecting, Eherhardt Rechtin (an engineer intrigued with architectural problem solving) addresses the role of the architect within the organization. His model has less to do with the individual professions and more about establishing functional connections within an organization. He begins describing different phases of program development using a waterfall (Figure 2). This logical progression defines a sequence of major programmatic steps moving from need and resource to adaptation. Because the conventional waterfall does not accurately represent today's complex systems, he provides further definition in an expanded waterfall (Figure 3) adding a box for the architect and showing organizational relationships. What is clear by this diagram is that the architect must not only have a comprehensive view of the product and process, but must be directly connected to key decisions from beginning to end. Dr. Rechtin believes that the system architect "is not a generalist, but a system oriented specialist." Furthermore, regarding the architects role, he states that "architecting is working *for* a client and *with* a builder." Then he upsets the applecart by saying, "engineering is working *with* an architect and *for* a builder." Within aerospace, this relationship is disruptive, but it is consistent with the fundamental nature of "architecting" because the architect must be well positioned within the organization to be effective. In other words, you cannot "architect" from below. Considering the nature of the work and role in the organization, it is logical that the number of architects is small compared to the number of engineers. In fact, along with others, Frederick Brooks and Robert Spinard believe that the greatest architectures are the product of a single architect or at least a very small, carefully structured team. Rechtin reinforces, "If the single mind is the essence of architectural integrity, then 'the disciplined team' is the essence of engineering integrity."

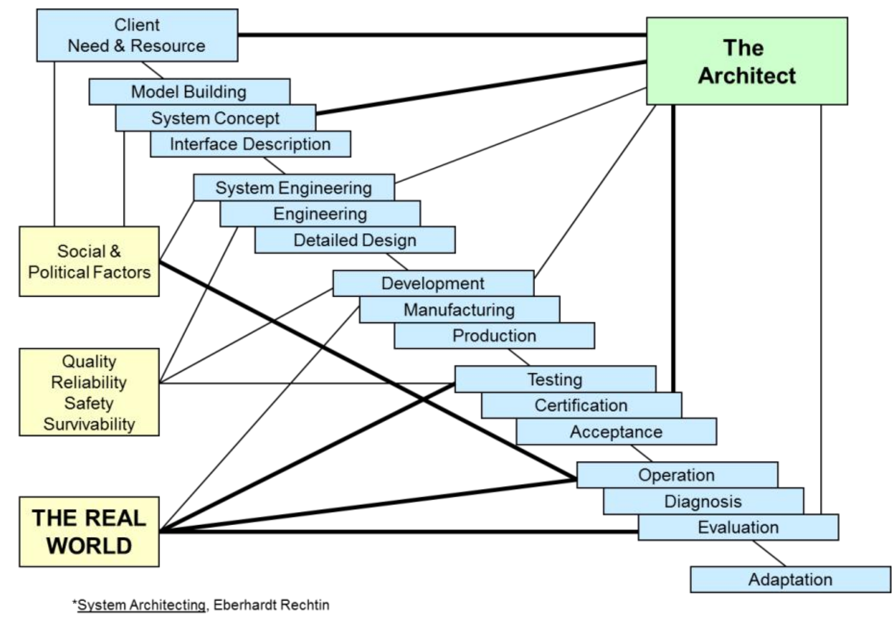

Figure 3. The architect's role in the expanded waterfall

Regarding roles, there is "little purpose to debate the jurisdictional question of just how much system engineering is done by the architects (not much because there are not that many architects) or how much system architecture is done by the typical systems engineer (not much-too many cooks spoil the soup). Overlap is essential-this interface looks fuzzy from either side. The serious mistake is to leave a gap.

III. The Work

A. Heuristics

Why all the fuss? Just design it, get management buy-in, build it, and then send it to the launch site (Figure 4). This approach is partially correct, but, to make a point, it over simplifies each step. In reality, the process for building complex systems relies on many decisions-making techniques, some logical, some heuristic and others a product of management decree.

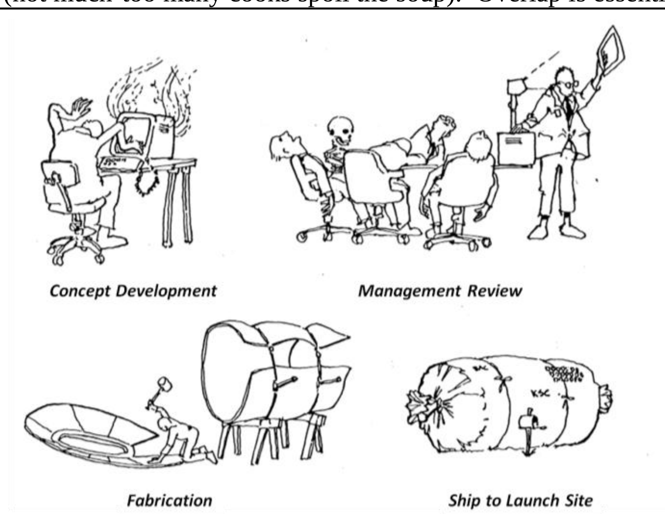

Figure 4. How to design and build a spacecraft

Georgia Tech's, Tom McDermont states "system architecting differs from system engineering in that it relies more on heuristic reasoning and less on the use of analytics." A similar, yet more forceful assertion is made in Systems Architecting. Heuristics, or experienced based reasoning, is characterized as essential to architectural problem solving. Rechtin says, "Practicing architects through education, experience, and examples accumulate a considerable body of contextual sense by the time they are entrusted with solving a system-level problem--typically 10 years." He adds, "…architects have insights, lessons learned, rules of thumb and the like that consciously or unconsciously are brought to bear on complex problems."

Three commonly cited examples of heuristics are: 1. Murphy's Law, if anything can go wrong it will, 2. the acronym KISS or Keep It Simple, Stupid; and 3. Occam's Razor: The simplest solution is usually the correct one. Heuristics are not new. In the Bible's book of Proverbs, King Solomon provides this Godly wisdom, "The first to present his case seems right, till another comes forward and questions him." In Poor Richard's Almanac, Benjamin Franklin suggests, "Three may keep a secret, if two of them are dead." And baseball legend Yogi Berra clarifies an important distinction with, "In theory there is no difference between theory and practice. In practice there is."

With regard to space architecture, von Tiesenhausen, one of the von Braun German "rocket scientists" who worked on the Apollo Program says, "If you want to have a maximum effect on the design of a new engineering system, learn to draw. Engineers always wind up designing the vehicle to look like the initial artist's concept." Furthermore, there are many applicable heuristics in Systems Architecting with others collected in personal lists of "laws." Selections from three notable listings are shown in Figure 5.

Akin's Laws*	Augustine's Laws**	Peter's Laws***
Engineering is done with numbers. Analysis without numbers is only an opinion.	There are no lazy veteran lion hunters.	When given a choice… take both!!
To design a spacecraft right takes an infinite amount of effort. This is why it's a good idea to design them to operate when some things are wrong.	The last 10 percent of performance generates one-third of the cost and two-thirds of the problems.	When forced to compromise, ask for more.
There is never a single right solution. There are always multiple wrong ones, though.	It costs a lot to build bad products.	If you can't win, change the rules.
The fact that an analysis appears in print has no relationship to the likelihood of its being correct.	Defense budgets grow linearly but the cost of military aircraft grows exponentially.	If you can't change the rules, then ignore them.
A bad design with a good presentation is doomed eventually. A good design with a bad presentation is doomed immediately.	It is very expensive to achieve high unreliability.	The squeaky wheel gets replaced.
The schedule you develop will seem like a complete work of fiction up until the time your customer fires you for not meeting it.	The process of competitively selecting contractors to perform work is based on a system of rewards and penalties, all distributed randomly.	The day before something is a breakthrough, it's a crazy idea.
Space is a completely unforgiving environment. If you screw up the engineering, somebody dies (and there's no partial credit because *most* of the analysis was right…)	Never promise to complete a project within six months of the end of the year, in any direction.	If it were easy it would have been done already.

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**Norman Augustine, former CEO of Lockheed Martin and Under Secretary of the Army, Chair of the Review of United States Human Space Flight Plans Committee
***Peter Diamandis, M.D., Harvard, B.S. MIT, Co-founder of International Space University, X-Prize and Singularity University

Figure 5. Three lists of representative heuristics

B. Three Major Areas

The work of space architecture can be grouped into three major areas, requirements, functional integration and design integration. Because both requirements and functional integration are thoroughly described in systems engineering documents, this paper concentrates on design integration, the area most closely associated with space architecture.

C. Design Integration

1. Process Description

Design integration is an ugly process. It is nonlinear and iterative; it advances and retreats. It simultaneously benefits from discipline and serendipity. And, considering what actually gets built, personality, pride, and position often trump process. For some this is too random, lacking affirmation and ultimately, discouraging. For others, it is the real-world overhead that comes with the work of design integration. The following descriptions provide insights on the design integration work of a space architect.

a. The Myth of "the" answer

Akins' law number 12 states, "There is never a single right solution. There are always multiple wrong ones, though." Brent Sherwood adds, there is no such thing as "the correct" answer. Both are trying to enlighten the analytical mind to the fact that design is not an algorithm with one repeatable answer. In fact, there is an observable behavior pattern associated with design maturity. Those with limited design experience tend to fall in love with their first solution then spend extraordinary resources defending that one concept. In contrast, mature designers create many workable solutions producing the opposite challenge of selecting from amongst the options. Although there is no single right answer, usually only one solution gets built. For this reason, the space architect is often the arbitrator amongst competing interests where the only ideal solution exists in the fantasy of a cartoon (Figure 6). Therefore, design integration is both about generating options and down-selecting to a solution.

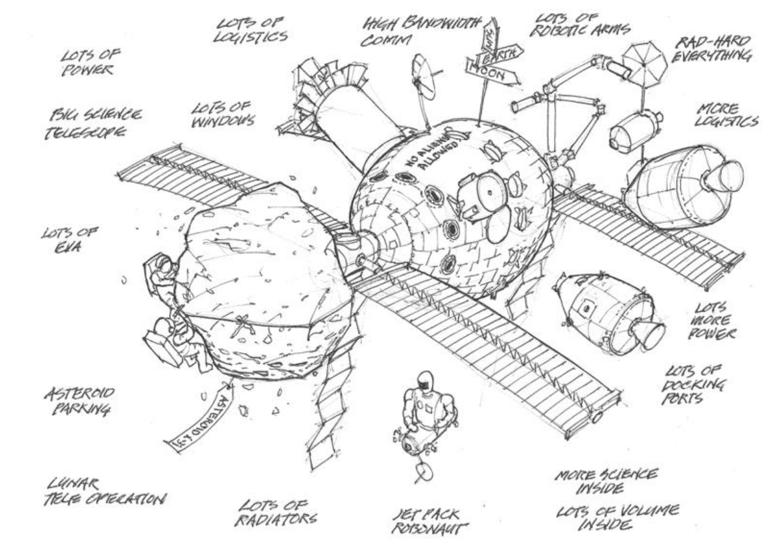

Figure 6. The ideal deep space habitat

b. Where to begin

Tabula rasa means blank slate and it can paralyze all designers. Confronted with a complex design problem and a blank page, it is hard to know where to start. Worrying about making a mistake, making a poor decision, starting in the "wrong" place, or pursuing a "dead end" often chokes progress because it keeps the designer from even getting started. Van Gogh saw it as a challenge, "You don't know how paralyzing that is, that stare of a blank canvas, which says to the painter, 'You can't do a thing'. [...] but the blank canvas is afraid of the real, passionate painter who dares and who has broken the spell of `you can't' once and for all."

Experienced space architects realize that rarely does the first mark or decision remain unaltered throughout the entire process. Therefore, it doesn't matter what the first step is, as long as the process is flexible enough to permit change. The process is cyclical so there are multiple entry points around the loop. The key to overcoming the terror of the blank page is to begin anywhere, with anything (an estimate, a trial mark, a guess) and then react to that initial decision (Figure 7). Professor Akin provides some additional wisdom, "Not having all the information you need is never a satisfactory excuse for not starting the analysis."

c. Balance

Balance is one of the tools space architects use to avoid majoring in the minors that is, focusing on lower level issues at the expense of comprehensive integration. Balance prevents any given aspect from exerting too much influence over the final result. This is generally good however, based on experience an unbalanced approach is sometimes used to preserve attributes that otherwise would disappear without early and strong advocacy. For example: maintainability. Maintainability is out of balance with the system definition during preliminary design, but a space architect may keep it in the mix knowing that it is extremely difficult and disruptive to integrate later in the process.

Rechtin stated the space architect is not a generalist, but a system oriented specialist. This still begs the question, is it more important to know a little about everything (knowledge breadth), or a lot about a few things (knowledge depth)? Design integration needs both. However, depth can be achieved through a team of specialists, while breadth is essential to the work of the space architect. This is because

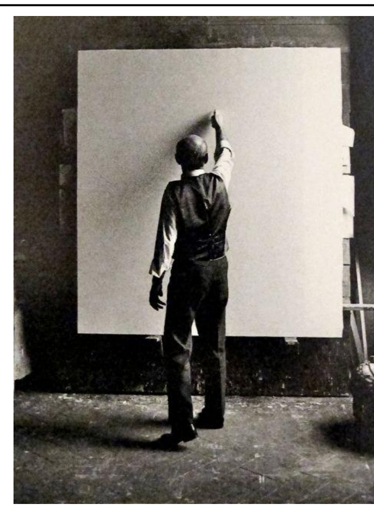

Figure 7. Blank slate paralysis

the architect is an integrator and this necessarily requires a comprehensive and simultaneous overview of technical and non-technical factors.

Integration also balances the resources of time, money, and capability. For this the space architect must have programmatic peripheral vision. That is to say, what is the funding profile for other "competing" projects within the organization and what is a realistic strategy for acquiring and managing monies. Budget busting solutions are not likely to be considered. Developing a schedule strategy for implementation including make/buy decisions and time for institutional procurement is essential for large scale systems integration.

Because all projects must work within resource constraints, it is important to prioritize decision-making. Resources must be allocated carefully because the project cannot afford to devote too much effort to decisions which affect limited aspects of the design.

Sherwood and Rechtin draw a decision-making parallel with the following analogy: The term *triage* is used by doctors in wartime or other disaster situations where the number of people needing treatment overwhelms the medical capacity to treat all of them. *Triage* is the process of dividing wounded people into three categories: those who will die no matter what the doctor does, those who will live even if the doctor does nothing, and those who will only live if the doctor treats them. The doctor only treats the third category, that is, the cases where his effort will make the most difference. Design integration requires the same philosophy. Effort should be focused first on making the most important decisions---that is, those which affect the greatest portion of the project, or which must precede the largest number of decision to follow. Decisions which will not affect the final outcome, and decisions which can be made later, should be avoided.

d. Spiral Evolution and Iteration

Most systems engineering textbooks include the concept of spiral evolution or the path to greater understanding with a convergence on a design solution. As decisions are made, the pathway enables more precise requirements guiding the process to the next higher level of project refinement (Figure 8). The spiral returns again and again to the same issues but with a more advanced understanding each time. The precision of the geometry is somewhat misleading, because in reality there are gaps and divergent rabbit trails.

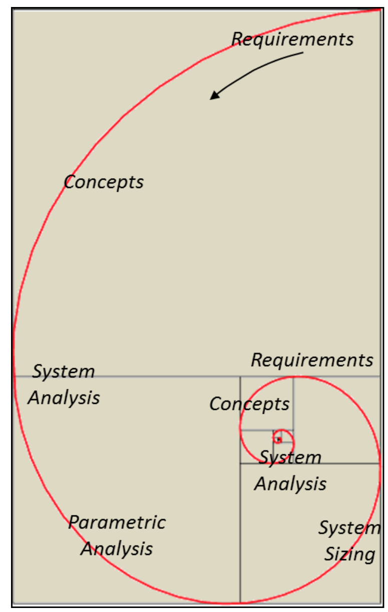

Figure 8. Spiral evolution.

Iteration or revisiting the same question multiple times is vital to integration for reasons of process efficiency and flexibility. Space architects include these revisits in the process to avoid getting stalled, losing balance, and getting locked into poor solutions. In addition, this discipline contributes to a healthy skepticism avoiding overconfidence in any one solution.

With the knowledge that the prior decisions were made to move the project forward, they should be held "loosely" and treated as temporary. This avoids getting stuck merely because there is not enough information to make a clear decision at that time. The space architect then chooses to insert a place holder deferring detailed treatment while keeping the process moving. Iteration provides a structured, cyclical way to incorporate new data as developed and automatically encourages a fresh look each time. On occasion discoveries expose impassable obstacles for which Akin advises, "Sometimes, the fastest way to get to the end is to throw everything out and start over."

The more iteration cycles a project can afford the more refined and robust the product can be. Therefore, for a given interval of time, increasing the frequency of cycles improves the prospect for a good result. In terms of the number of revisits, Akin's law 3 offers the following insight: "Design is an iterative process. The necessary number of iterations is one more than the number you have currently done. This is true at any point in time."

2. Developing Options

a. Gap and Overlap Identification

There are design challenges with what we already know, but it is the gaps or missing information that cause trouble, most often by invalidating or compromising our results. Therefore, key to effective integration is the identification and prioritization of knowledge gaps. Five steps to address high priority gaps are: 1.) characterize the state of present knowledge; 2.) identify the areas with the greatest uncertainty; 3.) decide the specific questions that need to be answered to reduce the uncertainty; 4.) decide which among the questions should be answered next; and 5.) take action to acquire those answers. Overlaps represented by disparate results are also a concern. If quantifiable, they should be resolved by analysis otherwise the space architect should make a decision with the option for review during the next iteration.

b. Literature Search

Making claim to concept originality without a thorough literature search is professionally irresponsible, a waste of resources and sometimes embarrassing. Granted, with pressure to show early progress, managers do not stress this research and it is often difficult to distinguish the credible sources. Regardless, as the integrator, space architects must encourage contributors to spend time exploring what has been done before. This is basic scholarship yet treated casually within the space community. A literature search should be done with an open yet skeptical mind, because there are built-in biases that may run counter to a balanced solution.

c. Concept Generation

Depending on the experience of the space architect, it is possible to begin developing mission options or configurations early in the spiral. This is the first scratch on the *tabula rasa* and serves the important step in organizing the team around a solution. As represented in Figure 9, it is recommended that before broad distribution, a small experienced team review and comment on the initial designs. This helps to prevent a large team from solving problems on immature or poorly conceived designs. Like inertia, once the expanded team starts working on the concept, it is difficult to redirect without changing the organization.

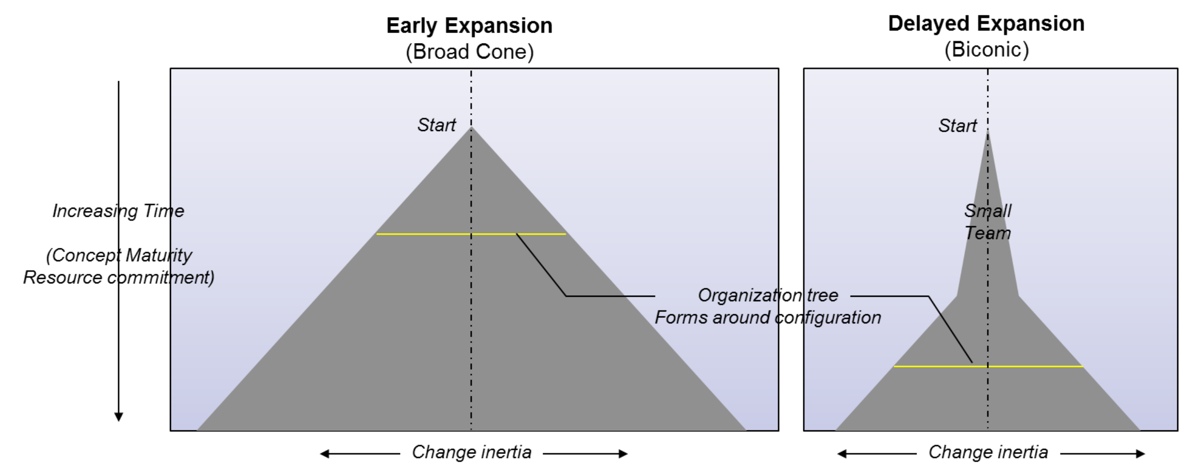

Figure 9. Concepts matured by a small team minimize change for configuration-based organizations

The easy and safe approach is to begin with a concept that is a derivation of a previous solution. This is reassuring to engineers. On the other hand, architects are intrigued with daring and innovative concepts which bring uncertainty. This is unnerving to engineers evoking the refrain, “You can’t do that!” For new, non-intuitive concepts, space architects must expand their role beyond a managerial integrator to that of a charismatic leader. WARNING: It is rare for large mature bureaucracies to eagerly embrace new concepts so, it is important to know how to persevere, when to lay low, and when to drop ideas.

Although the perception is otherwise, there is nothing about engineering that restricts creativity. In fact, engineers are responsible for many remarkable, novel solutions. For example, during WWII, the Germans wanted an observation airplane with excellent visibility. Unlike a conventional aircraft, their solution was an asymmetric design with a glass cockpit on the wing (Figure 10). This provided the pilot with forward, rearward and downward visibility that was not obscured by the fuselage. The plane was built and W. Green writes in Warplanes of the Third Reich, “Even the RLM

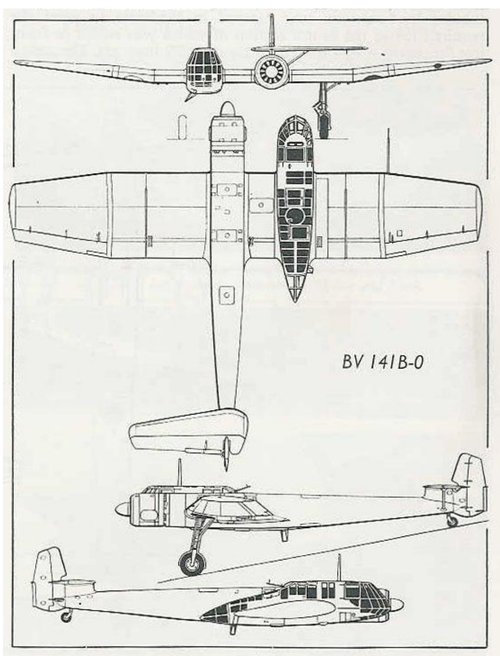

Figure 10. Innovative asymmetric aircraft

(Reichsluftfahrtministerium), which viewed the BV 141 with the utmost suspicion from the outset, was forced to admit that, despite its highly unorthodox appearance, the aircraft possessed extremely docile handling characteristics and fully met the original specifications."

Outside of science fiction, there were no precursors for the Apollo Lunar Excursion Module (LEM). The adaptation of Jules Verne's From the Earth to the Moon rendered the lander as an oversized 45 caliber bullet (Figure 11). From *tabula rasa*, The LEM engineers created a revolutionary archetype that continues to inspire today's spacecraft designers. As such, it stands out as a remarkable example of engineering creativity that made it through a large aerospace organization into reality.

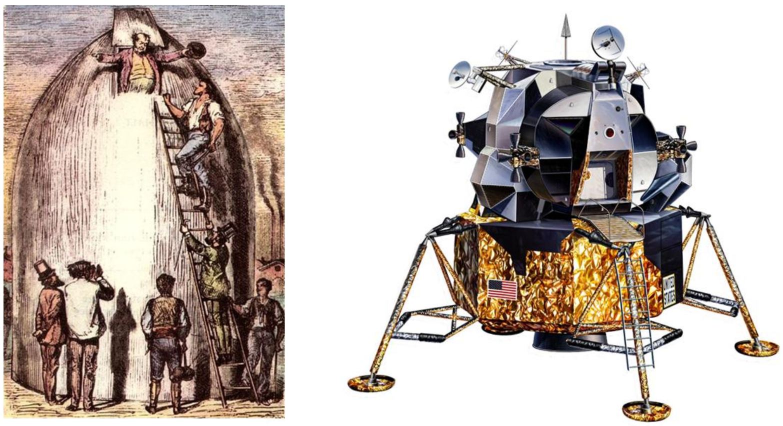

Figure 11. The design of the real lunar lander overcame preconceptions

d. Humans in space

Architects have always designed for humans. This relationship is symbolically represented by da Vinci's Vitruvian Man and through others including the *Modulor* by Le Corbusier. Because of the profound differences in space physiology, anthropometry and operations, a new Vitruvian Man is required. For weightless habitats, space architects use neutral body posture or the human's natural position without the influence of gravity. Muscles assume a neutral relaxed position, vertebrae "unload" extending the column approximately 2 in. (5cm) yet the projected height is reduced as much as 8 in. (20cm). Arms replace legs for translation and a bag on the wall serves as a bed. This Vitruvian Man (Figure 12) is the new datum for habitat sizing, internal layout, and translation paths. Furthermore, it guides the design of workstations, personal hygiene compartments, and the galley/wardroom.

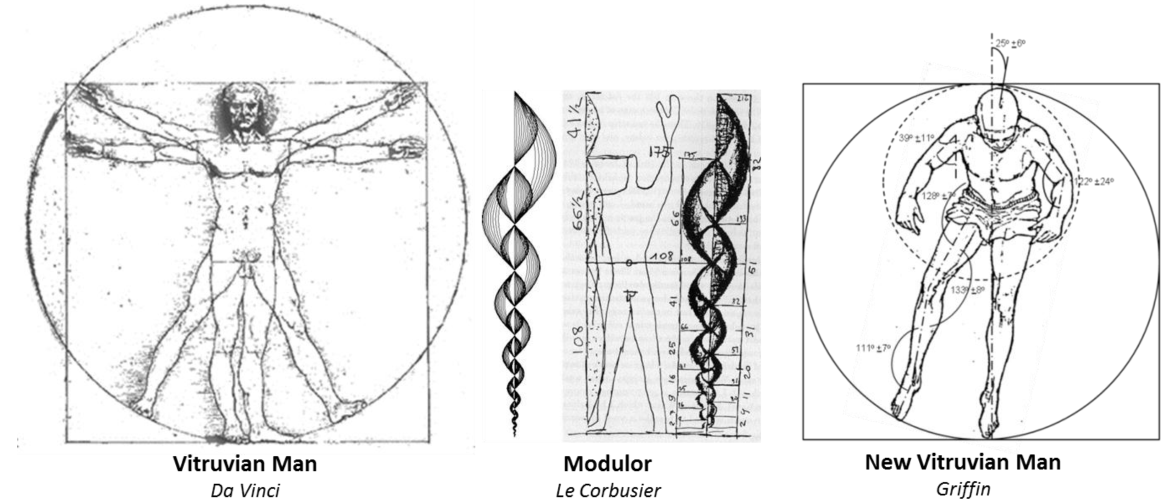

Figure 12. A new datum for space

e. System Sizing

System sizing and concept generation are interdependent activities swapping leadership roles. Experience (heuristics) allows the space architect to produce a "straw man" concept before actually sizing the systems, but sizing confirms or reshapes that initial concept. Design choices are quantified in the system sizing step of the spiral. Because this step inter-relates multiple components, systems, and elements, it is at the heart of design integration. Pursuing the interdependent effects of system selection and sizing choices through analysis is the engine which drives the integration cycles. During the first few cycles, space architects prefer parametric rather than specific solution analysis. This allows revisits and adjustments based on sensitivities in mass, volume, and power. For example, Figure 13 compares the hardware mass for the environmental control life support system as a function of mission duration. The data shows a crossover from an open to closed (regenerative) system at about 57 days. Other

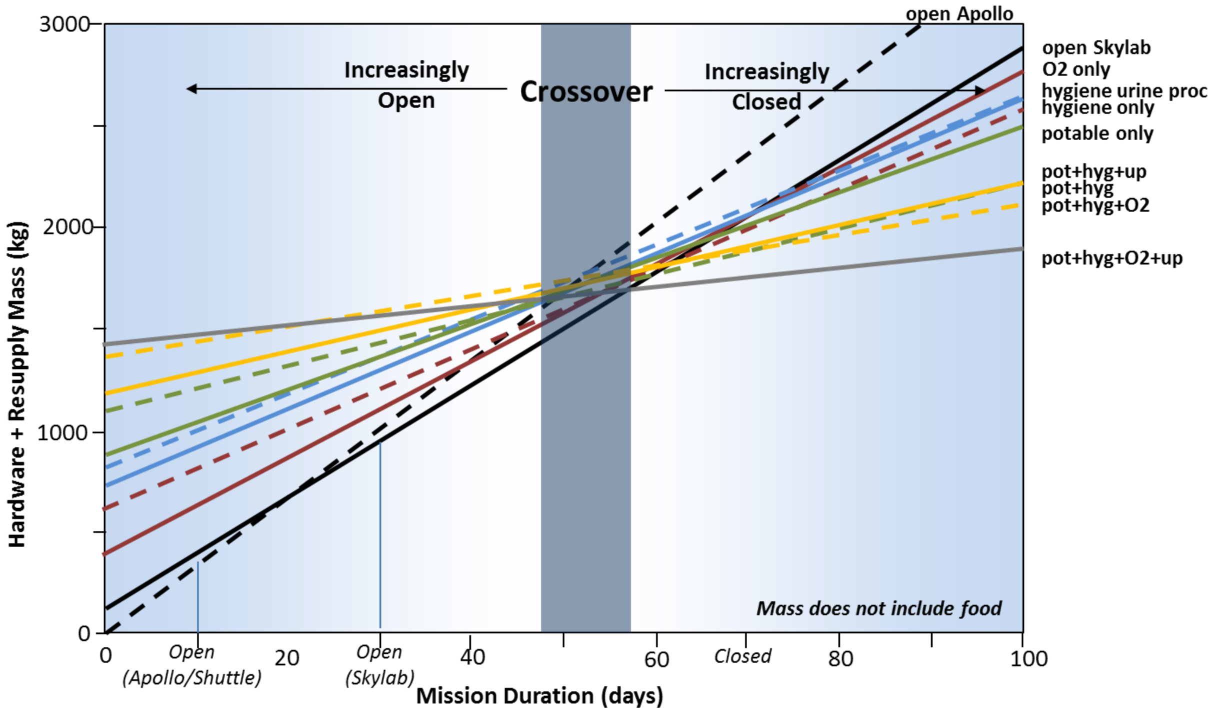

Figure 13. Parametric data allows flexibility in system sizing decisions

data, like consumable mass and technology readiness are required to make system sizing decisions, but if the mission duration changes with this presentation it is easy to assess the impact by revisiting the chart rather than running another dedicated analysis. It is not always possible to have all the data when it is needed so, Akin offers the following guidance, "When in doubt, estimate. In an emergency, guess. But be sure to go back and clean up the mess when the real numbers come along." The author of Sherlock Holmes stories, Sir Arthur Conan Doyle adds a cautionary note, "I never guess. It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts."

3. Internal Layout

The following steps provide a guide for spacecraft internal layout. Creating a consistent up/down (local vertical) is important even in the weightless environment. Zoning organizes activities and establishes physical proximity.

a. Local Vertical

Whether on a planetary surface or in weightless space, a local vertical is imposed to provide a common up and down across the spacecraft. This heuristic establishes the orientation for controls and display, labeling and is useful in face-to-face communication. Like sunlight and overhead lighting, spacecraft illumination is used to imply an "up" direction and because there is no convection, a head-to-toe airflow washes away exhaled carbon dioxide, provides a reinforcing orientation cue and is preferable to having air blow up the nose (Figure 14). Without foot restraints, weightless astronauts must stabilize themselves using their hands. Because this prevents two handed operations, having floor mounted foot restraints allows stability with both hands free. The local vertical provides a reference but does not

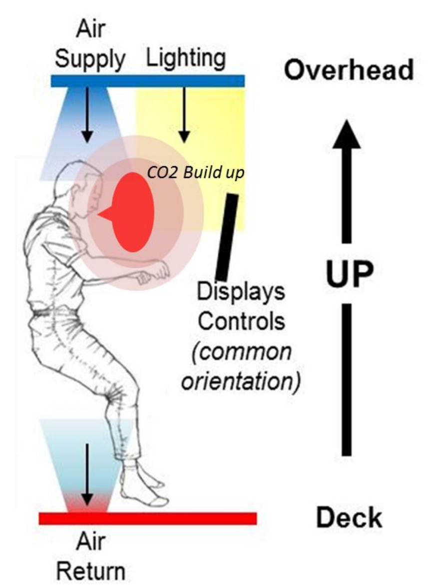

Figure 14. A common local vertical

restrict the crew from assuming different orientations out of personal preference or for improved accessibility.

b. Zoning and Functional Adjacency

Zoning and functional adjacency are guiding principles that provide constraints for positioning internal systems. Zoning is the grouping of elements that share common attributes or resources. Typically, this includes separating quiet and noisy activities, placing crew access functions such as galley/wardroom and personal hygiene in the wall location, positioning subsystems in the overhead and floor locations, and grouping microgravity science at the best location within the spacecraft. Functional adjacency refers to a proximity assessment determining which activities prefer to be next to one another, separated or are indifferent. An adjacency matrix is created to provide guidance on functional proximity (Figure 15). These guiding principles provide a point of departure for the internal layout; ultimately the final arrangement is the result of an iterative process that integrates other factors including mass, volume, cost, schedule, technology level, and maintainability.

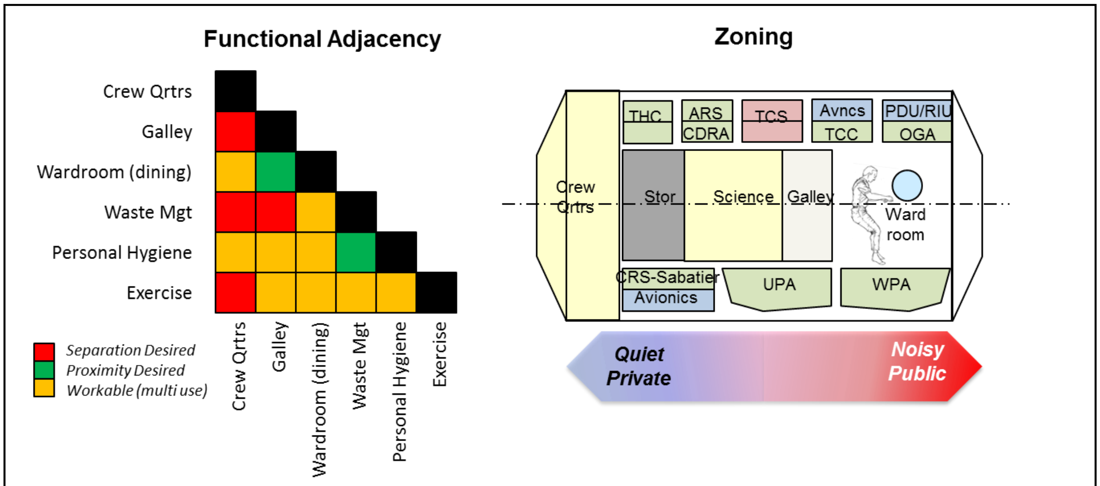

Figure 15. A functional adjacency matrix and zoning diagram help guide the internal layout.

c. Utility Distribution

The space architect is responsible for creating a logical, efficient, fault-tolerant, and serviceable system for the distribution of power, data, fluids, and gases. This critical task interconnects external elements like solar arrays, antennas, and radiators with internal conditioning and processing components to crew equipment such as in the galley and hygiene compartment. Line length and failure modes play key roles in determining the number, routing and isolation control of the utilities lines. Air handling dominates the layout because efficient, low-noise, ducts require a large diameter and particular placement for thermal control, fire detection, and crew gas exchange. Utility distribution is a highly iterative process integrating crew accommodations and secondary structure. Space architects tend to develop an integrated modular system that allows flexibility in layout.

d. Subsystem Schematics and Component Packaging

Most functioning subsystems can be characterized by a schematic diagram. This identifies the major components and the interconnectivity of power, data and cooling lines. In a Master Equipment List (MEL), subsystem analysts record component mass, power, dimensions, and technology readiness. Using the schematic, MEL, and a concept for line replaceable units, the subsystems are packaged for launch loads, connection to utilities and crew servicing. For the International Space Station, systems were packaged into identical racks then attached to standoff trays for utility connection. New approaches are being explored because this concept was based on delivery and outfitting by the retired Space Shuttle. New concepts are needed for long duration human missions beyond low-earth orbit (Figure 16). These mission will have infrequent and possibly no resupply and therefore must be designed for *in-situ* repair and maintenance.

D. Selecting Options

1. Constraints and Preserving Options

Constraints are the boundary conditions imposed on the design from requirements, specification standards, management, or the laws of physics. They also can be self-imposed, reducing a broad array of options in order to get the project moving with proper emphasis on important issues. Frank Lloyd Wright said that constraints are the architect's best friend.

Constraints can represent different levels of commitment. A temporary or soft decision keeps the design cycle moving while allowing changes based on future discovery. Hard decisions eliminate options fixing on a particular solution. As important as it is to constrain the problem, it is equally important to preserve options. This is difficult for the analytical mind which wants to simplify decision-making by imposing hard decisions. The synthetic mind wants to keep the options open until the last minute. Spinard puts it this way, “Hang on to the agony of decisions as long as possible.” This is why designers take as much time as given. Keeping many options viable as long as practical helps prevent fixating on a particular configuration prematurely, and trying subsequently to force it to fit new constraints. Systems Architecting offers “Build in and maintain options as long as possible in the design and implementation of complex systems. You will need them.”

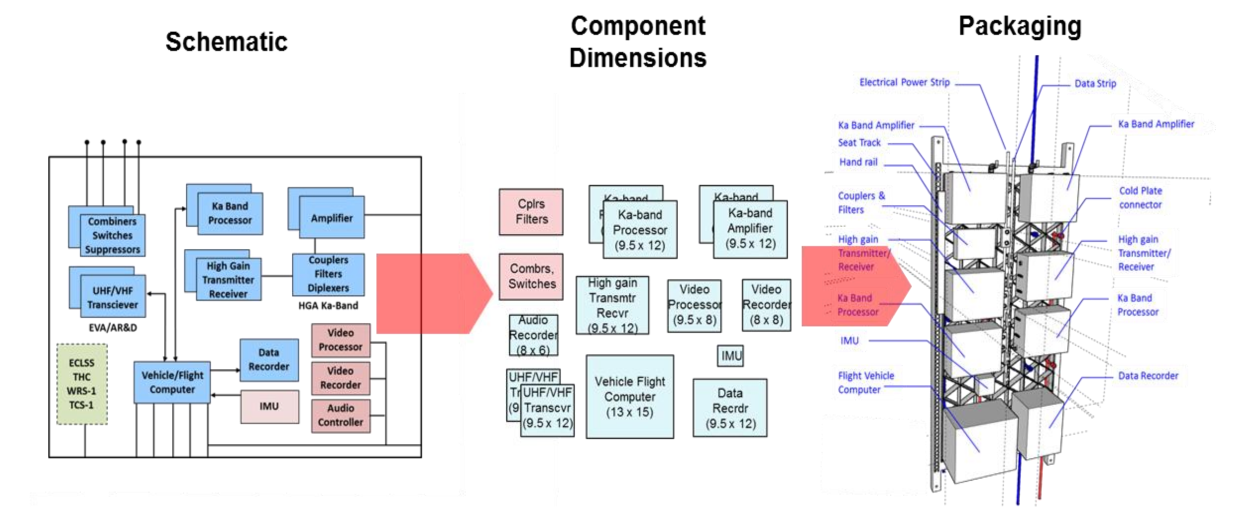

Figure 16. A step-wise process is used for packaging subsystems

Space architects must be cautious of “solutions looking for problems.” It is no surprise that contractors and vendors with a particular product line will promote solutions that benefit their services or products. This is not necessarily bad, but has a way of contaminating an otherwise pure trade space. For example: inflatable habitats. There are options for the primary structure, but once “inflatable” is accepted as a hard constraint, it directs many other decisions.

2. Optimization

Optimization is the process of adjusting multiple system parameters simultaneously to achieve overall system benefit. “In nature, the optimum is almost always in the middle somewhere. Distrust assertions that the optimum is at an extreme point.” Aiken’s law number 8.

Computational techniques are well-known for optimizing mathematically modeled problems, even extremely complex ones. Such techniques work better the more fully the system can be characterized quantitatively. Therefore, they are well suited for well-bounded subsystems where the problem domain is small enough to be captured by a practical credible numerical model.

The space architect is commonly faced with problems impossible or impractical to describe mathematically. There is no escaping the difficult job of exercising human judgment. Avoiding entrapment in the local optimum requires maintaining the most inclusive possible balance. Still, the space architect can apply numerical optimization techniques using them to derive partial constraints, or solution drivers or visibility of quantitative trends for assessing partitioned problem domains. Ultimately, the space architect’s human reasoning provides the ability for massively multivariate, fuzzy, simultaneous integration.

3. Compromise

Compromise is the negative way to optimize. It means forcing competing constraints each to yield part way. The result is workable, but only partially meets all “pure” functional requirements. In reality, compromise is the most common approach taken. In extreme cases compromise may represent the “lowest common denominator” of competing functions—the only characteristic acceptable to all. Like least-common-denominator treaties, such a resolution tends to be optimal only in making all parties equally unhappy; it represents minimal progress. Space architects should consider compromise like any other expediency: acceptable if no better way can be found.

4. Synergy

Synergy is the positive way to optimize. It means satisfying competing constraints in such a way that the satisfaction of one enhances the satisfaction of others. It resolves competing requirements by inventing ways to satisfy all of them, rather than resorting to "buying off" competing requirements by nibbling away at all of them. Figure 17 shows an example of arranging the stowage to assist in radiation protection for the crew. The unique gratification of design integration lays in innovating system configurations which achieve a high degree of synergy. Synergy generally implies efficient utilization of system resources, as well as the most complete satisfaction of individually competing requirements possible. Synergistic designs tend to appear more inevitable as integrated solutions, even to uninformed reviewers. "A designer knows that he has achieved perfection not when there is nothing left to add, but when there is nothing left to take away." (de Saint-Exupery's Law of Design)

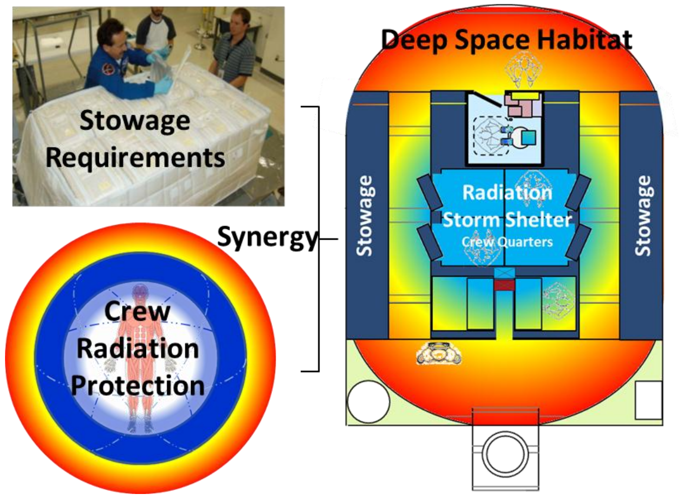

Figure 17. Stowage doubles as radiation protection

IV. Aptitude

"The ideal architect should be a man of letters, a skillful draftsman, a mathematician, familiar with historical studies, a diligent student of philosophy, acquainted with music; not ignorant of medicine, learned in the responses of jurisconsults, familiar with astronomy and astronomical calculations." This is a rather expansive description of an architect and what is even more remarkable is that it was written by Vitruvius 25 years before the birth of Christ. More than technical depth, the absolutely essential attribute of a space architect is to conceptualize. Space architects must possess technical breadth and must know how to get the depth from experts on the team. In this there is a positive mutual dependency building on individual inclination, training, and experience. To get the most out of this relationship, the space architect must also be a good manager, with the people skills necessary to lead a team. This skill involves knowing how to ask good questions and when to curtail non-productive discussion. Management consultant, W. Edward Deming says, "If you don't know how to ask the right question, you discover nothing."

What are some of the personality traits of successful, creative system (space) architects? Professor M. Chignell in an interview with Jonathan Losk derived the following list from questioning practitioners in the field:

1. Communication skills
2. A high tolerance for ambiguity
3. The ability to make good associations of ideas
4. The ability to work consistently at an abstract level
5. A level of technical expertise (level not specified)
6. A tempered ego; the opposite of arrogance
7. Leadership; gets the most out of others
8. The willingness to backtrack, to seek multiple solutions
9. The ability to build teams
10. Charisma
11. The ability to read people well
12. Self-discipline, self-confidence, a locus of control
13. A purpose orientation
14. A sense of faith or vision
15. Drive, a strong will to succeed
16. Curiosity, a generalist's perspective

Like the architect's description by Vitruvius, this is another expansive list of attributes. In a subset of these, being a creative space architect requires a strong combination, but not necessarily in equal measure of the following:

2. A high tolerance for ambiguity
4. The ability to work consistently at an abstract level
8. The willingness to backtrack, to seek multiple solutions
12. Self-discipline, self-confidence, a locus of control
13. A purpose orientation
14. A sense of faith or vision
15. Drive, a strong will to succeed
16. Curiosity, a generalist’s perspective

As is seen from the list of personality traits, space architects should have a high tolerance for ambiguity. In many ways this attribute is self-selecting because those who are comfortable with linear, analytic thinking become frustrated with the creative exploration in the synthetic approach.

1. Self-Starters

Surviving successful space architects are self-starters. That is to say, they take the initiative proposing and advancing ideas. In some cases this attribute is welcomed if not encouraged, while in others (in particular with large organizations) it is seen as self-serving and worse, bucking the chain of command. Being a self-starter does not imply avoiding or ignoring direction from managers (very career limiting), but is appropriate when the project is stalled or there is little or no direction.

2. Pride of Ownership

Concept originality is a very sensitive area. Most designers take pride in their ideas; it is connected with their image of self-worth. They want to be recognized for contributing innovative, well-reasoned concepts. From Vitruvius, to Bernini, to Le Corbusier and Gehry, ideas are associated with individuals. This is the history of architecture. However, space design is different (with the notable exception of Apollo era, Max Faget). The attitude is, “Thank you ma’am for the baby, we’ll take it from here.” If the project is successful, it will have many fathers, if not, it is an orphan. At the risk of stretching the metaphor, many ideas are conceived but few develop to full maturity. If so, the path from concept to hardware is so convoluted its true genealogy is untraceable. To avoid being discouraged, this realization should be an early career lesson for space architects.

3. Fork in the Road

Space architects do not start out wanting to be space architects. Usually, they spend long hours in schools of architecture (or engineering) with aspirations of a more traditional career. Somewhere along the way, there is the revelation of plying their trade to space. For architects, a large number assume they are the first to make this connection, charging off with grand visions of zero-g hotels and lunar condominiums. That is, until they discover there is a loose community of employed space architects actually designing space stations, deep space habitats, and planetary bases. Now, they are faced with the major career choice of practicing traditional architecture or chasing the dream. It is possible to carry the initial love of architecture into a space career, but to truly contribute; it will no longer be the “day job.” Because there are few full time opportunities for space architects, this is a risky decision. Some have chased the dream, but for the lack of government or contractor openings were forced to pursue other ambitions. Others have had the fortune of good timing, a broad skill set, or position in the organization to make a career of space architecture. If only it could be like Yogi Berra says, “When you come to the fork in the road, take it.”

4. Takes time to develop

The commitment to space architecture, even more than to engineering as a whole, is long term—decades. As with other professions, it takes about 10 years after graduation from college to acquire the knowledge and judgment necessary to head an architectural team. And those 10 years need to be well spent.

5. Maintaining the vision

The ideal situation is for the architect to maintain the integrity of the system from concept to operation. This is possible on some projects, but very unlikely with the multi-phase, competitive, government programs. The long ride down the waterfall creates opportunities to diverge from the original purposes, functions and form. The space architect, more than anyone else, must maintain and strengthen that integrity, must intervene when it is threatened, must retain its options “to the last agonizing minute” (Spinard, 1989), and must imbue the rest of the project with the values that were built into the customer’s judgment.

V. Conclusion

If it is possible to make a noun a verb, this paper is architected. It integrates developed, well-presented ideas into a different product for the purpose of providing an overview of the role, work, and aptitude of the space architect. The identified contributors have each done a masterful job articulating particular parts of the narrative, but liberties were taken. For the sake of compression, descriptions were truncated, amplified, reordered, or eliminated. Ideally, together the reader is able to extract a summary message, but is drawn to the original writings for a deeper understanding of space architecture.

The answer to the opening question, "Is space architecture a vocation?" is yes…for a handful. They have had to be flexible and engaged; sometimes taking on assignments only distantly related to the field. In closing, there is no perfect time, position, or team so, don't wait for the job posting, "Wanted: Space Architect." Theodore Roosevelt summarized it well, "Do what you can, with what you have, where you are."

VI. References

"A Baseline Design for the Space Station Habitat," R. L. Olson, B. N. Griffin, and J. S. Hawkins, Society of Automotive Engineers, Inc., paper no. 881119, 18th Intersociety Conference on Environmental Systems, San Francisco, California, July, 1988

"Akin's Laws," David L. Akin, Associate Professor in the Department of Aerospace Engineering, University of Maryland, Director of the Space Systems Laboratory.

Augustine's Laws, Norman R. Augustine, Viking Penguin Inc., 1993, ISBN 0-670-80942-X

"Collaborative Development of Systems Architecting Design Rules," T. McDermott, T. Ender, and N. Bollweg, 14th NDIA Systems Engineering Conference, Oct. 24-27, 2011. Presentation #13176

"Deep Space Habitat Configurations Based on International Space Station Systems," D. Smitherman, T. Russel, M. Baysinger, P. Capizzo, B. Griffin, L. Hornsby, D. Maples and J. Miernik, Global Exploration Conference, International Aeronautics Federation, May 21-25, 2012, Washington, D.C. Paper no. GLEX-2012.01.1.8x12219

"Internal Layout for a Cis-Lunar Habitat," Brand N. Griffin, D. Smitherman and A. S. Howe, AIAA Space 2013 Conference, San Diego, CA, September 10-12, 2013, AIAA 2013-5433

From Earth to the Moon, Jules Verne, 1865

"Introduction to System Architecture," Rev 2.0, January 5, 2007, Architecture to Value, Ed Crawley, Massachusetts Institute of Technology

Out of This World: The New Field of Space Architecture, ed. A. Scott Howe and Brent Sherwood, American Institute of Aeronautics and Astronautics, 2009

"Space Architecture, Core Curriculum Notes," International Space University, Huntsville, Alabama, ed. Brand Griffin, contributors John Connolly, Tim Vinopal, Stephen Capps, Brent Sherwood, 1993

Systems Architecting: Creating and Building Complex Systems, Eberhardt Rechtin, Prentice Hall, Inc. 1991, ISBN 0-13-880345-5

"Peter's Laws," Peter Diamandis, M.D., Harvard, B.S. MIT, Co-founder of International Space University, X-Prize and Singularity University

The Influence of Zero-G and Acceleration on the Human Factors of Spacecraft Design, Brand Norman Griffin, National Aeronautics and Space Administration, JSC 14581, 1978

"The Space Operations Center Habitable Service Module," B.N. Griffin, Boeing Document D180-27012-1, March 31, 1982

Warplanes of the Third Reich, William Green, Doubleday and Company, 1970, ISBN-88365-666-3