Space 2006
19 - 21 September 2006, San Jose, California

AIAA 2006-7317

A Design Pattern Language for Space Stations and Long-Term Residence Human Spacecraft

James D. Lowe*
Ottawa, Ontario, Canada

The purpose of this paper is to present the beginnings of an architectural design pattern language for use in studying and designing space-based human habitats. At present, the space habitat pattern language consists of 60 patterns, arranged into 4 hierarchical categories, derived from the history of space-station designs ranging from Salyut 1 to Skylab, Mir, and the International Space Station. This paper discusses the pattern language and how it was derived, presents a selection of its constituent patterns, presents instructions on how to use it when developing requirements, illustrates how it can be used in conceptual design studies, discusses how it can be extended and applied to Moon and Mars landers, and concludes with a discussion how to continue to develop the language.

I. Introduction

In 1977, Christopher Alexander (Alexander et al.,1977), an architect, builder, and scholar, along with a group of colleagues, published a book called *A Pattern Language: Towns, Buildings, Construction* in which they introduced the concept of the architectural design pattern, pattern discovery and analysis, and the pattern language. They proposed these ideas as a way of rigorously codifying the things that make certain aspects of a building's, or region's, organization good in certain situations and bad in others. The basic idea behind design patterns when applied to buildings, or other artifacts with which people interact, is: from a history of actual designs, recurring architectural solutions to specific life problems, called patterns, can be identified. Also, these are not just any repeated solutions, but ones that promote human activity in some positive way. The patterns that Alexander discusses do not specifically deal with matters of style, aesthetics or technical implementation, but with arrangements of architectural elements and their ability to solve organizational problems inherent in the activities of people. So, patterns and pattern discovery are a means of finding and communicating apparently implementation invariant, organizational design principles from a legacy of specific design solutions to problems that have also proven to enhance people's well-being. They also show how patterns link together to form a language from which new building designs can be generated that incorporate these timeless solutions into new projects.

The methods of design pattern discovery, analysis and language creation can be applied to the history of long duration crewed spacecraft - the Salyuts, Skylab, Space Shuttle, Mir, and the International Space Station - to extract design solutions that have essentially remained invariant over time. This information can then be used to augment the requirements development and discovery phase of the development of new human spacecraft that might be used for trips to Mars, our Moon, or for other space station-like craft, in order to help insert good solutions from the past into future forms. This paper will discuss the basic principles of design patterns and pattern languages; present a space residence design pattern language derived from the history of Low Earth Orbit (LEO) space stations; present a selection of example patterns, discuss how this information can be used during preliminary design, and requirements specification; and conclude by discussing how it might be extended to work on the development of Moon or Mars landers.

II. Pattern Fundamentals

A. Definition

Alexander and his colleagues (Alexander et al.,1977) define a pattern in a somewhat different way than we

*Member, AIAA

might expect to find in a dictionary:

> "Each pattern describes a problem which occurs over and over again in our environment and then describes the core of the solution to that problem, in such a way that you can use this solution a million times over, without ever doing it the same way twice."

They later went on to elaborate that a pattern is composed of three basic parts:

1. a context,
2. a system of forces arising within the context which constitutes the problem to be solved, and
3. a configuration or solution to the problem.

The context is the setting; that is, the circumstances within which the problem is to be solved. A pattern's system of forces is broadly defined and can comprise both physical pushes and pulls, as well as more abstract sources of impetus like social, psychological, and political ones. Clearly, the context and the system of operative forces influence implementations and need to be given consideration when applying any pattern in a new design**.** The configuration is a design solution whereby all of the active forces, acting within the context, come to resolution. It is fairly independent of the technology used in the implementation and its most salient aspects can be implemented using a variety of technological approaches.

This definition provides a structured framework for looking for what in simple terms amount to best practices that have been implemented over and over in the history of human spacecraft. Pattern discovery amounts to asking questions about how everyday life problems have been solved on various types of spacecraft and looking for common threads and pervasive themes.

B. Basic Pattern Format

There is no official standard for writing a pattern. One is free to create one from the basic concepts discussed in the previous section, but it should attempt to capture the context, forces, background information, and solution in a succinct fashion. Several styles are possible; however, the one used in this work is a straightforward format:

1. an evocative (and sometimes provocative) title;
2. a representative photograph;
3. a summary statement about the problem and pattern, and the linkages to other patterns;
4. a discussion;
5. a statement about the suspected invariance of the pattern;
6. an instruction; and
7. a simple diagram of an archetypal solution.

C. Some Pattern Properties: Invariance & Kind

Patterns typically have two dominant properties: invariance and kind. Invariance is an assessment about the immutability of the pattern, and kind refers to whether the pattern can be considered to be positive, negative, or neutral in its affect on residents.

1. *Invariance*

A Pattern Language (Alexander et al., 1977) takes care to assess the speculated invariance of each proposed pattern using a three-tiered scale. At the top are patterns that are thought to be truly invariant. In the middle are ones that there is strong evidence to suggest they are invariant, but require further investigation to confirm the assessment. At the bottom are ones that are just one of several possible solutions. The bottom level patterns are interesting because they might be more appropriately referred to as proto-patterns, or maybe even as patterns-in-waiting. They are truly not invariant. The patterns in the space station pattern language discussed in this paper are also rated on a three tier scale which is based on the *A Pattern Language* (Alexander et al., 1977) scale: High, Moderate, and Unknown.

In the world of design patterns, invariance is tightly bound with the idea of repetition. The more instances that can be found of a solution being used in a certain situation and acted upon by similar forces, the greater its level of invariance. In software related applications, a so-called 'rule-of-three' is sometimes applied as the threshold to invariance. The rule goes like this (Appleton, 1997): if at least three instances can be found, a proto-pattern is on its way to be being considered to be an actual pattern. Therefore, for something to be considered as a candidate pattern, it must have at least this level of recurrence in the field. Strictly speaking, the rule-of-three does not guarantee invariance, nor would a rule-of-one-thousand, or even a rule-of-one-million. The weight of evidence only suggests at invariance, it does not conclusively prove it. However, the more instances there are, the stronger the case for broad applicability in the field even though the claim to invariance may more of an academic point.

In the Alexandrian architectural patterns, invariance also has a non-quantitative component. As well as repetition, the ability of a pattern to enhance the well-being of the people with which it interacts is also a consideration. This is what allows patterns with seemingly low recurrence in the field to still be good candidate patterns. If a pattern consistently receives positive reports from different sources about how well it worked, or was always observed to bring about a certain harmony, it reinforces its candidacy as a pattern. This strength of character can help overcome a low-count repetition profile. Alexander (1979) refers to this as the Quality-Without-A-Name, or QWAN for short. This is definitely a tricky, but not completely impossible, property to assess in a somewhat objective fashion. For example, one way of getting the feel for the QWAN in an architectural project is through the method of Post-Occupancy Evaluation (POE) (Brand, 1994; Preiser, Rabinowitz, White, 1988). POE involves surveying the occupants of a building at certain times after it was built in order to try to objectively assess the building's livability. In aerospace applications, variations on the Cooper-Harper scale can be brought to bear on the problem

2. *Kind*

As we discussed in the section about invariance, the idea that patterns are beneficial in some regard, and not merely just repetitious occurrences of phenomena, is built right into what is considered to be a pattern. It is easy to imagine the opposite situation: patterns that are not beneficial, but are negative in their affects. Negative patterns are ones that diminish existence in some manner. William Brown (Brown, Malveau, McCormick, Mowbray,1998) has proposed that there is an especially virulent form of negative patterns called 'AntiPatterns' active in the field of software design and in software development organizations. These patterns discuss solutions - if we can call them that - which cause the active system of forces at play in a situation to not resolve and balance out, but to actually set into motion a divergent spiral that leads to failure and breakdown in behaviour. Brown et al. (1998) goes beyond just identifying AntiPatterns and their consequences, but also tries to present ways of rectifying them. However, the way to fix a negative pattern may not always be known.

Negative patterns need not always result in the extreme repercussions of the AntiPattern, but can indeed result in many forces being resolved; however, with overtones of lingering, or overt discontent, which implies the presence of unresolved force remnants. They can arise deliberately, as in the case, for example, of patterns that can be active in the design of prisons. On the other hand, they can arise as unintended side effects. This can happen when design solutions get perpetuated because they solve problems more closely related to some programmatic objectives of non-direct users and not necessarily the actual needs of direct users. This situation can easily develop in institutional-like settings, such as hospitals, schools or offices since a great deal of the design activity of these places is outside the scope of influence of the eventual intended direct users.

Between the positive and negative are the neutral patterns. They are almost like no patterns at all, since they do not contain archetypal solutions, but are almost entirely all context and forces. The context of a domain within which patterns are active can exist on many scales from the macro to the very micro. Neutral patterns are helpful in understanding the character of such multifaceted domains. For example, many neutral patterns in an architectural domain pertain to the physical world such as weather and environmental conditions, and biomedical responses. Neutral patterns are neutral because they exist independently of human wishes and existence. The full implications of neutral patterns are at times difficult to grasp because their complete resolution can span many positive and negative patterns, whose own contexts and force systems are but one narrowly defined aspect of one or more neutral patterns. Almost all positive and negative patterns in a domain flow in response to neutral patterns.

C. Pattern Languages

Patterns do not exist independently of one another. A complex artifact like a building or a human spacecraft consists of a large number of mutually interlocking patterns. Any particular pattern helps to bring about the full implementation of the solution of one or more other patterns, and, at the same time, that same pattern might also form part of the context for one or more entirely different patterns. Alexander et al. (1977) postulated that this form of interconnection implied that a hierarchical relationship existed amongst patterns whereby any given pattern helps solve higher level patterns and also helps set the context to lower level patterns. As well, if neutral patterns exist in a domain, they usually occupy the higher echelons of the interconnection hierarchy. In summary, patterns and their interconnections form a network that Alexander et al. (1977) calls a 'pattern language'. Alexander went so far as to state that the creation of the language - both the discovery of the patterns and their linkages - was the real work of designing any artifact. The artifact itself was merely an instantiation of particular instances of the patterns dependent upon unique conditions at the time of design.

It is possible for a pattern analysis of a class of artifacts to yield many pattern languages. What one arrives at can depend upon the criteria used for identifying and selecting the constituent patterns. In *A Pattern Language* Alexander et al. (1977) concentrates on presenting positive patterns active in architectural history with the criteria for selection as an invariance in the ability to have a good influence on human life as well as solving a particular organizational problem. One of the primary motivations behind *A Pattern Language* was a belief that the western world is almost completely embedded in a built environment dominated by negative patterns - not necessarily always of our conscious making - of varying degrees of severity. To overcome this situation his team suggested that we need to mine the positive patterns of history lest they be completely erased from our collective memory. However, any particular design pattern language need not be purely positive, or negative, but in general, a language could consist of a mixture of positive and negative patterns in order to properly reflect the true nature of the domain under analysis - the human spacecraft design pattern language discussed in this paper is such a mixed language.

Can a pattern language ever be called complete? In other words, is there a measure of completeness to give us an idea when a language is fully developed? In some respects the number of neutral and negative patterns in a language is a measure of completeness. Negative patterns are misfits, and in a developing language they should eventually be replaced by patterns that solve the problems they describe and, therefore, should be viewed as place holders. Neutral patterns point to areas that require further research, and should also eventually be eliminated; except possibly at the highest levels in the language where they help define the language's overall context. In general, negative and neutral patterns prevent full expression of a language's potential as they tend to form nodes of disconnection in a language's structure. However, the absence of negatives and neutrals can be misleading since this does not always imply completeness. One also needs to look at the number of invariant positive patterns, as well as the absolute number and types of patterns in the language. Too few invariants may indicate that the domain itself is too immature for a language to be constructed or that too little work has been done in pattern discovery. Also, one needs to review the vintage of the patterns. If they are old - the definition of old depends on the level of dynamism in the domain - they may be out of date with respect to current ideas and thereby reduce the completeness of the language. Another measure of completeness is the ability of the language to be used to generate good requirements, or complete and varied design solutions. It should also be noted that a healthy language is never truly complete, but is always in a state of openness to potential change.

III. Structure of the Proposed Human Spacecraft Design Pattern Language

A study of the literature of the history and engineering of human spacecraft, as well as publications of first hand accounts of life in space, has provided the basis for the codification of the proposed language's structure, and the identification of its basic patterns (Lowe, 2002). Some of the key documents in the construction of the language were, but were not limited to: Stuster (1996), White (1998), and Harrison (2001) provided initial sources on the effects of space flight on humans; Burroughs (1998), Cooper (1976), Harland (1997), Lebedev (1990), Linenger (2000), and Lucid (1998) formed an introductory group of accounts about day-to-day life in various space stations; and NASA's *Man-Systems Integration Standards* (NASA, 1995) provided a jumping off point into engineering-codified human factors design principles for spacecraft development.

Fig. 1 shows the overall structure of language, the pattern categories, titles of the patterns that currently form the language, and indications about pattern invariance and kind. In Fig.1 each pattern title is followed by two flags contained within square brackets. The first flag indicates the pattern kind using the following nomenclature: + for positive, 0 for neutral and - for negative. Some patterns have an indication of a mixed kind. For example, 0- means a neutral pattern that shows a negative bias. The second flag indicates the pattern's invariance using the following nomenclature: H for high, M for moderate and U for unknown. Pattern titles shown in bold face type are presented in detail in this paper and all patterns are discussed in detail in (Lowe, 2002).

Environment
(the conditions of space)
en.1 *No air* [0,H]
en.2 *Too much radiation* [0,H]
en.3 *No weight* [0,H]
en.4 *Light and dark* [0,H]
en.5 *Space junk* [0,H]
en.6 *Near and far* [0,H]

Being
(physical & mental survival)
be.1 *Shirt sleeve environment* [+, H]
be.2 *Body is a 1-g machine*[0-,H]
be.3 ***A sense of power over personal spac****e*[+,H]
be.4 *Visual vertica****l***[+,H]
be.5 *Deepening*[0+,M]

Doing
(formal activities & work)
do.1 *Incarceration melancholia* [0-,M]
do.2 *Autonomous work life*[+,M]
do.2.1 *Thoughtful & active participation*[+,M]
do.2.2 *Overlapping skill sets*[+,M]
do.3 *Buckling down & strapping in*[+,H]
do.4 *Cluttered niches*[-,H]

Supporting
(to get by for a couple of days or weeks)
su.1 *Keep a horse headed for home*[+,H]
su.2 *Single room*[+,H]
su.3 *Room with a view*[+,H]
su.4 *Eliminate edges*[+,H]
su.5 *A necessary toilet*[+,H]
su.6 *Structured storage*[+,M]
su.7 *Crash pad*[+,H]
su.8 *A variety of exercises*[+,M]

Remaining
(to get by for a long time)
re.1 *Human scale rooms*[+,H]
re.2 *Private places*[+,M]
re.3 *Multi-dimensional living space*[,+M]
re.4 *Shower*[+,UtoM]
re.5 ***A big room***[+,M]
re.6 *Entertainments & communications*[+,H]
re.7 *Mobilia*[+,MtoH]
re.8 *Salle commune*[+,H]
re.9 *Remote manipulation*[+,H]
re.9.1 *Remote viewing*[+,M]
re.10 *Garden*[+,M]
re.11 *Lookout tower*[+,M]

Shaping
(to form the individual living spaces)
sh.1 *Pressurized can*[+,H]
sh.1.1 *Protective coverings*[+,H]
sh.1.2 *Radiation shielding*[-,U]
sh.1.3 *Two ways out*[+,M]
sh.1.4 *Integrated ducts*[+,M]
sh.1.5 *Grapple fixtures*[+,H]
sh.1.6 *X marks the spot*[+,M]
sh.2 *Clear windows*[+,H]
sh.2.1 ***Shades and shutter****s*[+,H]
sh.3 *Inflatable volumes*[+,U]
sh.4 *Airlock*[0,H]
sh.5 *Minimize outside maintenance*[+,H]
sh.6 *Noises off*[+,M]

Organizing
(to arrange the living spaces)
or.1 *Ambient gravity*[+&-,H]
or.2 *Self-contained core*[+,H]
or.3 *Building over time*[+,H]
or.4 ***Visual transitions***[+,M]
or.4.1 *This end up*[-,H]
or.5 *Five minute float*[+,U]
or.6 *Workshop gradient*[+,M]
or.7 *Spaceship Earth*[0,U]
or.8 *Enhanced gravity*[+,U]
or.9 *Impermanence*[0,H]

Figure 1. Structure of the Human Spacecraft Pattern Language (Lowe, 2002)

The pattern language consists of 60 patterns arranged into seven categories: Environment, Being, Doing, Supporting, Remaining, Shaping and Organizing.

Patterns in the Environment category are neutral ones and deal directly with the physical conditions confronting people in the near Earth space environment: they deal mainly with the lack of life support. Patterns in this category, like environmental patterns on Earth, are not really independent entities as implied by the figure, but form multiple integrated and interdependent networks. The pattern presentation merely allows for certain aspects to be emphasized in order to clarify certain important features that need to be addressed in any design.

Directly below the Environment category are the patterns of human activity: Being and Doing. The Being category contains the patterns of immediate physical and mental survival. It includes patterns that discuss such physically based things as the requirements and limitations of a man-made life-support environment. As well, the Being category encompasses what might be called softer patterns that deal with the subtle mix of behaviors surrounding the experience of living in space inside relatively small volumes.

The contrasting Doing category deals with the patterns of work and other formal, or programmatic, activities that the residents may undertake such as scientific research. It contains patterns that deal with the physical apparatus needed to perform work while weightless, and on the physical, personal, workflow, and social organization of such activities. Along with these research-type activities there is also a certain amount of maintenance and repair work to be done. To accomplish these chores, patterns have arisen that support doing work in general and transcend many narrowly defined task objectives. These form the high level core of patterns in the Doing category. As well, a certain amount of work also happens outside the residence, but this working environment is not currently dealt with; however, this category could accept these patterns.

The Supporting and Remaining categories deal with satisfying short and long term needs. Supporting presents patterns that are necessary for people to get by for a few days to a couple of weeks, and Remaining deals with patterns necessary for stays on the order of many weeks or months. The Supporting and Remaining level is where the patterns in the language begin to deal with the hardware requirements of living arrangements.

The Supporting category contains patterns for such things as the need for a private bathroom, sleeping space, and the structure of common areas. In the Supporting category the period of residence is somewhat like an extended camping trip, so the amenities are generally subordinate to the programmatic objectives. It is important to note that patterns in the Supporting category are heavily influenced by the history of space flight as being primarily for research and military purposes. In the future, other contexts for short-term stays may arise, such as the space hotel for travelers and tourists. New contexts would cause new patterns to flow into the Supporting category, or derive from the basic ones already there. We might also see patterns flow in from the Remaining category, since an enhanced experience of space, which is one of the aspects provided by Remaining patterns, may be what hotel residents desire.

The Remaining category contains patterns for things such as privacy, gardens, big rooms, dining, observation sites, work areas, and external remote manipulation. The patterns typically characterize situations necessary to enable people to get by for a long time, which so far means for a few months up to and including about a year. These patterns expand and elaborate upon Supporting patterns, but do not necessarily supplant them. A space residence capable of providing long term occupancy requires patterns from both the Supporting and Remaining categories, but a short term occupancy residence need not contain patterns from the Remaining category.

The Shaping and Organizing patterns, at the level below Supporting and Remaining, begin to deal with more specific technological implementation choices for patterns at the higher levels. Shaping and Organizing contain both patterns and the beginnings of the highest level requirements for detailed specification of actual hardware that would occur below this level. Patterns end at this level, and specific technology based engineering specification begins in earnest from here on.

The Shaping category deals with how to form the actual living spaces, and Organizing deals with the patterns of arranging the living spaces. It is important to note that Shaping patterns are driven by architectural concerns from above and by technology from below. As technology changes then so will the available repertoire of shapes.

The Organizing category, which contains patterns about how to arrange spaces to generate complete residences, is comprised of patterns dealing with such things as the gravitational needs of the residents, visual orchestration of the spaces while moving, modularity, and decommissioning.

Table 1, the following table, lists pattern titles and summary statements for each pattern in order to gain a sense of what each pattern defines. Some examples of full pattern definitions are given in section IV and linkages between the patterns are shown in the Appendix.

en.1 *No Air*
There is no air in low Earth orbit and, so far, we have not found any places with naturally occurring breathable air away from our Earth.

en.2 *Too much radiation*
Once we leave the Earth's atmosphere for space, we enter a realm that is soaked in levels of radiation that we are never exposed to on Earth.

en.3 *No weight*
Being weightless is probably the condition most popularly associated with living in space. It is one of the first things we notice when we see television images of spacefarers. We are confronted with what on Earth would be considered to be hallucinatory scenes of people floating, flying, walking on ceilings, and bouncing off walls while their hair is standing on end.

en.4 *Light and dark*
The space near our Earth is filled with light, but it is not of the same quality as we experience here on the surface. There is no dappled light, no foggy light, no diffuse light, no dim cafe light, no sultry summer light, and no crisp winter light. There are none of the myriad light conditions - like that celebrated by the great impressionist painters - that we are privileged to experience day in, day out, year after year on Earth that help set the scene of our lives. Well, this is of course an exaggeration, but not an extreme one. There are varying light conditions in space, but not what we are used to.

en.5 *Space junk*
Space is not as pristine as we might like to think. Near the Earth, space is filled with all kinds of orbiting debris, some natural, some not.

en.6 *Near and far*
Even though a LEO space residence might be only 300 to 500 km from Earth, it's isolated. There are no nearby settlements to go to for help, supplies, or sociability. The trip back to Earth, if unplanned, is fraught with dangers. The situation is even worse on the Moon or Mars. In the end the transportation available to go to these places defines what is nearby and what is far away

---

be.1 *Shirt sleeve environment*
The normal environment inside a space residence is one that allows its residents to go about their activities wearing common, everyday lightweight clothing. The residents require no special life-support apparatus to be worn as long as they remain indoors.

be.2 *Body is a 1-g machine*
Humans experience both short and long term induced changes while living in a weightless condition because our bodies are adapted to Earth's gravitational conditions; some are pleasant, but others are problematic.

be.3 *A sense of power over personal space*
Weightlessness gives people the ability to fly. It brings with it a heightened sense of freedom of movement and is just plain fun.

be. 4 *Visual vertical*
A resident needs a visual impression that the immediate environment has an up-and-down orientation the same as one would expect in a similar room on Earth in order to help overcome the body's sensory impression that up-and-down is missing since gravity is missing.

be.5 *Deepening*
The confined and distant environment of a space residence can enhance the well-being of occupants who somehow exploit the conditions and solitude in which they find themselves.

---

do.1 *Incarceration melancholia*
The confined and distant environment of a space residence can provoke, or exacerbate, stress-reactive, depressive, neurotic, and antisocial tendencies in its residents. One might refer to it as a syndrome since it is actually a collection of symptoms.

do.2 *Autonomous work life*
Residents need a certain level of autonomy in setting and executing their work schedules with positive support from external sources.

do.2.1 *Thoughtful & active participation*
The official goal of most visits to a space residence is to conduct scientific, military, or commercial research; however, the research workers in the residence perform best when they act as an active participant in the work, and not just as a pair of hands for performing rote and pre-orchestrated tasks.

do.2.2 *Overlapping skill sets*
The residents need to have overlap in the skills they possess - as opposed to everyone being a specialist - for both logistical reasons and so the residents can take an interest in and relate to each other in a supportive fashion.

do.3 *Buckling down & strapping in*
This pattern discusses various type of body restraints that are necessary for holding a person in place while doing work to prevent them from drifting away from their task.

do.4 *Cluttered niches*
As a consequence of being active in a gravity-free environment, three-dimensional clutter easily develops throughout a residence.

---

su.1 *Keep a horse headed for home*
A space residence needs to have a ready means of escape in the event of a catastrophe.

su.2 *Single room*
The interior space of a space residence is dominated by a single large general-purpose room. It serves as a working area as well as a social area and is not allocated specifically for any one particular activity or person.

su.3 *Room with a view*
One of the most important features of a space residence is the view it affords of the Earth and space. Appropriately placed windows enhance the space experience.

su.4 *Eliminate edges*
Since the residents are capable of full three-dimensional motion in a weightless condition, the objects in their environment need to be shaped to accommodate the needs of human beings that can fly and float. In its simplest incarnation, edges and corners need to be designed to minimize injury in a collision.

su.5 *A necessary toilet*
Needless to say, any place that will accommodate people for more than a few hours needs a toilet, and space residences are no different. Some may argue that the provision of this facility is not really an architectural concern, merely a necessary piece of support equipment, and at best a negative pattern with regard to its architectural properties, but obviously positive in its ultimately useful, but indelicate function. On the contrary, this facility is highly representative of many aspects of the space residence experience in that it is emblematic of many other patterns in its realization; it is the quintessential space residence pattern.

su.6 *Structured storage*
It is even more important in weightless conditions to keep things organized and secured in their own unique places because if they are not, they will float and drift in response to the whims of air currents and other disturbances of even the feeblest nature.

su.7 *Crash pad*
Even though the *Single room* pattern is the major spatial theme in the Supporting category, portions of the available space may need to be transformed into semi-private sleeping accommodations when required. The new conditions are similar to a dormitory, or bunkhouse, and can be converted back to other uses when not needed.

su.8 *A variety of exercises*
Daily physical exercise is necessary to slow the atrophy of muscle, organs, and bone in the absence of weight. Providing a variety of exercises helps to stave off monotony and stimulate interest.

---

re.1 *Human scale rooms*
Spaces that scale with respect to the size of the residents enhance a feeling of well being and comfort with a room.

re.2 *Private places*
Everyone needs a private life to some extent, even in the quasi-public arena of space travel.

re.3 *Multi-dimensional living space*
This pattern looks at the use of interior space by residents in unintended ways - that is gravitational ways - that results from the ability to stand on the ceiling, or a wall, as easily as the floor. On a prosaic level it helps to alleviate problems with cramped spaces.

re.4 *Shower*
For residencies longer than a few days, a facility must be provided for full body cleansing.

re.5 *A big room*
Oversize spaces are necessary to balance the human-sized everyday spaces and allow for weightless conditions to be fully experienced.

re.6 *Entertainments & communications*
A variety of forms of entertainment, personal pursuits, and means of communicating with people on the Earth are necessary to help ward off *Incarceration melancholia*. The communication channels required are in addition to the normal ones necessary for the everyday operation of the residence.

re.7 *Mobilia*
Furniture, equipment, and fixtures require a degree of mobility in order to allow interior space to adapt to the inhabitants' varying needs.

re.8 *Salle commune*
Even though private spaces emerge when residencies get larger, public space for group activities, such as dining and meetings, are still required.

re.9 *Remote manipulation*
It is good to have external robotic devices that can be controlled from inside the residence in order to do outside work without actually going outside. Preparing for extravehicular activity is time consuming, and space walks are fraught with their own dangers.

re.9.1 *Remote viewing*
If you are using a remote manipulation device, and you do not have proper out of the window views of what you are doing, you need extra visual input in order to understand what's happening in the manipulator's workspace.

re.10 *Garden*
Ostensibly, plants have been grown in space only for scientific purposes - to see if it is actually possible to grow them - and to determine what happens to them in these strange, weightless, high radiation conditions. The flip side is that they also provide a necessary psychological link to the Earth for residents living in a rather sterile environment.

re.11 *Lookout tower*
Travelers frequently go afar just to take in the airs and contemplate dramatic views in distant lands. In some sense it is no different for today's space travelers. The view from the loftiest of perches above the Earth is for many the main attraction, and it needs to be exploited to help enhance the experience of the grandeur of the Earth and heavens.

---

sh.1 *Pressurized can*
The dominant form of enclosure for space residences to date has been the rigid, prefabricated, pressurized metal shell.

sh.1.1 *Protective coverings*
Protective wrappers are needed to shield against the temperature extremes of space and from the impact of micrometeoroids and space junk.

sh.1.2 *Radiation shielding*
A residence must provide its inhabitants protection from the high radiation levels encountered in space.

sh.1.3 *Two ways out*
If something goes wrong and an exit is blocked, there needs to be a second way out that can be used for escape.

sh.1.4 *Integrated ducts*
Ducting for ventilation and cabling should be built into the walls, floor, and ceiling of a module and not be exposed to the flow of people and objects in the living space.

sh.1.5 *Grapple fixtures*
If a *Pressurized can*, or any other object for that matter, is to be moved around by *Remote manipulation*, special handles, called grapple fixtures, are required for the manipulator to grab onto.

sh.1.6 *X marks the spot*
If a *Pressurized can* is to be moved around by *Remote manipulation*, it may need visual targets on its surface so that a *Remote viewing* system can accurately establish its position and orientation.

sh.2 *Clear windows*
Unadorned exterior windows are necessary to maximize the viewing conditions of a residence's high vantage point.

sh.2.1 *Shades and shutters*
Each window needs a covering(s) that the residents can pull down to block out the light and protect against radiation, micro-meteoroids and debris.

sh.3 *Inflatable volumes*
This pattern addresses the possibility of utilizing inflatable, non-rigid, nonmetallic materials to construct inhabitable volumes in a variety of shapes. It is one of several patterns in the Shaping and Organizing category that are presented not so much because they have a long history of proven success in the field, but because they represent a persistent experimental idea with enduring potential. The patterns *Shirt sleeve environment*, *A big room*, *Room with a view*, and *Private places* provide architectural impetus for *Inflatable volumes*, which in turn holds out a promise of generating further new patterns that could ultimately expand the range of architectural expression. However, lack of use of *Inflatable volumes* in the field indicates that the true invariance of the pattern is unknown.

sh.4 *Airlock*
In order to go outside to do chores, a room is required around an exit that can be isolated from the main volume and have its air evacuated prior to opening the door to the outside.

sh.5 *Minimize outside maintenance*
Going outside is generally time consuming in both the actual time spent outside and in preparation for the activity. It's dangerous too. The less time spent outside by people to fix, maintain, or construct the residence the better.

sh.6 *Noises off*
A space residence, maybe needless to say, is a highly technologically infiltrated environment, and the noise associated with this must be suppressed. However, all noises should not be completely eliminated because they provide cues as to the correct operation of the various life support systems.

---

or.1 *Ambient gravity*
This pattern discusses organizations of living spaces that do not modify the real or apparent

gravitational field experienced by the residents.

or.2 *Self-contained core*
The utility of a space residence - whether a single or multi-component construction - can be enhanced by having the core living volume be a fully functioning, self-contained unit that can be used by itself as a residence if required. Basically, soon after launching and insertion into orbit, it only needs to be powered-up and possibly supplied with some consumables to be made livable. No further construction is required.

or.3 *Building over time*
A space residence need not be constructed all at once, but can be spread out over a number of years as money and needs change.

or.4 *Visual transitions*
This pattern discusses how the visual flow of a residence's constituent spaces need to be organized to allow a continuous, understandable transition from one space to another and how Earth conditioned transitions can be overridden by the weightless experience of space - basically, as a weightless traveler floats from one space to another, they are biased to perceive their plane of entry as the floor and this needs to be maintained as their trip continues.

or.4.1 *This end up*
The visual cues necessary to understand where an entry to a passage may lead, and what its orientation may be, could be poor, and explicit labels might be necessary to help orient a resident on the move.

or.5 *Five minute float*
This pattern deals with the need to keep related spaces no more than 5 minutes apart as the 'crow' flies.

or.6 *Workshop gradient*
As opposed to a special purpose industrial workstation, a workshop provides tools, equipment, and workspace in a designated area for a wide variety of repair, construction, maintenance, assembly, and inspection tasks. Because it is a hive of activity it needs to be separated from areas where privacy and solitude are necessary.

or.7 *Spaceship Earth*
As Buckminster Fuller pointed out, Earth itself can be thought of as a spaceship and it is also the perfect space residence. The majority of patterns we have examined so far, like *Shirt sleeve environment*, *Necessary toilet*, *Garden*, and *Pressurized can* at best define only temporary residences because these patterns and their organizations are not self-sustaining like the Earth. And since we are Earth beings, most likely Earth is what we will need to recreate in varying degrees before we can migrate anywhere else. This is a tall order. In the near term, residences need at least a regenerating source of food which implies closing the internal carbon cycle - basically linking *Necessary toilet* back into *Garden* and *Shirt sleeve environment*.

or.8 *Enhanced gravity*
Enhanced gravity deals with organizations that modify the gravitational conditions experienced by the residents.

or.9 *Impermanence*
Even though space residences are some of the most complex and sophisticated artifacts ever built, they are also some of the most ephemeral. All, with one exception, have ended their lives by falling back to the Earth, disintegrating upon reentry.

Table 1. Pattern titles and summary statements (Lowe, 2002)

IV. Example Patterns

In this section extracts from 4 patterns (Lowe, 2002) in the language will be shown - the ones shown in bold in Fig.1 - in order to give a flavor for the contents of the language. The sections that follow are structured in accordance with the pattern format shown in section II(B). Please note that patterns are written for a broad constituency of users ranging from the technical, user, academic, business and marketing communities in order to help engage all potential stakeholders in the design activity. One of the ideas behind a patterns based approach is to extend the design discussion to many constituencies.

A. Pattern Title: be.3. ***A sense of power over personal space***

1. *Problem statement & linkages to other patterns*

Weightlessness gives people the ability to fly. It brings with it a heightened sense of freedom of movement and is just plain fun. This pattern flows from *No weight* in the Environment category. It has an instantiating and contrasting relationship to *Visual vertical* in the Being category, and with *Buckling down and strapping in* in the Doing category. *Visual vertical* tries to give a resident a visual sense of gravity, and *A sense of power over personal space* emphasizes the special conditions of weightlessness. It helps instantiate *Eliminate edges*, *Multi-dimensional living space*, *A big room*, and *Visual transitions*. *A sense of power over personal space* is a positive pattern.

2. *Discussion*

When novices are still getting the hang of their new found freedom they have a tendency to move around a lot like hesitant Supermen: arms outstretched in the direction of travel, instinctively trying to forestall head-on collisions as if there might be a meeting with stray kryptonite around the next bend. After awhile, they become more relaxed about moving around as confidence builds. To help novices and seasoned drifters alike get around, the internal surfaces are commonly outfitted with handholds, or handrails placed in strategic locations. They tend to get used as a means to change direction, stop, or turn, which means they do not have to placed, or spaced to be used for hand-over-hand translations. The design intent of these mobility aids is to keep the three-dimensional experience flowing, and not to block, or overly inhibit it. The most common locations for handrails is in front of workstations, or other pieces of fixed equipment that a resident may need to stop at for awhile in order to do some work. Also, one can imagine, not all flights will be along marked out paths, so any convenient piece of fixed equipment may get used as a handhold as necessary which implies all the internal structures must have a certain level of rigidity and robustness.

Figure 2. A representative photograph for the *A sense of power over personal space* pattern [NASA].

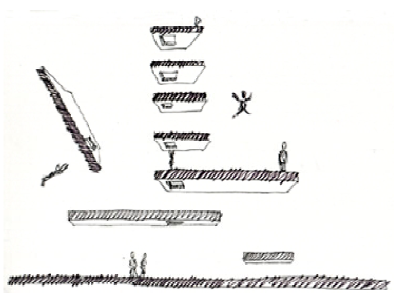

Figure 3. An archetypal sketch for the *A sense of power over personal space* pattern.

Full three-dimensional mobility also has some drawbacks. Equipment and workstation controls must be guarded against accidental adjustment due to being knocked, or bumped by a stray flyer, or a wayward piece of equipment. But, at the same time, the same controls need to be fairly easy for someone to adjust even though gravity is not acting to help them out as on the Earth. The *NASA Man-Systems Integration Standards* (NASA, 1995) present a thorough discussion of various ways of accommodating this situation.

3. *Invariance*

High.

4. *Instruction*

Residents enjoy the enhanced sense of personal mobility in weightlessness. Provide unimpeded space for full three-dimensional motion where bounding structures are solid and equipped with guides to support the flow of such travel.

B. Pattern Title: re.5 ***A big room***

1. *Problem statement & linkages to other patterns*

Oversize spaces are necessary to balance the human-sized everyday spaces and allow for weightless conditions to be fully experienced. This pattern flows from *A sense of power over personal space* in the Being category, and *Multi-dimensional living space* in the Remaining category. *A big room* has a contrasting relationship to *Visual vertical* in the Being category, *Human scale rooms* in the Remaining category, and with *Five minute float* in the Organizing category. It helps to instantiate *Visual transitions* and *Entertainments & communications*. *A big room* is a positive pattern.

2. *Discussion*

Most of what is known about this pattern comes from Skylab. Skylab's living area was a single cylindrical volume that was about 14.6 m long. It was divided into two main rooms: a little one and a big one. The little one was human-scale in height and was further subdivided into a bedroom, bathroom, experiments room, and a common area for dining and socializing. The big room was stacked directly on top of the little one. The two main rooms were separated by a see-through floor of metal grid work that had a hole in the center. If one were a good shot and aimed carefully, one could stand on the floor of the little room, launch oneself through the hole, and drift clear through to the ceiling of the big room. The big room was not subdivided into smaller rooms. It just had storage and equipment attached along its perimeter, so it was, more or less, a big open space.

Figure 4. A representative photograph for the *A big room* pattern: Acrobatics in Skylab's big room [NASA].

By most accounts the big space was a good place. A place for three-dimensional acrobatics, gymnastics, flying contests, long paper airplane flights, diving and leaping, and just good fun experiencing weightlessness. It seemed to provide a sense of freedom from work and helped alleviate the sense of cabin fever that developed after spending long periods in the tighter spaces of the smaller room

Eight out of the nine of Skylab's inhabitants ranked having a big room like Skylab's a necessity for long stays in space (Cooper, 1976, p.78). However, no space stations before or after have had a big room like Skylab's, and this appears to call into question the invariance properties of this pattern. Skylab had a big room because it was built from large Saturn V rocket components that happened to be available at the time. By contrast the size of the International Space Station's components were driven by a desire to construct the volumes for living from vessels that were able to fit inside either the Space Shuttle's cargo bay or in a Russian launch vehicle. So, although *A big room* is apparently architecturally desirable, its application can be limited by technological constraints that govern both how it will be constructed and how it is to be launched. If the pattern is to be incorporated into a design, the patterns available to implement it in the Shaping category will be constrained to some extent by the technologies available for launching and on-orbit construction. The result has been that the pattern has not been deliberately selected out of the legacy on design grounds, but more because of constraining technologies. The invariance rating of the pattern is therefore based on the comments of all the users of one residence, as opposed to a sampling of comments across several implementations of the pattern.

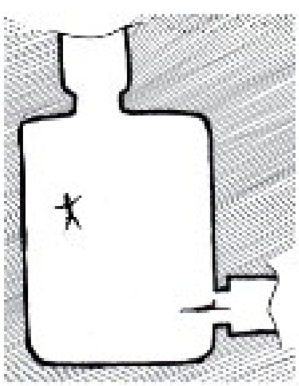

Figure 5. An archetypal sketch for the *A big room* pattern.

A big room is also useful in illustrating the care that must be taken in any future experimental studies involved with deducing patterns from inhabitants' impressions of life in a particular space residence. Several years after their Skylab experiences some residents reported a change of thinking on this pattern (Reichhardt, 1990) and felt that windows alone might compensate just as well for feelings of confinement. This highlights the necessity to use direct questioning while impressions are fresh in the mind in conjunction with other independent observational methods in any future studies in pattern discovery. As well, it is important to note that all residents will not give the same verbal impressions of the same conditions, so independent observation helps to provide a balancing set of data.

Surprisingly, getting any sort of opinion about a residence's internal environment from the residents themselves can be controversial. During the NASA / Mir residencies, Kanas (Kanas et al., 2000) regularly had various residents fill out a questionnaire aimed at rigorously evaluating their interpersonal relationships as it affected work activities. A subset of questions dealt with evaluating aspects of the internal environment, and these always resulted in the lowest rankings of all the factors for both American and Russian residents. In fact the environment questions began to annoy the residents so much they had to be dropped from a similar study carried out during the early ISS residencies. This response could be a side effect of the population under study where one is trained to endure adverse conditions which might be encountered while doing a job. This in itself does not invalidate the questions, but indicates that population group characteristics may influence what questions can be asked and what sort of answers might be obtained. Something to consider if user questioning is used as a means of pattern discovery.

Finally, *A big room* should be applied with some caution. The Skylab experience suggested that inhabitants should probably not be exposed to it too early. Ideally, they need to have become acclimatized to the weightless condition in a more confined space, because the large, undifferentiated volume can exacerbate adaptation problems. On Skylab one entered the big room from the Apollo capsule via a rather small diameter tunnel which would abruptly open into the large open space. This transition, coupled with the sight of the floor far way, could induce some uneasiness when entering the big room. So, the positioning of the pattern in a design will have an impact on the patterns in the Organization category that are incorporated.

3. *Invariance*

Moderate.

4. *Instruction*

Provide a large volume, undifferentiated open space for full three dimensional activities that has enough room to accommodate several people at a time.

C. Pattern Title: sh.2.1 *Shades & shutters*

1. *Problem statement & linkages to other patterns*

Each window needs a covering(s) that the residents can pull down to block out the light and protect against radiation, micro-meteoroids and debris. This pattern flows from *Light and dark* and *Too much radiation* in the Environment category and *Protective coverings* in the Shaping category. *Shades and shutters* is a positive pattern.

2. *Discussion*

The light coming through a window from space is intense, because, as discussed in *Light and dark*, there is no atmospheric filtering as on Earth. In the space shuttle orbiter all the windows have flexible shades that can be installed on their inner surfaces for light blocking. They can be stored away in cabinets when not needed. The window in the side access hatch on the lower level is an exception and has a small hinged, inside shutter for light blockage.

A window also usually requires an internal or external shutter that can be closed over the window to provide protection against debris and micro-meteoroid impacts or radiation storms when the window is not being used. Each window on ISS has such an aluminum shutter.

Figure 6. A representative photograph for the *Shades & shutters* pattern: A window and its shutter in Zvezda [NASA].

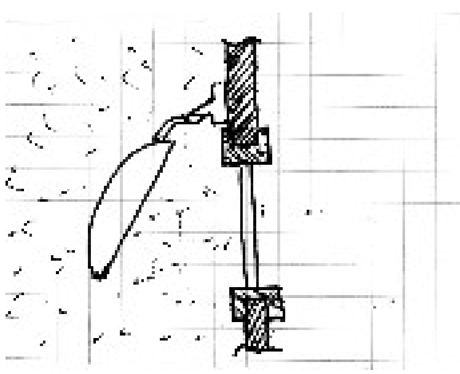

Figure 7. An archetypal sketch for the *Shades & shutters* pattern.

3. *Invariance*

High.

4. *Instruction*

All windows must be equipped with either internal or external shades and shutters.

D. Pattern Title: or.4. *Visual transitions*

1. *Problem statement & linkages to other patterns*

This pattern discusses how the visual flow of a residence's constituent spaces need to be organized to allow a continuous, understandable transition from one space to another and how Earth conditioned transitions can be overridden by the weightless experience of space - basically, as a weightless traveler floats from one space to another, they are biased to perceive their plane of entry as the floor and this needs to be maintained as their trip continues. This pattern flows from *Multi-dimensional living space* and *A big room* in the Remaining category, and *Visual vertical* and *A sense of power over personal space* in the Being category. This pattern helps instantiate *Five minute float* in the Organizing category. *Visual transitions* is a positive pattern.

2. *Discussion*

The two story arrangement of the shuttle's orbiter presents an interesting arrangement of volumes. The upper and lower levels are separated by a plane with a rectangular hole in it for passage between the levels. The plane forms the floor of the upper level and the ceiling of the lower level. For some residents this plane becomes the 'down' direction for both the upper and lower levels. Many residents typically begin their stay with the up-down orientation they have been trained with on the ground, but they find this mental construct changes after about four days of actually living in the orbiter while weightless. It is possibly the arrangement and placement of the hole, the windows in the upper level, and the lack of dominant windows in the lower level that make this so. In the upper level, the high placement of the windows with respect to the floor reinforces the years of Earth-bound conditioning about which direction is up, since this arrangement corresponds to that experienced in most buildings. When a resident travels to the lower level, she does not encounter strong cues like the windows on the upper level, which provide powerful psychological prompts as to which end of the space is up. The keys that are there, like locker arrangement, electric lighting, and other residents, are more artificial in nature and are not as strong in comparison; so after entering the lower space, some find that the feet naturally find a home on the ceiling. Since the visual environment is weak, it's not too hard to transition to a new gravitational understanding of the recently entered space. After a few times - getting used to the sight of things that they were previously conditioned to be perceived as 'upside-down' - this becomes natural. This is not that unusual a phenomena - the ability to mentally re-map our perceptions of up-and-down against our training - and has been recognized since 1896 in a classic experiment performed by G.M. Stratton. In it Stratton constructed a piece of weird optical headgear that when worn caused the visual field of the wearer to be turned upside down and flipped so that right was left and left was right. In a classic experiment, he wore it while awake for eight days, but removed it at night while sleeping and covered his eyes. It took about three days to get to the point where he could move around and manipulate things without too much trouble. After five days it was becoming almost second nature. At the end of the test, it took several hours to get used to the normal view of the world again, but it did all snap back into place.

Figure 8. A representative photograph for the *Visual transitions* pattern: Looking from the lower to the upper level in the orbiter [NASA].

Figure 9. Another representative photograph for the *Visual transitions* pattern: The corridors of ISS [NASA].

On the reverse trip back through the hole into the upper level from the lower level. When a resident enters head first, he pops into a volume that strongly maps to a normal up-down upon entering. This is a strong visual transition. On the upper level the defined floor also makes sense as the perceived floor. So, even though a floor is structurally and conceptually defined on each level, the transition between the volumes, when arranged with other visual cues, can override this definition.

Skylab presented a unique transitional problem. Entering Skylab's big room via the docking adapter sometimes had its difficulties. Compton and Benson (1983) report that some residents would get a feeling of being very high up when entering the docking adapter feet first from the Apollo command module. Most likely because one could look past their feet all the way through the big room down to the smaller living room, thereby inducing the feeling of being high up.

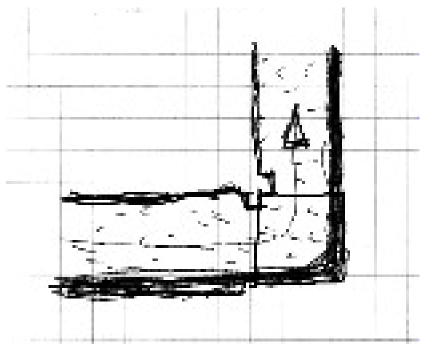

Figure 10. An archetypal sketch for the *Visual transitions* pattern.

Mir was not without its own quirks. The final configuration of Mir was organized in what might be called an axle and spoke arrangement. The base block and Kvant 1 formed the axle, and the other modules radiated off the front of the base block like spokes. If we consider the floor of the base block to be ground zero, then Kvant 2 was the second story, Spektr was the basement, and Priroda and Kristall were the left and right wings respectively. Floating into Priroda from the base block was interesting because its internal spaces were upside-down with respect to the base block floor. There was no gradual or managed visual transition, just an abrupt shift of where the floor and ceiling were located. The entering resident did not have the leisure to arbitrarily decide upon a new visual vertical to suit themselves because this module was outfitted with workstations that require a certain body orientation to be operated. So the residents had to reorient themselves in order to function in this space.

3. *Invariance*

Moderate.

4. *Instruction*

The perceived vertical orientation of a space should be arranged with respect to the orientation of a resident's body as she enters and exits a volume. Consider the flow of the visual perceptions as the residents move throughout the complex. Consider how some visual transitions are strong and others are weak. Don't be misled by Earthbound training mockups.

V. Using Design Patterns in Spacecraft Development

It is possible to make use of design pattern languages at several points in the process of developing new human life supporting artifacts, be they low Earth orbit facilities, planetary landers, off-Earth residences, or interplanetary spacecraft. In this section we will examine some simple pedagogical examples in order to demonstrate how this might work. Please note that spacecraft development is a complex, multidisciplinary activity and these examples must be simple in order to emphasize the salient uses of patterns within the confines of a paper: use them as a starting point and guide, not as an explicit recipe or procedure. Specifically, the examples and discussion will cover:

1. Requirements Development: selecting patterns and languages phrases during the requirements development phase for a low Earth orbiting laboratory and a tourist hotel in order to help develop the requirements for such facilities;
2. Construction of Graphs: developing language graphs, and using those graphs and associated language to examine forms and requirements for planetary landers;
3. Language Development: thoughts on organizations to grow and develop pattern languages, and a discussion on how to use and develop pattern languages utilizing Earthbound long duration simulation facilities.

A. Requirements Development

One of the most important tasks - and many have argued that it is the most important task - in the development of any artifact is the development of its high level requirements. That is, understanding and clearly stating what it is that is expected of an artifact to satisfy a particular purpose. Pattern languages are tools that can be used in this process along with other techniques for discovering and developing requirements. What they add is a structured way of introducing and considering best-practices legacy information from the history of previous designs that have some degree of similarity along one or more dimensions with the new artifact.

There are several ways pattern languages can be used in the requirements development process. Three of the most straightforward are:

1. As a catalogue of individual best practices that could be converted to specific requirements;
2. As a way of generating interconnected strings of patterns called phrases which can then be developed into collections of requirements; and
3. As a source of negative patterns that can be used to investigate and create new requirements to overcome them.

Robertson & Robertson (1999) describe a phase of the requirements definition process called 'trawling'. That is, given some preliminary insight into the highest level requirements of an artifact, there comes a point where the requirements team must attempt to unearth all requirements that could potentially be applicable. They liken this activity to trawling with a net. Many requirements may be discovered, but after review and evaluation, many will be discarded and some will be retained as necessary requirements that themselves require further investigation. The important aspect of trawling is to cast the net wide so as to give the greatest chance for discovering all the applicable requirements. In essence, the spirit and intent of the trawling phase is no different from the program definition phase presented by Pena and Parshall (2001). There are many techniques that can be applied during trawling, and the examination of available design pattern languages is one.

Before using any collection of patterns, one needs to review its context, history and state. This information needs to be applied when reviewing any selected patterns for relevance and importance to the current project.

The first approach to using a language is the most basic: simply read though the pattern catalogues, noting context, and look for patterns that could be appropriate. Although, a seemingly obvious approach, it causes the team to explicitly consider hard-won lessons from the past and not just rely upon the accidental knowledge that the team itself can bring to the situation. This in itself can help overcome conceptual blocks, as well as knowledge limitations, the team might have and may not recognize. Once any appropriate patterns have been identified, the process can begin of defining requirements for the current project based upon the information in the patterns.

The second approach is a natural extension of the first: once patterns of interest have been selected, the links to other patterns can be walked to find other patterns that could be necessary for a full instantiation of a particular organization of elements. Alexander recommends one way of making such a walk and generating pattern phrases from the language, and we will use this as an example of how to make a pattern walk. We will look at that method first using the development of a Low Earth Orbiting laboratory as an example, and then following up with a look at developing some of the requirements for a Low Earth Orbiting tourist hotel.

1. *Requirements development using a Low Earth Orbiting laboratory as an example*

Let us consider selecting patterns for a simple residential LEO space laboratory. Please note that this example is for pedagogical purposes to illustrate the principles of pattern selection for eventual requirements extraction.

The simple approach would be to use the space architecture pattern language in its entirety - eliminating the patterns of unknown invariance - for this example since it was derived from the world of residential LEO labs, suitability supplemented with additional task-oriented patterns of course. However, we will take a two-tiered approach. First, we will identify the patterns contained in *A Pattern Language* that might be applicable to space habitations and use those for an initial pattern walk. Then, we will supplement them with some space residence patterns.

In order to classify the Alexandrian patterns, a nomenclature where each subcategory of patterns is identified by the first letter of the category name to which it belongs along with a sequence number that identifies its position within the category will be adopted. Below each subcategory are listed the pattern titles within the subcategory along with Alexander's asterisk notation to indicate the invariance of the pattern. Two asterisks indicate that it is believed to be truly invariant, a single asterisk indicates that it is invariant but requires further verification, and no asterisks indicates that it is not thought to be invariant, but merely shows one possible way of solving a problem. I have introduced an additional ranking, a '†', to indicate that the pattern might be transferable to space residence design. The assignment of a '†' ranking is admittedly a somewhat subjective reading of the patterns; however, I have tried to be conservative about what might be applicable. The main criteria for assigning a '†' was that from a reading of the pattern, the pattern appeared to describe a human condition that would be encountered in space as well as on the Earth; that is, people and their activities provided the link between Earth and space applicability. I invite the reader to review the selection and consider others. In theory, any pattern, if truly invariant on Earth, may be a strong candidate for inclusion in a space residence, as long as the context appears applicable to a space residence.

There are three categories of Alexandrian patterns: Towns, Buildings, and Construction. The first category in the language pertains to towns, and within the current space residence milieu the patterns in this category do not have a great deal of applicability. Space residences at present are more like individual buildings than social organizations like cities, towns, counties, provinces, states, and other such macro-organizations. However, if artifacts like the so-called O'Neill space colonies (O'Neill, 1978) ever come to pass, these patterns may be worth examining in more detail. In any case, here is a first cut at a selection of applicable Town (T) patterns along with their speculated relevance:

1. *Independent regions* ** †

T3. Patterns that encourage piecemeal development of a city's major structures.
8. *Mosaic of subcultures* ** †
9. *Scattered work* ** †

T5. Patterns dealing with networks that connect communities.
18. *Network of learning* * †

T6. Patterns dealing with policies to control a region's character.
24. *Sacred sites* * †
27. *Men and women* †

T7. Patterns that encourage the formation of local centers.
30. *Activity nodes* ** †

T8. Patterns that encourage growth around the local centers
36. *Degrees of publicness* ** †

T9. Patterns that encourage the growth of work communities
41. *Work community* ** †

T11. Patterns that encourage the growth of large-scale public, open land.
59. *Quiet backs* * †
62. *High places* * †

T13. Patterns that encourage the formation of the smallest social groups.
79. *Your own home* ** †
75. *The family* * †
76. *House for a small family* * †
77. *House for a couple* * †
78. *House for one person* * †

T14. Patterns that encourage workgroups.
80. *Self-governing workshops and offices* ** †

82. *Office connections* * †
83. *Master and apprentices* * †

T15. Patterns that encourage local stores and gathering places
91. *Traveler's inn* * †
94. *Sleeping in public* * †

The next category of patterns deals with Buildings (B); individual ones and groups. These patterns appear somewhat more applicable to space residence applications, and in many cases the similarities are striking from the titles alone.

B1. Patterns dealing with the general organization of a group of buildings
95. *Building complex* ** †
98. *Circulation realms* ** †
101. *Building thoroughfare* †

B2. Patterns dealing with the position of individual buildings on a site.
107. *Wings of light* ** †
108. *Connected buildings* * †
109. *Long thin house* * †

B4. Patterns dealing with paths and squares around the building
125. *Stair seats* *†
126. *Something roughly in the middle* †

B5. Patterns dealing with the fundamental divisions of space.
127. *Intimacy gradient* ** †
129. *Common areas at the heart* ** †
130. *Entrance room* ** †
128. *Indoor sunlight* * †
132. *Short passages* * †
134. *Zen view* * †
135. *Tapestry of light and dark* * †
131. *The flow through rooms* †

B6. Patterns dealing with the definition of the most important areas and rooms.
139. *Farmhouse kitchen* ** †
136. *Couple's realm* * †
142. *Sequence of sitting spaces* * †
143. *Bed cluster* *
144. *Bathing room* * †
145. *Bulk storage* †

B7. Patterns dealing with offices, workshops, and public buildings
148. *Small work groups* ** †
147. *Communal eating* * †
151. *Small meeting rooms* * †
146. *Flexible office space* †

B8. Patterns dealing with outbuildings
158. *Open stairs* * †
157. *Home workshop* †

B9. Patterns dealing with connecting the inside to the outside.
166. *Gallery surround* * †

B10. Patterns dealing with the arrangement and organization of the garden.
172. *Garden growing wild* ** †
177. *Vegetable garden* * †
175. *Greenhouse* †
176. *Garden seat* †

B11. Patterns dealing with secondary rooms
179. *Alcoves* ** †
180. *Window place* ** †
183. *Workspace enclosure* ** †
188. *Bed alcove* ** †
185. *Sitting circle* * †
189. *Dressing rooms** †
182. *Eating atmosphere* †
186. *Communal sleeping* †
187. *Marriage bed* †

B12. Patterns to fine tune the size and shape of the various rooms
191. *The shape of indoor space* ** †
192. *Windows overlooking life* * †
196. *Corner doors* * †
194. *Interior windows* †

B13. Patterns dealing with adding depth to the walls
198. *Closets between rooms* * †
202. *Built-in seats* * †
201. *Waist-high shelf* †
204. *Secret place* †

The last category of patterns deals with Construction (C). Although not strictly applicable to space residence construction, they contain insight into general principles.

C1. Patterns dealing with a philosophy of structure.
205. *Structure follows social space* ** †
208. *Gradual stiffening* ** †
206. *Efficient structure* * †

C2. Patterns dealing with the structural layout.
None.

C3. Patterns dealing with the construction of the building shell.
None.

C4. Patterns dealing with the construction of door and window openings
223. *Deep reveals* †

C4. Some miscellaneous patterns.
229. *Duct space* †

C5. Patterns dealing with surfaces and interior details
238. *Filtered light* * †

C6. Patterns dealing with exterior details
241. *Seat spots* ** †

C7. Patterns dealing with ornament

249. *Ornament* ** †
250. *Warm colors* ** †
252. *Pools of light* ** †
253. *Things from your life* * †

Now, let us begin the selection of patterns. In this example, the concept of laboratory is used in the most general sense as meaning a place to do work of a somewhat unique or experimental nature involving a high degree of hands-on human involvement - not mechanistic, rote, or industrial production tasks.

To begin, one selects a pattern that best seems to exemplify the reason for doing the project; that is, pick one that best represents the most fundamental requirement. In this case it seems appropriate to pick two in order to capture the two main ideas in the project: performing some laboratory experiments and living full-time in the facility. One should select the base patterns from as high up the language's hierarchy as possible, going only as high as one can expect to have influence on the design and no higher. The base patterns selected are: 41. *Work community* and 75. *The family*.

Selecting *Work community* for the laboratory side is pretty straightforward in that it is the highest level pattern dealing with the organization of work activities. Basically, it discusses the need to interlace diverse work activities with non-work activities in order to build a strong, integrated community. Selecting *The family* for the habitation side is not so clear since there are no classically defined family groups to be accommodated; however, consider the instruction for this pattern (Alexander et al., 1977, p.380):

Set up processes which encourage groups of 8 to 12 people to come together and establish communal households. Morphologically, the important things are:

1. Private realms for the groups and individuals that make up the extended family: couple's realms, private rooms, sub-households for small families.
2. Common space for shared functions: cooking, working, gardening, child care.
3. At the important crossroads of the site, a place where the entire group can meet and sit together.

Although our example project does not deal with traditional family groups, which is within the bounds of the pattern, the pattern does lay out a high-level principle for organizing accommodation for more loosely defined, family-like groups which is typically accommodated in an orbiting laboratory.

That part was fairly easy; the harder part is selecting the patterns below these. For brevity, I recommend working through the exercise with a copy of *A Pattern Language*. It explains how all the patterns are linked and describes them in sufficient detail so that one can decide whether a particular pattern should or should not be included - this is what would be done by the team in an actual pattern selection process. Some selections are clear-cut, based on the structure of the language and invariance properties of the pattern, and some are open to interpretation. This is where a lot of the difficult selection work comes in: figuring out what should be incorporated and what should not.

I have used three guidelines for including a pattern in the candidate project language. First, I do not include any patterns dealing with organizing the world outside buildings: landscape, roads, and paths, for example. Second, patterns dealing with the particularities of construction details of Earth-bound buildings are not included since the actual building techniques used will be very different. Third, only the patterns with the highest degree of invariance - indicated by ** in the language - are included. This last rule is probably overly strict, and I would invite the reader to consider other patterns with lesser invariance while working through the example.

The following subset of patterns for the laboratory requirement were selected when starting from 41. *Work community*:

41. *Work community*
80. *Self-governing workshops and offices*
95. *Building complex*
98. *Circulation realms*
148 *Small workgroups*,
183. *Workspace enclosure,*
205. *Structure follows social space*
250. *Warm colors*

115. *Courtyards which live*
129. *Common areas at the heart.*
252. *Pools of light*

In selecting the patterns for the residential requirement, I bent the third guideline a bit. In order to generate any set of phrases, I had to select the one asterisk pattern 78. *House for one person* since it best describes the situation for a potential resident in our project. The set of patterns works out to be when starting from 75. *The family*:

75. *The family*
78. *House for one person*
129. *Common areas at the heart*
139. *Farmhouse kitchen*
147. *Communal eating*
180. *Window place*
183. *Workspace enclosure*
188. *Bed alcove*

One can see there is a little bit of overlap in the two sets of patterns which could make for some interesting design possibilities. Also, notice that this pattern phrase comes very close to describing much of the organizational structure of Skylab.

At this point, we need to supplement the sets with patterns from the space architecture pattern language in order to introduce space specific qualities into the language. Now, since the entire language is based on artifacts that are primarily work oriented, we could suggest using the entire language. However, to derive a potentially smaller and more succinct set to begin with, we will follow a similar exercise as was used with the Alexandrian patterns. *Buckling down & strapping in* in the Doing category was chosen as a starting point for the laboratory requirement. Following the connections in the pattern hierarchy presented in Fig. 12 in the Appendix, restricting our selection to positive patterns with high invariance, and eliminating those with contrasting relationships, the following short list of patterns was obtained:

do.3 *Buckling down & strapping in*

su.2 *Single room*
su.5 *A necessary toilet*
su.7 *Crash pad*

re.1 *Human scale rooms*
re.7 *Mobilia*
re.8 *Salle commune*

or.2 *Self-contained core*
or.3 *Building over time*

For the residential requirement, *Shirt sleeve environment* in the Being category was chosen as the starting point, producing the following pattern collection:

be.1 *Shirt sleeve environment*

su.2 *Single room*
su.5 *A necessary toile*
su.7 *Crash pad*

re.7 *Mobilia*
re.8 *Salle commune*

sh.1 *Pressurized can*
sh.1.1 *Protective coverings*
sh.1.5 *Grapple fixtures*
sh.2.1 *Shades and shutters*

or.2 *Self-contained core*
or.3 *Building over time*

One can see that the lists are indeed merely starting points for injecting space unique requirements into a project. Many important patterns like *Keep a horse headed for home*,*Visual vertical* and *Structured storage* do not appear. If the selection criteria are loosened up a bit by allowing patterns of both high and moderate invariance the lists fill out somewhat. This is not an altogether bad thing to do because with the sparse set of legacy artifacts, moderate invariance patterns are more the norm in occurrence. So, once again beginning with do.3 *Buckling down & strapping in* as the root pattern of the laboratory requirement, the following set of moderate and high invariance patterns is obtained:

be.5 *Deepening*

do.3 *Buckling down & strapping in*
do.1 *Incarceration melancholia*
do.2 *Autonomous work life*
do.2.1 *Thoughtful & active participation*
do.2.2 *Overlapping skill sets*

su.2 *Single room*
su.3 *Room with a view*
su.5 *A necessary toilet*
su.6 *Structured storage*
su.7 *Crash pad*
su.8 *A variety of exercises*

re.1 *Human scale rooms*
re.2 *Private places*
re.4 *Shower*
re.6 *Entertainments & communications*
re.7 *Mobilia*
re.8 *Salle commune*
re.9 *Remote manipulation*
re.9.1 *Remote viewing*
re.11 *Lookout tower*

sh.1.4 *Integrated ducts*
sh.1.5 *Grapple fixtures*
sh.1.6 *X marks the spot*
sh.2 *Clear windows*
sh.2.1 *Shades and shutters*
sh.4 *Airlock*
sh.5 *Minimize outside maintenance*
sh.6 *Noises off*

or.2 *Self-contained core*
or.3 *Building over time*
or.6 *Workshop gradient*

Likewise, selecting both moderate and high invariance patterns for the residential requirement, and starting from *Shirt sleeve environment*, the following set of patterns is obtained:

be.1 *Shirt sleeve environment*
be.5 *Deepening*

do.1 *Incarceration melancholia*
do.2 *Autonomous work life*
do.2.1 *Thoughtful & active participation*
do.2.2 *Overlapping skill sets*

su.2 *Single room*
su.3 *Room with a view*
su.5 *A necessary toilet*
su.6 *Structured storage*
su.7 *Crash pad*

re.2 *Private places*
re.4 *Shower*
re.6 *Entertainments & communications*
re.7 *Mobilia*
re.8 *Salle commune*
re.9 *Remote manipulation*
re.9.1 *Remote viewing*
re.11 *Lookout tower*

sh.1 *Pressurized can*
sh.1.1 *Protective coverings*
sh.1.3 *Two ways out*
sh.1.4 *Integrated ducts*
sh.1.5 *Grapple fixtures*
sh.1.6 *X marks the spot*
sh.2 *Clear windows*
sh.2.1 *Shades and shutters*
sh.4 *Airlock*
sh.5 *Minimize outside maintenance*
sh.6 *Noises off*

or.2 *Self-contained core*
or.3 *Building over time*
or.6 *Workshop gradient*

We certainly get far more patterns in each phrase - but with considerable overlap. The laboratory requirement yields 32 patterns and the residential has 33; a little more than half the patterns in the entire language in each phrase. But, still those important *Keep a horse headed for home* and *Visual vertical* patterns are missing from both phrases. This occurs because *Keep a horse headed for home* flows directly from 2 patterns in the Environment category: *No air* and *Near and far*. Likewise, *Visual vertical* flows in a straight line from *No weight* in the Environment category through *Body is a 1g machine*. Maybe this omission is not too surprising since we generated the phrases starting only from two requirements on human activity; however, the unique conditions of the environment enforce their own requirements which can't be derived from human activity requirements alone. The Alexandrian pattern language doesn't explicitly define any environmental patterns. They appear to be implicitly bound into the human activity patterns, but in space, and like on Earth for that matter, the environment has its own requirements that must be met. When deriving phrases from the space architectural pattern language, one should also identify a number of the most relevant patterns in the Environment category to inject additional space-specific patterns into the candidate phrases. So, in this example, the starting patterns might be *Shirt sleeve environment*, *Buckling down & strapping in*, *No air* and *No weight*.

For example, starting from *No air* and picking up only the patterns of high invariance we get the following phrase - which does in fact yield the *Keep a horse headed for home* pattern as expected, but also produces the usual overlap with previously derived patterns:

en.1 *No air*

be.1 *Shirt sleeve environment*

su.1 *Keep a horse headed for home*
su.2 *Single room*
su.5 *A necessary toilet*
su.7 *Crash pad*
sh.1 *Pressurized can*
sh.1.1 *Protective coverings*
sh.1.5 *Grapple fixtures*
sh.2.1 *Shades and shutters*
sh.4 *Airlock*
sh.5 *Minimize outside maintenance*

re.7 *Mobilia*
re.8 *Salle commune*
re.9 *Remote manipulation*

or.2 *Self-contained core*
or.3 *Building over time*

Note that the phrases contain negative patterns like *Incarceration melancholia*. This doesn't mean to say that one should explicitly set about to instantiate conditions that bring these about in one's design. It does mean that the set of patterns will potentially give rise to the negative patterns as a side-effect. It would be useful to consider adding in patterns that contrast the negative ones, which may not be completely picked up in any particular phrase because the selection process did not explicitly search for them. In general, the incorporation of contrasting patterns needs some further investigation into how it should be built into the pattern selection process.

As mentioned above, if we had started directly from the Environment category, more and deeper pattern linkages would come into play. More significantly, this situation happens because the basic language derived herein is only loosely, not deeply, connected; it is still quite stringy and interstitial patterns - and most probably several fundamental patterns - are missing that interconnect other patterns. As well, since the language derives from residences that are primarily orbiting laboratories there is considerable overlap in the sets of derived patterns contained within each phrase. One alternative approach to selecting a sublanguage for both requirements would be to select all positive patterns in Doing, Being, and Supporting, and for implementation concerns, the high invariance patterns in Shaping and Organizing. This choice implicitly assumes the laboratory requirement dominates the residential requirement and that periods of residency will be on the order of only a few weeks.

Now that several collections of patterns, or phrases, have been developed the team needs to go through the net and examine each pattern for applicability. The patterns remaining can then be used to create requirements statements. When writing requirements from the selected patterns start by examining the instruction and the archetypal image. They will provide the most essential elements needed in order to instantiate the pattern. From there, move into the pattern’s descriptive text. This will provide further detailed information about particular legacy instantiations and help one make judgments about other elements associated with the pattern that may need to be specified. All the while one must provide scrutiny to the process since this is not an algorithmic approach that will automatically generate design requirements or design alternatives; it is more of a heuristic that one applies to a particular situation.

As well, the team needs to keep in mind that they need to feed these requirements back into the overall development activity in order to assess things like mass, volume, power, maintenance and logistical impacts of the requirements and be prepared to justify their need. It is likely that the selection of patterns and the associated assessment will go through several iterations.

2. *Requirements development using a low Earth orbit tourist hotel as an example*

For comparison, consider a second example whose goal is to maximize probably the only unarguable QWAN condition so far experienced in a space residence: viewing the Earth in its totality from on-high, and in this case from a space hotel. To start the selection process, I have begun with the Alexandrian pattern 62. *High places* which discusses the need for a town to have a place that is taller than all the other buildings for looking out over the landscape. This is a tough phrase set to get started because there are no two asterisk patterns below pattern 62, only three single asterisk patterns, and the choices essentially disappear below that level. The resulting language is somewhat restricted in its vocabulary, but does provide some starting points for further work:

62. *High places*	134. *Zen view*
125. *Stair seats*	158. *Open Stairs*

If one abandons the strict selection guidelines at the outset and attempts to read the patterns a little more abstractly about what they might contribute to a space-based observation point, the project language becomes a great deal richer (accompanying phrases in braces are mine and concern a possible space-based interpretation):

62. *High places*
125. *Stair seats*
134. *Zen view*
158. *Open stairs*
161. *Sunny place*
163. *Outdoor room* {EVA opportunity for the adventurous}
168. *Connection to the Earth* {provide a contrast with other possible views}
180. *Window place*
221. *Natural doors & windows*
222. *Low sills*
223. *Deep reveals* {refer to (NASA, 1995), section 8.11.2, for possible technical details}
238. *Filtered light*
239. *Small panes*
241. *Seat spots*
243. *Seating wall* {refer to (NASA, 1995), figure 11.7.2.4-3, for a possible implementation}
247. *Front door bench*

Once again, these patterns need to be supplemented with appropriate ones from the space architecture pattern language, or from one's own research. In this example the space architecture language component is somewhat sparser than in the previous one, showing the limits of its heritage in this problem. Starting with *Room with a view* in the Supporting category, and selecting patterns of high and moderate invariance, we get the rather straightforward subset:

su.3 *Room with a view*	re.11 *Lookout tower*
sh.2 *Clear windows*	
sh.2.1 *Shades and shutters*	

The patterns are naturally similar in intent to the Alexandrian patterns, but with a space-based bias. An alternative pattern selection in this case could consist of all the patterns in Being, Supporting, and Remaining, and once again making conservative choices from Shaping and Organization. Although the periods of residency of the guests will be probably be of short duration, Remaining patterns are included to make the period easier and more interesting.

As with the first example, regular assessment of the impact of the patterns on the overall mission properties such as mass, power, volume and other relevant metrics is essential.

B. Language Graphs and Planetary Landers

Lowe (2005) discusses how to create a design pattern language that is applicable to a Mars lander for humans based on observational data from the various expeditions to lander simulators operated by the Mars Society. There are numerous patterns in that language that are similar to, or are derived from, patterns in both the space architecture language discussed in this paper and the Alexandrian pattern language presented in *A Pattern Language*. The existence of such points of contact and overlap are not hard to envision since space-related aspects discussed in the space architecture language, and everyday human life activities presented in the Alexandrian language will no doubt also be active in even a remote location like Mars.

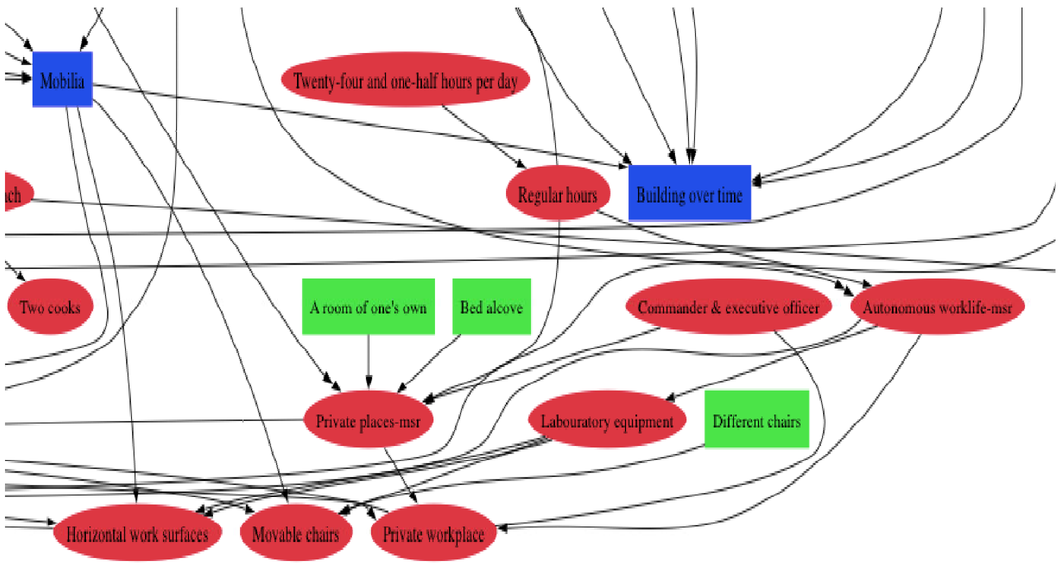

Figure 11. A selection of patterns governing the *Private places - msr* pattern.

The pattern and phrase selection methodologies discussed in the previous examples can also be applied to Mars lander design work. To help facilitate this activity, and make the interconnections between all three languages clear, the languages can be graphed using commonly available software tools. When drawn on very large sheets, larger-scale patterns of interconnection become clearer. Given the physical limitations of a paper such as this, only relatively small portions of the graph can be shown and Fig 11 illustrates a typical area of interest.

Figure 11 shows a section of the graph surrounding the Mars lander language pattern *Private places - msr*. The '-' designation in the '-msr' suffix indicates that this pattern is a variant of the pattern *Private places* in the space architecture pattern language, and the 'msr' stands for Mars Surface Residence. The complete nomenclature system is presented in Lowe (2005). The red ellipses are patterns in the Mars lander language, the blue rectangles are space architecture patterns, and the green rectangles are patterns from the Alexanderian language. This section of the graph gives a glimpse of how patterns in other languages affect patterns in the Mars lander language, and illustrate how a graph clarifies the interrelationship amongst a wide range of patterns. However, as with the linkages shown in Fig. 12 in the Appendix, the linkage structure is a first approximation in an ongoing dialogue about structure.

C. Growing and Developing the Languages

Design pattern languages are not static entities. They develop and change over time in response to new observations, ways-of-life, activities and technological developments. Although the patterns in *A Pattern Language* are printed in a book, that does not mean they are the final word on the subject, merely a snapshot of understanding at a particular time and in a particular milieu. Some of the patterns will indeed be truly invariant, others will be shown to be less so.

The space architectural pattern language - and by extension its offshoots like the Mars lander pattern language - is no different. At present it is nowhere near complete and still requires significant detailing to make it fully useful. One might say it is ‘stringy’ and only hints at the complete language. No matter how much detail the language might have at any given time it is never really complete, because, as is the case for Earthbound residences, places for people to live in space and on other planets will continue to develop and mature as time goes on. Contexts will change and people will change.

The biases of the individuals that create the language will change too. To be quite honest, design pattern languages are not completely objective. The patterns do contain distinct traces of the subjective biases of their creators. But, in fact, every architectural act is to some extent an act of the expression of bias. It is unavoidable. Just looking around at our Earthbound environment we see in buildings biases of all sorts: no-nonsense functionalism, aesthetics and art both subtle and outrageous, displays of wealth and power, marginality of resources, concern or lack thereof for the environment, entertainment, comfort, business, spirituality, tradition, conformity, and on and on. The space pattern language discussed in this paper certainly has its bias. It attempts to emphasize architectural responses, both intentional and evolved, to human life above instrumental and programmatic requirements leveled on a space residence design. This being the case, the whole collection of work related patterns in the Doing category are weak since the language is currently biased to other concerns. For the Doing patterns to be fully useful in design work, they need to be more completely defined. For example, whole subcategorizes for laboratory work and extravehicular activity need be developed.

Continued development of a language helps to balance out the various biases. What needs to be done is to establish a working group or organization to mine the various research studies being undertaken at facilities such as the ISS, the Mars Society’s Mars lander simulators MDRS, FMARS and Euromars, the isolation simulators of the various space agencies, and Antarctic bases. Clearly, this organization needs to be international in nature to properly integrate the findings in space-based human habitation research that is being undertaken around the world. As well as observational work, this group can pursue its own studies, and continue to mine legacy systems as has been the basis for the patterns discussed in this paper. This would result in the establishment of a thorough and continually developing archive of patterns that would be available to a broad range of human spacecraft designers. Stringiness and biases would be reduced by density of connections, patterns of higher quality and subtlety, elimination of negative patterns and an improvement in objectivity. A static design pattern language is a dead one. The language presented in this paper is only a beginning.

VI. Conclusions

This paper has shown how to create an architectural design pattern language for LEO space stations. The language, although currently containing only 60 patterns, can be used in the requirements definition phase and preliminary design work of new vehicle development. Discussions were presented on how to develop requirements, the usefulness of graphs of the language, how to extend the language for planetary landers and continue to develop the languages utilizing information from a variety of sources. At present the language and its derivatives are in a very rudimentary state and require ongoing development; however, the methodology presented has the potential for capturing and making readily available in an easy to use form a vast array of information for designers working on future human spacecraft developments.

Appendix

The linkages of each pattern to the other patterns in the language are shown in Fig. 12. It should be noted that this is a first cut at developing linkages between the patterns - it is by no means definitive. Like the patterns themselves, it should be considered to be an initial point of departure in a continuing dialogue about how one pattern influences others. The connection notation used in the figure is as follows: > means 'is partially derived from', ø means 'has a contrasting relationship with' and < means 'helps to derive'. The linkage information is necessary when using the patterns to help derive project requirements, and will be useful when following the examples on that topic discussed in section V(A). of this paper. As with Fig 1, pattern titles appearing in bold face type in Fig.12 are discussed in detail in this paper.

Environment

en.1 *No air*
< be.1 *Shirt sleeve environment*
< do.1 *Incarceration melancholia*
< su.1 *Keep a horse headed for home*
< su.5 *A necessary toilet*
< re.9 *Remote manipulation*
< sh.1.1 *Protective coverings*
< sh.4 *Airlock*

en.2 *Too much radiation*
< re.4 *Shower*
< sh.1.2 *Radiation shielding*
< sh.2.1 *Shades and shutters*

en.3 *No weight*
< be.2 *Body is a 1-g machine*
< be.3 *A sense of power over personal space*
< do.3 *Buckling down & strapping in*
< do.4 *Cluttered niches*
< su.4 *Eliminate edges*
< re.3 *Multi-dimensional living space*
< or.1 *Ambient gravity*

en.4 *Light and dark*
< su.3 *Room with a view*
< sh.1.1 *Protective coverings*
< sh.2.1 *Shades and shutters*

en.5 *Space junk*
< sh.1.1 *Protective coverings*

en.6 *Near and far*
< be.5 *Deepening*
< do.1 *Incarceration melancholia*
< su.1 *Keep a horse headed for home*

Being

be.1 *Shirt sleeve environment*
> en.1 *No air*
< su.2 *Single room*
< sh.1 *Pressurized can*
< sh.1.1 *Protective coverings*
< or.7 *Spaceship Earth*

be.2 *Body is a 1g machine*
> en.3 *No weight*
< be.4 *Visual vertical*
< su.5 *A necessary toilet*
< su.8 *A variety of exercises*
< or.8 *Enhanced gravity*

be.3 ***A sense of power over personal space***
> en.3 *No weight*
ø be.4 *Visual vertical*
ø do.3 *Buckling down & strapping in*
< su.4 *Eliminate edges*
< re.3 *Multi-dimensional living space*
< re.5 *A big room*
< or.4 *Visual transitions*

be.4 *Visual vertical*
> be.2 *Body is a 1g machine*
ø be.3 *A sense of power over personal space*
ø re.3 *Multi-dimensional living space*
ø re.5 *A big room*
< su.2 *Single room*
< re.1 *Human scale rooms*
< or.4 *Visual transitions*
< or.4.1 *This end up*

be.5 *Deepening*
> en.6 *Near and far*
> re.6 *Entertainments & communications*

ø do.1 *Incarceration melancholia*
< do.2 *Autonomous worklife*
< do.2.1 *Thoughtful & active participation*
< su.3 *Room with a view*
< re.11 *Lookout tower*

<u>Doing</u>

do.1 *Incarceration melancholia*
> en.1 *No air*
> en.6 *Near and far*
> sh.1 *Pressurized can*
> sh.6 *Noises off*
ø be.5 *Deepening*
ø do.2.1 *Thoughtful & active participation*
ø do.2 *Autonomous worklife*
ø re.6 *Entertainments & communications*
ø re.11 *Lookout tower*
< sh.6 *Noises off*

do.2 *Autonomous worklife*
> be.5 *Deepening*
> do.3 *Buckling down & strapping in*
ø do.1 *Incarceration melancholia*
< do.2.1 *Thoughtful & active participation*
< do.2.2 *Overlapping skill sets*
< re.7 *Mobilia*
< re.9 *Remote manipulation*
< sh.4 *Airlock*
< sh.5 *Minimize outside maintenance*
< or.6 *Workshop gradient*

do.2.1 *Thoughtful & active participation*
> be.5 *Deepening*
> do.2 *Autonomous worklife*
< re.8 *Salle commune*
< sh.6 *Noises off*

do.2.2 *Overlapping skill sets*
> do.2 *Autonomous worklife*

do.3 *Buckling down & strapping in*
> en.3 *No weight*
ø be.3 *A sense of power over personal space*
ø do.4 *Cluttered niches*
< do.2 *Autonomous worklife*
< su.2 *Single room*
< su.5 *A necessary toilet*
< su.7 *Crash pad*
< su.8 *A variety of exercises*
< re.1 *Human scale rooms*
< re.7 *Mobilia*
< or.5 *Five minute float*
< or.6 *Workshop gradient*

do.4 *Cluttered niches*
> en.3 *No weight*
ø do.3 *Buckling down & strapping in*
ø sh.1.4 *Integrated ducts*
< su.6 *Structured storage*
< re.3 *Multi-dimensional living space*

<u>Supporting</u>

su.1 *Keep a horse headed for home*
> en.1 *No air*
> en.6 *Near and far*
< or.3 *Building over time*

su.2 *Single room*
> be.1 *Shirt sleeve environment*
> be.4 *Visual vertica*l
> do.3 *Buckling down & strapping in*
ø re.2 *Private places*
< su.5 *A necessary toilet*
< su.6 *Structured storage*
< su.7 *Crash pad*
< re.7 *Mobilia*
< re.8 *Salle commune*
< or.2 *Self-contained core*
< or.6 *Workshop gradient*

su.3 *Room with a view*
> en.4 *Light and dark* > be.5 *Deepening*
ø re.9.1 *Remote viewing*
< re.11 *Lookout tower* < sh.2 *Clear windows*

su.4 *Eliminate edges*
> en.3 *No weight* > be.3 *A sense of power over personal space*
< re.1 *Human scale rooms* < or.5 *Five minute float*

su.5 *A necessary toilet*
> en.1 *No air* > be.2 *The body is a 1g machine*
> do.3 *Buckling down & strapping in* > su.2 *Single room*
ø re.2 *Private places*
< su.6 *Structured storage*

su.6 *Structured storage*
> do.4 *Cluttered niches* > su.2 *Single room*
> su.5 *A necessary toilet*
< sh.1.4 *Integrated ducts*

su.7 *Crash pad*
> do.3 *Buckling down & strapping in* > su.2 *Single room*
< re.2 *Private places* < re.7 *Mobilia*
< sh.6 *Noises off*

su.8 *A variety of exercises*
> be.2 *Body is a 1g machine* > do.3 *Buckling down & strapping in*
< re.7 *Mobilia*

Remaining
re.1 *Human scale rooms*
> be.4 *Visual vertical* > do.3 *Buckling down & strapping in*
> su.4 *Eliminate edges*
ø be.3 *A sense of power over personal space* ø re.5 *A big room*
< re.2 *Private places* < re.8 *Salle commune*
< or.6 *Workshop gradient*

re.2 *Private places*
> su.7 *Crash pad* > re.1 *Human scale rooms*
ø su.2 *Single room* ø su.5 *A necessary toilet*
ø re.8 *Salle commune*
< re.4 *Shower* < re.6 *Entertainments & communications*
< sh.6 *Noises off*

re.3 *Multi-dimensional living space*
> en.3 *No weight* > be.3 *A sense of power over personal space*
> do.4 *Cluttered niches*
ø be.4 *Visual vertical*
< re.5 *A big room* < or.4 *Visual transitions*

re.4 *Shower*
> en.3 *No weight* > re.2 *Private places*

re.5 ***A big room***
> be.3 *A sense of power over personal space* > re.3 *Multi-dimensional living space*
ø be.4 *Visual vertical* ø re.1 *Human scale rooms*

ø or.5 *Five minute float*
< re.6 *Entertainments & communications*
< or.4 *Visual transitions*

re.6 *Entertainments & communications*
> re.2 *Private places*
> re.5 *A big room*
ø do.1 *Incarceration melancholia*
< be.5 *Deepening*

re.7 *Mobilia*
> do.2 *Autonomous worklife*
> do.3 *Buckling down & strapping in*
> su.2 *Single room*
> su.7 *Crash pad*
> su.8 *A variety of exercises*
< or.3 *Building over time*

re.8 *Salle commune*
> do.2.1 *Thoughtful & active participation*
> su.2 *Single room*
> re.1 *Human scale rooms*
ø re.2 *Private places*

re.9 *Remote manipulation*
> en.1 *No air*
> do.2 *Autonomous worklife*
ø sh.4 *Airlock*
< re.9.1 *Remote viewing*
< sh.1.5 *Grapple fixtures*
< sh.5 *Minimize outside maintenance*
< or.3 *Building over time*

re.9.1 *Remote viewing*
> re.9 *Remote manipulation*
ø su.3 *Room with a view*
ø re.11 *Lookout tower*
< sh.1.6 *X marks the spot*

re.10 *Garden*
ø en.1 *No air*
ø en.2 *Too much radiation*
ø en.3 *No weight*
< or.7 *Spaceship Earth*

re.11 *Lookout tower*
> be.5 *Deepening*
> su.3 *Room with a view*
ø do.1 *Incarceration melancholia*
ø re.9.1 *Remote viewing*
< sh.2 *Clear windows*

<u>Shaping</u>
sh.1 *Pressurized can*
> be.1 *Shirt sleeve environment*
ø sh.3 *Inflatable volumes*
< do.1 *Incarceration melancholia*
< sh.1.1 *Protective coverings*
< sh.1.2 *Radiation shielding*
< sh.1.3 *Two ways out*
< sh.1.4 *Integrated ducts*
< sh.1.5 *Grapple fixtures*
< sh.1.6 *X marks the spot*
< or.2 *Self-contained core*
< or.3 *Building over time*

sh.1.1 *Protective coverings*
> en.1 *No air*
> en.4 *Light and dark*
> en.5 *Space junk*
> be.1 *Shirt sleeve environment*
ø sh.2 *Clear windows*
< sh.2.1 *Shades and shutters*

sh.1.2 *Radiation shielding*
> en.2 *Too much radiation*

sh.1.3 *Two ways out*

sh.1.4 *Integrated ducts*
> su.6 *Structured storage*
ø do.4 *Cluttered niches*

sh.1.5 *Grapple fixtures*
> re.9 *Remote manipulation*
< or.3 *Building over time*

sh.1.6 *X marks the spot*
> re.9.1 *Remote viewing*

> sh.2 *Clear windows*
> su.3 *Room with a view*
> re.11 *Lookout tower*
ø sh.1.1 *Protective coverings*
< sh.2.1 *Shades and shutters*

sh.2.1 ***Shades and shutters***
> en.2 *Too much radiation*
> en.4 *Light and dark*
> sh.1.1 *Protective coverings*

sh.3 *Inflatable volumes*
ø sh.1 *Pressurized can*
< or.3 *Building over time*

sh.4 *Airlock*
> en.1 *No air*
> do.2 *Autonomous worklife*
ø re.9 *Remote manipulation*
ø sh.5 *Minimize outside maintenance*

sh.5 *Minimize outside maintenance*
> do.2 *Autonomous worklife*
> re.9 *Remote manipulation*
ø sh.4 *Airlock*

sh.6 *Noises off*
> do.1 *Incarceration melancholia*
> do.2.1 *Thoughtful & active participation*
> su.7 *Crash pad*
> re.2 *Private places*
< do.1 *Incarceration melancholia*

<u>Organizing</u>

or.1 *Ambient gravity*
> en.3 *No weight*
ø or.8 *Enhanced weight*

or.2 *Self-contained core*
> su.2 *Single room*
> sh.1 *Pressurized can*
< or.3 *Building over time*

or.3 *Building over time*
> su.1 *Keep a horse headed for home*
> re.7 *Mobilia*
> re.9 *Remote manipulation*
> sh.1 *Pressurized can*
> sh.1.5 *Grapple fixtures*
> sh.3 *Inflatable volumes*
> or.2 *Self-contained core*

or.4 ***Visual transitions***
> be.3 *A sense of power over personal space* > be.4 *Visual vertical*
> re.3 *Multi-dimensional living space* > re.5 *A big room*
< or.4.1 *This end up* < or.5 *Five minute float*

or.4.1 *This end up*
> be.4 *Visual vertical*

or.5 *Five minute float*
> do.3 *Buckling down & strapping in* > su.4 *Eliminate edges*
> or.4 *Visual transitions*
ø re.5 *A big room*
< or.6 *Workshop gradient*

or.6 *Workshop gradient*
> do.2 *Autonomous worklife* > do.3 *Buckling down & strapping in*
> su.2 *Single room* > re.1 *Human scale rooms*
> or.5 *Five minute float*

or.7 *Spaceship Earth*
> be.1 *Shirt sleeve environment* > re.10 *Garden*

or.8 *Enhanced gravity*
> be.2 *Body is a 1g machine*
ø or.1 *Ambient gravity*

or.9 *Impermanence*

Figure 12. Pattern language linkages (Lowe, 2002).

The detailed linkage information shown in Fig. 12 is needed for generating phrases from the language while doing requirements development.

Acknowledgments

The author would like to thank David Connolly, Terence Gibson, Albert Harrison, and Paul Wertz for taking the time to review, and provide helpful comments on, various sections of the original manuscript (Lowe, 2002) from which sections of this paper are extracted; however, any and all shortcomings naturally reside solely with the author. As well, Antoinette Cickello of the Canadian Space Agency library was instrumental in helping me track down many references, and Elizabeth Knox at the National Archives of Canada was generous in providing access to microfiche readers.

References

Alexander, Christopher; Sara Ishikawa; Murray Silverstein; Max Jacobson; Ingrid Fiksdahl-King; Shlomo Angel (1977). *A Pattern Language: Towns, Buildings, Construction.* New York:Oxford University Press.

Alexander, Christopher (1979). *The Timeless Way of Building*. New York:Oxford University Press.

Appleton, Brad (1997). Patterns and Software: Essential Concepts and Terminology. http:// www.enteract.com/ ~bradapp/ docs/ patterns-intro.html .

Brand, Stewart (1994). *How buildings learn: What happens after they're built*. New York: Viking.

Brown, William H.; Raphael C. Malveau; Hays W. "Skip" McCormick III; Thomas J. Mowbray (1998). *AntiPatterns: Refactoring software, architectures, and projects in crisis.* New York: John Wiley & Sons.

Burroughs, Bryan (1998). *Dragonfly: NASA and the crisis aboard Mir.* New York: Harper Collins Publishers.

Compton, W. David; Charles D. Benson (1983). *Living and Working in Space: A History of Skylab*. NASA-SP-4208, p. 348.

Cooper, Henry S. F. (1976). *A house in space.* New York: Holt, Rinehart, and Winston, Inc..

Harland, David M. (1997). *The MIR space station: A precursor to space colonization.* Chichester, UK: John Wiley & Sons / Praxis Publishing.
Harrison, Albert A. (2001). *Spacefaring: The human dimension.* Berkeley: University of California Press.
Lebedev, Valentin (1990). *Diary of a cosmonaut: 211 days in space.* New York: Bantam Books.
Linenger, Jerry M. (2000). *Off the planet: Surviving five perilous months aboard the space station Mir.* New York: McGraw Hill.
Kanas, N., V. Salnitskiy, E. Grund, V. Gushin, D. Weiss, O. Kozerenko, A. Sled, and C. Marmar (2000 Sept). Interpersonal and Cultural Issues Involving Crews and Ground Personnel During Shuttle/Mir Space Missions. *Aviation, Space and Environmental Medicine,* Vol 71, no. 9, Section II.
Lowe, James D. (2002). *Patterns in space architecture.* unpublished manuscript completed in 2002; for copies contact jlowe@synapse.net.
Lowe, James (2005).On the Use of Pattern Languages in the Development of Crewed Martian Spacecraft and Habitats. Frank Crossman and Robert Zubrin (Eds.), *On to Mars 2*, Burlington, Ont: Apogee Books.
Lucid, Shannon W. (1998 May). Six Months on Mir. *Scientific American,*Volume 278, Number 5, p. 46-55.
NASA (1995). *Man-Systems Integration Standards.* NASA-STD-3000, Revision B.
O'Neill, Gerard K. (1978). *The High Frontier,* New York: Bantam Books.
Pena, William M.; Steven A. Parshall (2001). *Problem Seeking*. New York: John Wiley & Sons, Inc.. p. 176-205.
Preiser, Wolfgang F.E.; Harvey Z. Rabinowitz; Edward T. White (1988). *Post Occupancy Evaluation*. New York: Van Nostrand Reinhold, New York.
Reichhardt, Tony (1990 Jan/Feb). Marathon Men, *Final Frontier*, p. 42-45, 55-59.
Robertson, Suzanne; James Robertson (1999). *Mastering the Requirements Process*. New York: Addison-Wesley. p. 79-103.
Stuster, Jack (1996). *Bold endeavors: Lessons from polar and space exploration.* Annapolis: Naval Institute Press, Annapolis.
White, Frank (1998). *The overview effect: Space exploration and human evolution.* Washington: American Institute of Aeronautics and Astronautics, Washington.