Space System Architecture

Required Reading:

a) Framing document (02010 week_2_framing.pdf)
b) Wertz, James R. and Larson, Wiley J., *Space Mission Analysis and Design*, Chapters 1 to 4 (02020 SMAD1 to 4.pdf)
c) Report of the DSB/AFSAB Joint Task Force on Acquisition of National Security Space Programs, a.k.a. Tom Young Report (02030AcquisitionReport_2003.pdf)
d) Charles F. Lillie, Michael J. Wehner and Tom Fitzgerald, "Multidiscipline Design as Applied to Space," AIAA Paper, 1998 (02050 Multidiscipline.pdf)
e) Cost Estimating Viewgraphs (02999 Cost Estimating. pdf)

Recommended reading:

a) NASA Systems Engineering Handbook

For over 40 years, space systems have been successfully designed, built, and operated. Over this time, a methodology has evolved for determining an initial architecture for such systems, refining it, and transitioning to detailed design of the space vehicles and other systems in the architecture. These methods were built on a legacy of large, well financed, technology driven programs such as the Apollo lunar exploration missions, early communication satellite work, and a variety of national asset programs focused on cold war needs.

There are good technical and historical reasons for current practices. The overwhelming technical reason is that, if done competently and with sufficient resources, they work. Systems engineering practices growing out of the aerospace and defense industries of the 1950's and 60's have allowed the creation of systems of unprecedented complexity and technical sophistication. Historically, they were developed in an environment of relatively abundant resources and the attention of a large and highly competent workforce. Most systems were doing either unprecedented new missions, pushing the limits of performance, or incorporating new technologies – often all three at once. Performance and mission success, for national defense and prestige, were the driving motivations.

With the conclusion of the cold war, shrinking budgets and shifting national needs in the 1990's lead to experiments in "Cheaper, Faster, Better" programs designed to do simpler tasks, much faster with much less money. These programs were not always successful, as in general lower cost and tighter schedules were accomplished by accepting increased technical and program risks.

In this unit, we will review existing methods for determining space systems architectures, as expressed in Space Mission Analysis and Design (SMAD)[1] and the NASA Systems Engineering handbook.[2] The NGST article[3] provides a case study in a properly executed architecture study using 1998's state of the art techniques on a large, expensive system. The Young report provides a pointed critique of these methods and their implementation on several ongoing programs. This document will amplify some of the points made in the Young report. Finally, the cost estimation viewgraphs get at a basic weakness of all current methods – the reliance on cost estimates that are very likely to be badly off.

SMAD

The SMAD method for handling the "front end" of the design process consists of the following steps:

1. Define broad objectives and constraints
2. Estimate quantitative mission needs and requirements
3. Define alternative mission concepts
4. Define alternative mission architectures
5. Identify system drivers for each
6. Characterize mission concepts and architectures
7. Identify critical requirements
8. Evaluate mission utility
9. Define mission concept (baseline)
10. Define system requirements
11. Allocate requirements to system elements

The first four chapters of the SMAD book lay out this process in detail. Note the process starts with the establishment of needs and requirements, which are driven through a set of alternative concepts and architectures to define a baseline mission concept. From this baseline, the hard system requirements are set, and allocated to the various system elements. The emphasis is on narrowing the design choices to produce a tractable set of concepts that can be evaluated. Most of the steps are qualitative, involving using experience and expertise to make good choices. The choices themselves tend to be localized (e.g. which orbit or propulsion system to use) without a formal method for dealing with interactions between the choices. Lessons learned along the way *can* be used to iterate the process (e.g. if the choices made result in poor mission utility at step 8), however this requires doing much work over again and so will be an unattractive choice.

Wertz, in the first paragraph of the book, notes that "**Broad** (Wertz's emphasis) objectives and constrains are the key to the process. Procurement plans for space systems too often substitute detailed numerical requirements for broad mission objectives." The SMAD method is logical and systematic, and intelligent, experienced users can use it to find reasonable solutions to reasonably stated mission needs. However, this process has requirements, for a single concept, as its goal, and there will always be a temptation to proceed quickly to this goal. In the presence of uncertain or poorly poised needs, new technologies with unknown performances, unstable funding, and difficult-to-estimate costs, this may not be the best approach.

The NASA Systems Engineering Handbook presents another take on proceeding from needs to requirements. It places more emphasis on upfront work, and the need to consider the relationship between cost and "effectiveness" through trade studies and mission utility analysis.

The execution of the "classical" method is illustrated by the NGST study. Based on a defined need, as set of mission requirements are generated, and a series of logical design choices are made to narrow the tradespace down to a good baseline design. Further refinement is carried out by doing parametric studies, in one design variable at a time, about the baseline. In cases where design solutions cannot be found, the requirements are challenged as necessary. This is a reasonable representation of the state of the art, properly executed.

Critical role of front-end work in program success

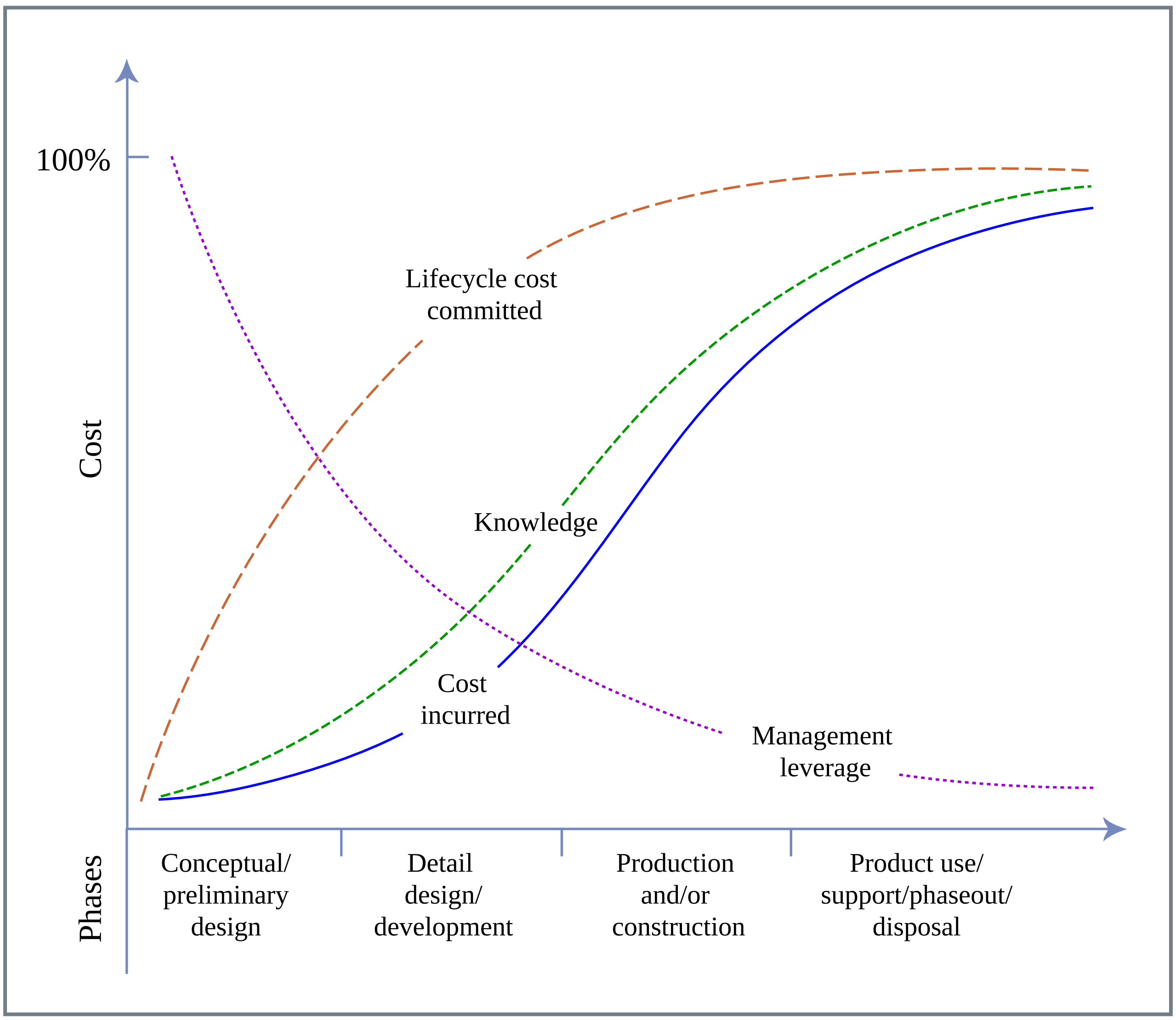

Figure 1. Notional view of costs committed vs. costs incurred over time (Adapted from W. J. Fabrycky, Life Cycle Cost and Economic Analysis, Prentice-Hall, NJ, 1991.)

Good up-front work in the eventual success of a program. It has been stated that 80% of the eventual costs of a system are determined before the first 20% of the funds have actually been spent.[4] Figure 1 illustrates this graphically. It is therefore not surprising that programs that under-fund front-end work (from mission feasibility through preliminary design) will have higher costs later in the program. This trend is dramatically illustrated in Figure 2, taken from the NASA Systems Engineering Handbook.[2] Note that this figure does not consider *failed* programs, many of which fail because of poor up-front work.

Problems with classical architecting methods

The Young Report on Acquisition of Nation Security Space Systems[5] found several causes for concern about the current state of systems architecting. They noted that the emphasis on cost as a management driver was causing excessive technical and schedule risks; that the costs were poorly estimated; that poor or unstable requirements, based on poorly defined needs, were driving cost and schedule problems, and that the government lacks the experienced personnel and other tools necessary to provide proper oversight. Three of the above problems can be tracked directly to poor "up front" work; the first (that cost was traded against other risks) can also be a product of choosing the wrong architecture, such that cost, performance, and schedule targets can not all be met to the users satisfaction.

The importance of good front-end work is clear. However, the methods for doing it are often ill-suited to the current environment and do not exploit the power of modern tools and computational capabilities. From Ross *et al.*:[6]

> Space system engineers have been developing effective systems for about fifty years and their accomplishments are a testament to human ingenuity. In addition to tackling the complex technical challenges in building these systems, engineers must also cope with the changing political and economic context for space system design and development. The history, scope, and scale of space systems results in a close tie with government and large budgets. The post-Cold War era has resulted in much smaller budgets and a space industry that needs to do more with less. Time and budget pressures can result in corner cutting (such as the Mars Program), and careless accounting (such as Space Station Program).
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> Space system design often starts with needs and a concept. Engineers perform trade studies by setting baselines and making minor changes to seek improvement in performance, cost, schedule, and risk. The culture of an industry that grew through an Apollo race to the moon and large defense contracts in the 1970s and 1980s is slow to adapt a better way to design systems to ensure competitiveness in a rapidly changing world.
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> Current approaches to creating aerospace systems requirements do not adequately consider the full range of possible designs and their associated costs and utilities throughout the development and lifecycle.[7] These approaches can lead to long design times and designs that are locally optimized but may not be globally optimized. This paper develops a systematic approach for space system design by addressing the following problems: 1) A priori design selections without analysis or consideration of other options; 2) Inadequate technical feasibility studies in the early stages of design; 3) Insufficient regard for the preferences of key decision makers; 4) Disconnects between perceived and actual decision maker preferences; 5) Pursuit of a detailed design without understanding the effects on the larger system; and, 6) Limited incorporation of interdisciplinary expert opinion and diverse stakeholder interest.

Ross *et al.* concentrate on the fact that current processes may not result in an optimal solution. Current processes are also badly disrupted by changes in environments and/or user needs. If the technology used on a subsystem changes (due to lack of readiness, for example), the effects on the other systems, and the ability to meet requirements, "ripples out". If a top level requirement changes, changes flow down to all subsystems, and then the effects of the changes on interfaces and system integration must be considered. Such disruptions take time, and may result in a "patched" solution which is not optimal (even locally).

Examining Figure 1, we would like a process that would put off the commitment of program costs as long as possible, maintain management leverage as long as possible, and increase knowledge as quickly as possible, while not increasing costs incurred. In light of the above comments, we would also like it to avoid early a priori design selections, include the preferences of key stakeholders, and increase knowledge specifically of technical feasibility and system interactions, while remaining flexible to changes in environments and/or user needs. MATE –CON, to be examined next week, is an attempt to create such a process.

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[1] Wertz, James R. and Larson, Wiley J., Space Mission Analysis and Design, Microcosm Press and Kluwer Academic Publishing, 1999.

[2] NASA Systems Engineering Handbook, National Aeronautics and Space Administration SP-610S, June 1995.

[3] Charles F. Lillie, Michael J. Wehner and Tom Fitzgerald, "Multidiscipline Design as Applied to Space," AIAA Paper, 1998.

[4] W. J. Fabrycky, Life Cycle Cost and Economic Analysis, Prentice-Hall, NJ, 1991, and W. J. Fabrycky, Engineering Economy, Pearson Education, Inc., NJ, 1991.

[5] Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, May 2003.

[6] Ross, A. M., Diller, N. P., Hastings, D. E., and Warmkessel, J. M., "Multi-Attribute Tradespace Exploration as a Front-End for Effective Space System Design," *Journal of Spacecraft and Rockets*, January 2004.

[7] Diller, N. P., "Utilizing Multiple Attribute Tradespace Exploration with Concurrent Design for Creating Aerospace Systems Requirements," SM, Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2002.