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Space Infrastructure Planning

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Abstract

The human settlement of space will involve the design, fabrication, testing, deployment, operation, replenishment, maintenance, repair, and disposal of a wide spectrum of space operations and transportation systems. These will include reusable launch vehicles, orbiting space stations, space tugs, interplanetary transports, and planetary bases. This paper discusses the importance of carefully and systematically undertaking the systems engineering planning of the basic infrastructure for the first phase of this settlement. Further, this paper proposes a basic space infrastructure planning requirement, derived functional requirements, functional elements and functional interfaces that may serve as a starting point for further analysis and refinement.

Introduction

If we take a leap of imagination into the not so distant future, say to the year 2030, it is possible to envision what the successful completion of the first phase of the human settlement of space may look like. We would expect to see safe and routine launches into space of commercial reusable launch vehicles or RLVs, a multitude of orbiting space bases to serve governmental, commercial, and educational needs, the first permanent settlements on the moon and the start of the human exploration of Mars. In essence, we would expect to see a complex infrastructure consisting of a wide range of small-to-large space systems providing all the needed capabilities to live and work in space.

This presumed existence of a complex space infrastructure is the result of our living in a technologically advanced civilization. Because such complex systems as telecommunications, transportation, potable water, sanitation, energy supply, health care, natural resource supply, waste disposal, and food delivery and preparation are commonplace on Earth, we naturally expect similar systems will be in existence in space as well. Yet, is this a reasonable assumption? With some certainty we can presume that such systems will come into existence by the year 2100 or 2150, judging by our rate of technological advancement in the last 100

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years. But, can we presume they will be in existence by the year 2030? Or 2040? Or, even, 2050? The unfortunate answer to this critical question appears to be no. We can’t simply presume that the necessary infrastructure of space operations and transportation systems will be in existence in 2030-2050 to support the initial steps of the expansion of human civilization into space.

Without this often overlooked presumption, detailed studies of building human settlements on the moon, orbiting colonies at L5 and Mars exploration missions may be considered premature. It may asked why such plans, when developed in isolation without building upon a well-defined space infrastructure, should be taken seriously? For example, how can building techniques for a lunar colony be considered other than an academic exercise when the infrastructure to get colonists to the moon is ignored? How can the potential benefits of asteroidal resource recovery be evaluated when we have no realistic way to get to the asteroid in the first place? Should serious evaluations of solar power satellite designs be undertaken when there will not be anyone in space to build the satellites or lunar colonies to provide raw materials? Why undertake planning a first generation of RLVs when what they will be used for remains largely undefined -- payload, destination, mission frequency, et cetera?

It is not that undertaking such detailed engineering evaluations is wrong at this time. Rather, it is that such work cannot be done in isolation, as is now the case. Specific engineering research and development for lunar colonies, RLVs, orbiting space bases, interplanetary transportation systems, et cetera, can be most effectively undertaken when integrated into a master plan of the overall space infrastructure. Therefore, defining this space infrastructure should be a priority among space planners.

Planning the Space Infrastructure

Within the engineering community, the process of planning and system development coordination falls within the discipline of systems engineering. The Defense Systems Management College defines systems engineering as:

> *Systems engineering is the management function which controls the total system development effort for the purpose of achieving an optimum balance of all system elements. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to optimize the overall system effectiveness.*

Planning an effective space infrastructure for the first phase of the human settlement of space is clearly a systems engineering task. Expressed in somewhat simplistic terms, its function is to translate the need for a basic space infrastructure into the detailed engineering plans, procedures, and processes that when implemented will actually build and deliver the many individual elements of this infrastructure. This translation process is highly complex, involving many engineering and non-engineering specialties. Yet, the steps that begin this process are fairly straightforward and can be explored within the scope of this paper to identify the direction this systems engineering process may take.

<u>Initial Operational Need</u>

The systems engineering process begins with an operational need, such as the following proposed need:

> *Phase 1 (2000-2040) will design, develop, build, deploy, and operate a* ***space operations and transportation network*** *extending from the earth's surface to the surface of the moon and the surface of Mars. This network will support exploratory, research, civil governmental and commercial human and robotic activities in circumterrestrial space, in circumlunar space and on the lunar surface. This network will support routine human exploration of Mars and the near-earth asteroids.*

To help guide Phase 1 planning, a preliminary Phase 2 need is also proposed:

> *Phase 2 (2040-2100) will extend the space operations and transportation network to provide extensive human settlement and industry in circumterrestrial space, in circumlunar space, and on the lunar surface. The network will support the initial human settlement of Mars and the exploitation of near-earth asteroids. The network will support direct human exploration of the other planets and the more distant asteroids.*

<u>Space Infrastructure Functional Analysis</u>

The first step in the systems engineering process is functional analysis starting with the definition of the primary functional areas required of the space infrastructure to satisfy the above stated operational need. A proposed set of these functional areas is shown in Figure 1 and described below:

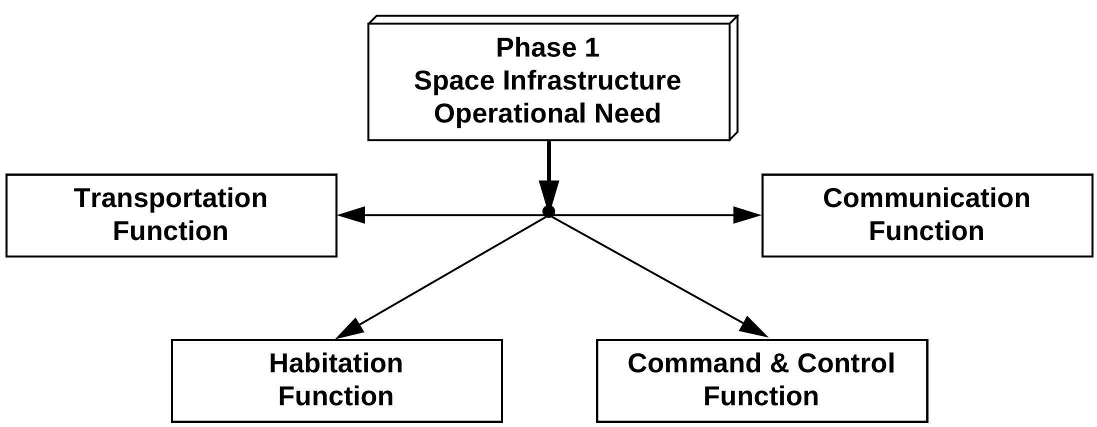

Figure 1 - Primary Functional Areas

- The transportation function moves people, hardware, and supplies from the earth's surface to and throughout terrestrial, lunar, and Martian space and on the moon and Mars. Transportation functions are required to support robotic and human exploration of near-earth asteroids.
- The habitation function provides support for human and robotic activities in terrestrial, lunar and Martian space as well as on the Earth, moon and Mars. The habitation function is also needed in deep space to support exploration missions.
- The communication function provides for data exchange between the hardware, software and personnel elements of the space transportation and habitation network.
- The command and control function plans, directs, schedules and integrates the activities of the other three functions to ensure that the space operations and transportation infrastructure operates in an effective and affordable manner.

Top-Level Function Decomposition

These four primary functional areas can now be further defined in terms of the individual functions (Figure 2) required to be performed within each of these areas.

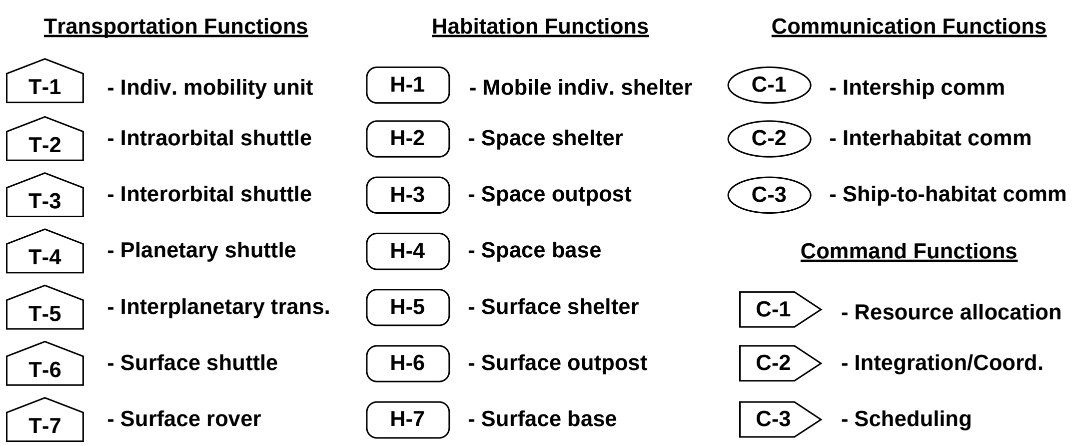

Figure 2 - Functions Within Each Area

Phase 1 Transportation and Operations Infrastructure Functional Architecture

The last of the initial steps in the systems engineering of the Phase 1 space infrastructure is to organize the essential functions into an overall architecture that satisfies the operational need for the time frame of 2000-2040. The proposed architecture for the transportation and habitation functions is shown in Figure 3. (For clarity, the communication and command and control functions are not

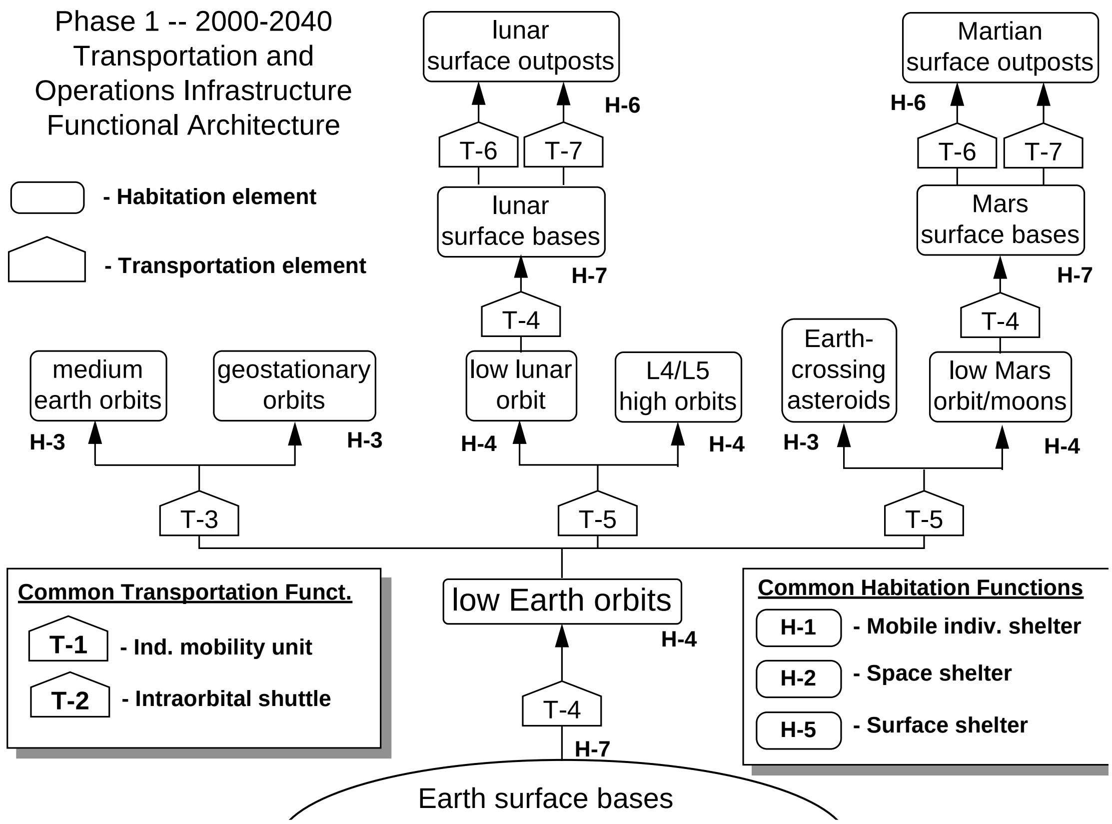

Figure 3 - Phase 1 Functional Architecture

included. These functions overlay on top of the transportation and habitation functions and are common to all displayed functions.)

Phase 1 Transportation and Habitation Functional Interfaces

The functional architecture shown in the above figure portrays the general relationship between the individual transportation and habitation functions. However, the complexity and number of functions prevents an accurate depiction of all the primary functional interfaces. This important relationship can be better portrayed in a functional interface matrix as shown in Figure 4.

Continuation of the Systems Engineering Process

The systems engineering process is inherently iterative. At each stage in the development process, additional details and refinements are made as the systems move from the initial concept to the final detailed design. The proposed space infrastructure functional areas, the specific functions within these areas, the overall architecture and the functional interfaces discussed in this paper are only the beginning of this iterative process. Ultimately, this initial stage of the planning process will produce specific functional requirements, performance requirements, and interface specifications for each major system in the basic space infrastructure. These requirements and specifications will, in turn, serve as the starting point for the next stage of systems engineering -- system synthesis -- where the actual design and development of the hardware, facilities, and software that will form this space infrastructure will be undertaken.

Phase 1 Transportation & Habitation Functional Interfaces	Indiv. mobility unit	Intraorbital shuttle	Interorbital shuttle	Planetary shuttle	Interplanetary trans.	Surface shuttle	Surface rover	Mobile indiv. shelter	Space shelter	Space outpost	Space base	Surface shelter	Surface outpost	Surface base
Indiv. mobility unit		★	★	★	★			★	★	★	★			
Intraorbital shuttle	★		★	★	★			★	★	★	★			
Interorbital shuttle	★	★		★	★			★	★	★	★			
Planetary shuttle	★	★	★		★			★	★	★	★			★
Interplanetary transport	★	★	★	★				★	★	★	★			
Surface shuttle							★	★				★	★	★
Surface rover						★		★				★	★	★
Mobile indiv. shelter	★	★	★	★	★	★	★		★	★	★	★	★	★
Space shelter	★	★	★	★	★			★		★	★			
Space outpost	★	★	★	★	★			★	★		★			
Space base	★	★	★	★	★			★	★	★				
Surface shelter						★	★	★					★	★
Surface outpost						★	★	★				★		★
Surface base				★		★	★	★				★	★	

Figure 4 - Phase 1 Transportation and Habitation Functional Interfaces

<u>Advantages of Formal Systems Engineering Planning</u>

Adopting and formally implementing a systems engineering planning process for Phase 1 will have these clear advantages:

1. It will shorten the time to develop and achieve the initial operational capability of the Phase 1 space infrastructure because a well-developed systems engineering plan is preferable to relying upon the hit-or-miss, trial-and-error approach that has traditionally been the mechanism for technological advancement.
2. It provides a common framework for cooperation and coordination among the diverse group of system planners, engineers and technologists working to build this space infrastructure.

3. It provides a common framework for organizing the products (reports, specifications, analyses, designs, et cetera) of the research, planning and, ultimately, development activities so that this information is readily available within the overall space infrastructure development community.
4. It minimizes the likelihood of missing key elements or design considerations as specific systems are developed and placed into service.
5. It improves our understanding of the complexity of the task of human settlement of space and permits the preparation of higher quality estimates of the time and resources required.
6. It provides a common framework for cooperation between nations and civil and private enterprises as the work to be accomplished is undertaken by the many participants.
7. It helps to transform the broad objective of human settlement of space from a incomprehensible political issue into a definable engineering challenge. It helps us to "know" what we are talking about.
8. Ultimately, it helps to make sure that bolt A fits into hole B and can be fastened with nut C on the dark side of the moon when it is your life on the line.

Conclusion

Opening the space frontier to human settlement will be one of the major engineering and technological challenges of the next century. If this is something we wish to be taken seriously, then we need to plan this undertaking seriously. We need to know specifically what is needed and how it will be accomplished. Further, we need to be able to prepare realistic estimates of the resources required to complete this undertaking. All of this requires careful and detailed planning. The steps outlined in this paper have identified one approach and a starting point for accomplishing this planning.