The original paper, Space Infrastructure Planning, was presented at the ASCE Space '96 Conference on Engineering, Operations, and Construction in Space, Albuquerque, NM, June 1-6,1996. The original paper is updated here.

Spacefaring Logistics Infrastructure Planning (2018 update)

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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 spacefaring logistics operations. These will include reusable, aircraft-like space access systems, expendable and reusable traditional launch vehicles, Earth-orbiting space bases, space tugs and ferries, interplanetary spaceships, surface and orbiting bases on the Moon and Mars, extraterrestrial space and surface mobility systems, and space colonies throughout the central solar system. This paper discusses the

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importance of carefully and systematically undertaking the systems engineering planning of the basic logistics infrastructure for the first phase of humanity's spaceward expansion. Further, this paper proposes an initial spacefaring logistics 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 (hopefully) not too distant future, 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 commercial travel to and from Earth orbit; a multitude of Earth-orbiting space habitats to serve government, commercial, and educational needs; commercial human transport within Earth-Moon space; the first permanent settlements on the Moon; and the start of the human exploration of Mars. Essentially, we would expect to see a complex infrastructure consisting of a wide range of small-to-large space systems providing all the needed logistics capabilities to live and work in space with acceptable safety.

The presumed existence of a complex spacefaring logistics 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, food delivery and preparation, and emergency services are commonplace on the Earth, we naturally expect similar capabilities will be in existence in space as well. Yet, in public discussions of the expansion of human civilization into Earth-Moon space, there is little, if any, consideration given to creating the enabling spacefaring logistics infrastructure. We should not simply presume that the necessary infrastructure enabling routine human spacefaring operations will exist to support the initial expansion of human civilization into space. Further, we should not presume that the expansion of human civilization into space is practical without making human spacefaring logistics operations an extension of terrestrial human logistics operations. Are we to live and work differently in space? Of course not. Therefore, defining this spacefaring logistics infrastructure should be a priority among spacefaring planners.

Defining Spacefaring and Spacefaring Logistics

Two important changes in this update to the original 1996 paper is changing "space" to "spacefaring" and using "spacefaring logistics" to properly describe the topic being discussed.

Spacefaring

From the 2002 *Commission on the Future of the United States Aerospace Industry*:

> *The Commission concludes that the nation will have to be a spacefaring nation in order to be the global leader in the 21st century—our freedom, mobility, and quality of life will*

> *depend on it. America must exploit and explore space to assure national and planetary security, economic benefit, and scientific discovery.*

While "space" is a place, "spacefaring" describes an activity or operation that humans undertake. Obviously, it is an extension of "seafaring", used to describe human operations at sea. Hence, while it remains appropriate to use "space exploration" to describe the temporary human and robotic exploration of outer space, "spacefaring" properly conveys what comes next—permanence of human space operations.

In 2001, the *Commission to Assess United States National Security Space Management and Organization* drew these conclusions regarding America's future spacefaring enterprise:

> *The first era of the space age was one of experimentation and discovery. Telstar, Mercury and Apollo, Voyager and Hubble, and the Space Shuttle taught Americans how to journey into space and allowed them to take the first tentative steps toward operating in space while enlarging their knowledge of the universe.* ***We are now on the threshold of a new era of the space age, devoted to mastering operations in space.*** *(Emphasis added.)*

> *Mastering near-earth space operation is still in its early stages.* ***As mastery over operating in space is achieved, the value of activity in space will grow.*** *Commercial space activity*

> *will become increasingly important to the global economy. Civil activity will involve more nations, international consortia and nonstate actors. U.S. defense and intelligence activities in space will become increasingly important to the pursuit of U.S. national security interests. (Emphasis added.)*

Spacefaring logistics

There are many types of infrastructure. While businesses create unique infrastructure to facilitate their business operations, most terrestrial infrastructure is commonly used. Common terrestrial infrastructure includes highways, electrical power utilities, hotels and motels, etc. This infrastructure is essential for commercial, government, and private operations and, for this reason, is built as common infrastructure.

The need for such common spacefaring infrastructure will develop as we transition to permanent commercial, government, and private operations in outer space. For clarity, spacefaring logistics infrastructure is used to refer to common spacefaring infrastructure.

Finally, it helps to be clear on the meaning of spacefaring logistics. The starting point is the definition of military logistics. The Department of Defense Joint Publication 1-01, Dictionary of Military and Associated Terms, defines military logistics as:

> *Planning and executing the movement and maintenance of forces. It includes those aspects of military operations that deal with:*

> *1) Design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of materiel;*
>
> *2) Movement, evacuation, and hospitalization of personnel;*
>
> *3) Acquisition or construction, maintenance, operation, and disposition of facilities; and,*
>
> *4) Acquisition or furnishing of services.*

Using this comprehensive definition of military logistics, this definition of spacefaring logistics is proposed:[3]

> *Spacefaring logistics is the science of planning and carrying out the movement of humans and materiel to, from, and within space combined with the ability to maintain human and robotics operations within space. In its most comprehensive sense, spacefaring logistics addresses the aspects of spacefaring operations both on the Earth and in space that deal with:*
>
> *1) Design and development, acquisition, storage, movement, distribution, maintenance, evacuation, and disposition of spacefaring materiel;*

3 This definition is based on a definition of space logistics adopted by the American Institute of Aeronautics and Astronautics' Space Logistics Technical Committee.

> *2) Movement, evacuation, and hospitalization of people in space;*
>
> *3) Acquisition or construction, maintenance, operation, and disposition of facilities on the Earth and in space to support human and robotics space operations; and,*
>
> *4) Acquisition or furnishing of services to support human and robotics space operations.*

This definition illustrates the scope that spacefaring logistics infrastructure planning should encompass. This is far more than the logistics planning associated with only space exploration missions.

Planning the Spacefaring Logistics 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 spacefaring logistics 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 spacefaring infrastructure into the detailed engineering plans, procedures, and processes that, when implemented, will actually build and deliver the many individual elements of an integrated 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 will take.

Operational need statements

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

> *Phase 1 will design, develop, build, deploy, and operate a* ***spacefaring logistics infrastructure*** *extending from the Earth's surface to the surface of the Moon and the surface of Mars. This network will support civil, government, and commercial human and robotic activities in circumterrestrial space, in circumlunar space, and on the lunar surface. This network will support the routine human and robotic exploration of Mars and the near-Earth asteroids.*

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

> *Phase 2 will extend the spacefaring logistics infrastructure 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.

Functional analysis

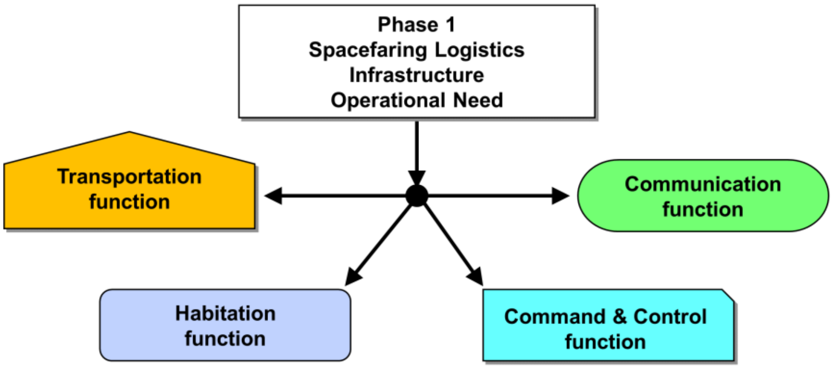

Figure 1: Primary functional areas. (Credit: J.M. Snead.)

The first step in the systems engineering process is to define the primary functional areas required of the spacefaring logistics infrastructure to satisfy the above stated Phase 1 operational need. A proposed set of these functional areas is shown in Figure 1 and described below:

- 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 also required to support the 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 and real-time communications between the hardware, software, and personnel elements of the spacefaring logistics infrastructure.
- The **command and control function** plans, directs, schedules, and integrates the activities of the other three functions to ensure that the spacefaring logistics infrastructure operates in an effective and efficient manner.

Top-level function decomposition

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

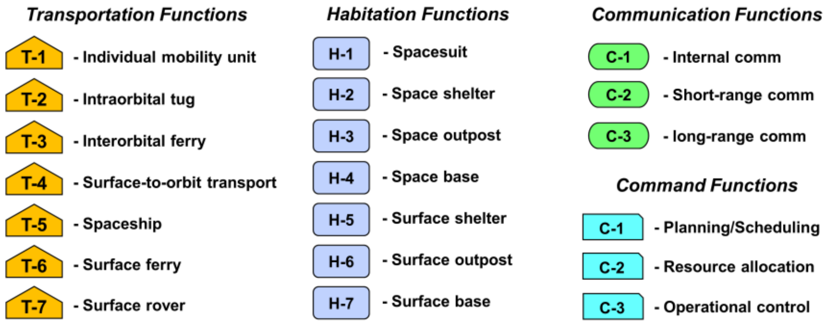

Figure 2: Functions within each area. (Credit: J.M. Snead.)

Phase 1 spacefaring 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. The proposed architecture for the identified primary functions of transportation and habitation is shown in Figure 3. (For clarity, the communication and command and control functions are not included. These functions overlay on top of the transportation and habitation functions and are common to all displayed functions.)

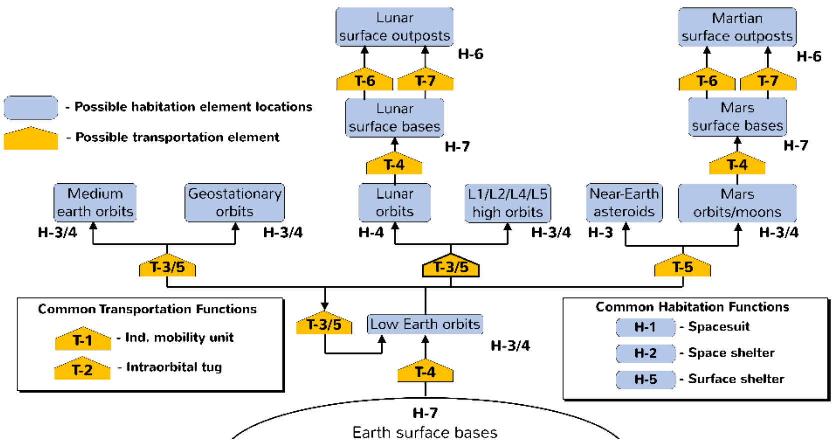

Figure 3: Phase 1 transportation and habitation infrastructure functional architecture. (Credit: J.M. Snead.)

Phase 1 Transportation and Habitation Functional Interfaces

The functional architecture shown above 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.

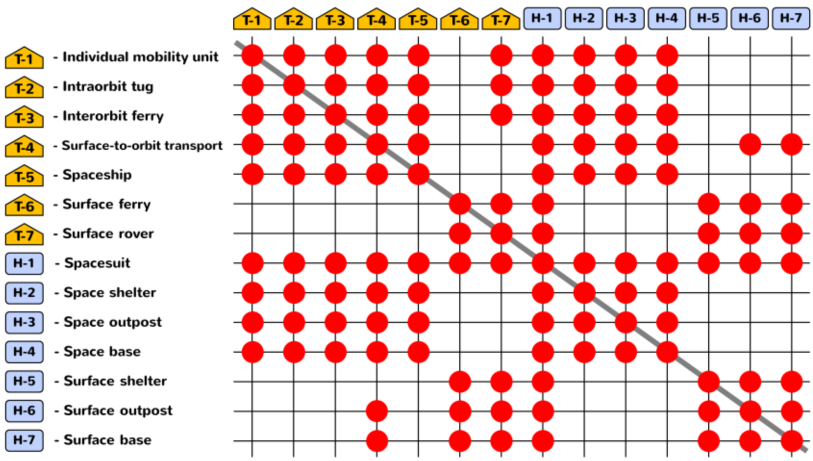

Figure 4: Phase 1 transportation and habitation functional interfaces. (Credit: J.M. Snead.)

Phase 1 Operational Need Decomposition

As shown in Figure 5, Phase 1 is decomposed into these sub-phases:

A. Achieving low Earth orbit and creating the initial LEO common logistics infrastructure.
B. Extending the LEO common logistics infrastructure and extending this to medium- and geostationary Earth orbits, the Earth-Moon LaGrange orbits, lunar orbit, and the lunar surface.
C. Extending the common logistics infrastructure to support human and robotic exploration of Mars,

near-Earth asteroids, and throughout Earth-Mars space.

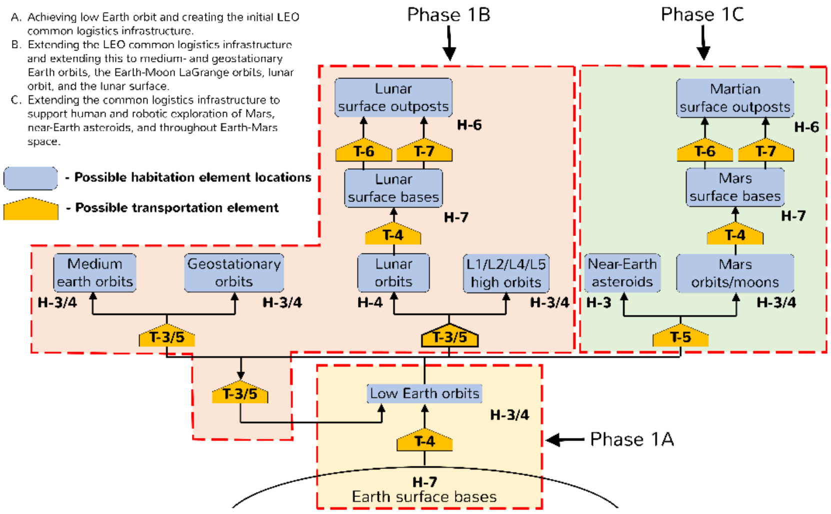

Figure 5: Decomposition of the Phase 1 functional architecture. (Credit: J.M. Snead.)

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 spacefaring logistics 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 spacefaring logistics infrastructure will be undertaken.

Advantages of Formal Systems Engineering Planning

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, etc.) 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 back side of the Moon when it is <u>your</u> life on the line.

Conclusion

Opening the space frontier to human settlement and commerce 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.