Appendix E

NEW APPROACHES TO SPACECRAFT DESIGN

INTRODUCTION

The design phase lies at the core of any complex system. In relation to spacecraft, it encompasses not only the development of actual flight hardware and software but also the preceding mission definition, the procedures for test and operation, and, ultimately, a strategy for synthesizing data from the mission into useful scientific knowledge. Design is, therefore, a comprehensive process, the outcome of which depends on cooperation among a team of experts under the guidance of seasoned management.

Engineers have long experimented with new ways of designing systems, but the pressures that have resulted from shrinking the cost and size of spacecraft have greatly accelerated natural process improvement. The design process is now expected to deliver less-expensive, more-capable spacecraft. Achieving this while improving performance and reliability presents significant challenges to design teams.

This appendix will first review how constrained budgets have influenced approaches to design. It will then describe what steps have been taken to develop new, lower-cost design processes. The implications of new design approaches will also be discussed.

DESIGNING WITHIN CONSTRAINED BUDGETS

The primary driver for improving the design process is cost. Design engineering is the largest element in the overall cost of building space systems. Typically, 60 percent of the budget for building a spacecraft is expended prior to fabrication. (Wong, 1992, p. 734.) As discussed in Appendix A, the small spacecraft NASA is currently building retain much of the complexity of their larger predecessors. Not surprisingly, nonrecurring costs remain typically 50 to 60 percent of the cost of a small spacecraft. (Bearden, 1996, p. 44.)

Because design is a major factor in the cost equation, managers must be especially careful to avoid growth in this area. One element of a “design-to-cost” strategy is to maintain a firm cutoff in the amount of engineering allowed for a given spacecraft. Designs are frozen early, and attention is shifted to the test phase. “Testing the hell out of the design” has always been an element of spacecraft engineering, but many small spacecraft rely on testing to an exceptional degree. Trading design costs for additional testing can help mitigate risk, as demonstrated in the recent Mars Pathfinder mission. Mars Pathfinder’s design was high risk in that it was single-string and relied extensively on new design approaches. (Muirhead, 1996, pp. 7–9.) To improve the probability of success, the spacecraft was rigorously tested prior to launch.

Controlling design costs is mandatory in a small spacecraft program, but to reduce costs, the design effort must be reduced. For example, many small programs forgo the development of the engineering test units that have traditionally been used to work out design and system-level bugs prior to committing to actual flight hardware. In the past, these test units took various forms—structural models, protoflight units, proof test models, etc.—but today they have been replaced by less expensive analytical models.

Reductions in the design effort can work against other mission objectives. Shortening the design phase can, for example, limit the ability of a program to incorporate advanced technology. When all mission elements are considered, advanced designs are sometimes rejected—not because of fear that new components will fail, but because of the time it takes to integrate them. This is potentially limiting in that future small spacecraft are expected to deliver increasingly impressive performance. Less attention to design can also adversely affect reliability. Appendix B showed that design errors are the major source of failure in spacecraft systems. This suggests that the design phase should be the focal point for risk reduction and urges more, not less, attention to design.

Close monitoring of design costs and keeping the design phase as brief as practical are strategies that have helped bring down the cost of building spacecraft. To reduce costs further, however, new processes are needed that reduce the time required to perform the engineering function and speed the incorporation of new technology. To reduce risk, new processes also need to integrate (a) the knowledge gained from advanced failure-analysis efforts, (b) the results of improved test strategies, and (c) information related to high-reliability parts and components.

RETHINKING THE DESIGN PROCESS

Rethinking the design process means changing not only the drawing-board phase, when actual engineering drawings are prepared, but also the earlier mission planning phase, when critical trades and selections are made. The SMEX program, one of NASA's premier small spacecraft programs, recognizes that "the mission design, not just the spacecraft, must be optimized to reduce the workload and to shorten the development/integration/test activities." (Watzin, 1996b, p. 2.)

One approach to living with limited budgets while attempting to mitigate risk and increase performance is to attempt to spread design costs across a vertically integrated program, achieving some degree of cost recovery. NASA's Explorer program employs this approach. Each new Explorer spacecraft, regardless of size, builds on the heritage of the past; each new design introduces features with the next unit in mind. Purposely designing systems to scale up or down helps to minimize the time, and thus the cost, of maturing a design for use on a new mission. Errors in design can also be eliminated in future versions of a given design. This approach has paid dividends, as demonstrated by the history of performance and reliability of Explorer spacecraft.

Collaborative Approaches to Design

One of the most important improvements related to design is a greater degree of collaboration within design teams. Underlying this shift is a fundamental change in how engineers view spacecraft systems. A traditional definition of a spacecraft would be based on a hierarchical view of discrete systems that communicate through predefined interfaces. A current definition might view spacecraft systems as interrelated, dynamic, and reconfigurable.

The traditional view of spacecraft relied heavily on a work breakdown structure (WBS), a top-down strategy for approaching the design task. Each WBS element represented a discrete design element, and engineers were given budgets (both cost and technical, in terms of mass, power, etc.) that they were expected to stay within. Expert teams solved the design challenges of each element of the WBS in relative isolation. At predefined points in the schedule, the overall team, or subsets of the team at the system level, would gather to check on progress and share relevant information. There were some drawbacks to this approach:

- The WBS approach tended to focus on designing spacecraft systems; how it was to be operated and even how it was to be tested were often not considered until the design was nearly complete.
- Optimization was difficult and usually occurred only locally within the design.
- Segregating the design effort ignored the obvious interconnectedness of spacecraft systems and subsystems.

- A good deal of internal documentation and communication was required to define interfaces.
- Communication failures within the design team, formal or informal, often caused critical items to be overlooked, later necessitating expensive fixes and workarounds.

The presence of a WBS usually influenced the organization of the design team. Teams formed in a hierarchy found it inherently difficult to communicate, and they often acted competitively rather than cooperatively. Perhaps the biggest problem with the traditional model, however, was that elements of the design came together only periodically. This meant that managers could get an accurate picture of the overall progress only at prescribed review points defined by NASA's program management guidelines. (Casani et al., 1994, p. 230.)

Despite these limitations, the traditional approach worked and produced dramatic successes. Eventually, however, a more collaborative view of the design process began to take hold. System engineering became rooted in spacecraft design practices, an improvement that began to broaden the focus of the effort to include life-cycle considerations.[1] Establishing the system engineering function to integrate across the design and development processes was an important innovation, but it concentrated on improving the technical aspects of design and retained the inherent hierarchical organization of the effort.

When viewed collaboratively, the importance of subordinate elements shrinks in relation to the increasing importance of the whole system. This approach focuses on broad-scale goals; not just technical performance, but cost, risk, operability, manufacturability, and end use, are optimized within the design process.

Concurrent engineering and the corollary innovation, *integrated product teams* (IPTs), are manifestations of collaborative design. These techniques place less emphasis on hierarchical team organization and linear approaches to design. Formal design phases (mission concept to preliminary design to final design) are replaced by an iterative process in which designers, test engineers, operators, and mission planners communicate directly and form multidisciplinary teams. This approach is well suited to the small spacecraft environment, in which many variables must be optimized. Indeed, many of the small spacecraft programs in this study have experimented with or wholly adapted concurrent engineering practices and the use of IPTs.

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[1] Most of the small satellite programs reviewed in this study treated system engineering as a discrete element of the design process with its own budget.

Computer-Based Design Environments

Use of computer-based tools has expanded rapidly, helping to control design costs and reducing the need for test models. The majority of small spacecraft builders now use advanced design tools, such as the Computer-Aided Three-Dimensional Interactive Approach (CATIA) platform Boeing used to design the 777 aircraft. Although this capability is expensive, it is cost-effective in terms of reducing design time. Stand-alone design tools like CATIA can be limited, however, in their ability to interact with modeling and simulation (M&S) systems.

Advanced M&S systems began to reach a high state of fidelity in the early 90s and are a natural evolution of independent computer-based design tools. Collaborative approaches to design have proven to be well matched to advances in the M&S field. JPL and the then–Martin Marietta Corporation were both innovative in the creation of spacecraft design environments with extensive M&S capabilities. Martin Marietta's Spacecraft Technology Center (STC) in Denver promoted an intensive team environment in which aspects of mission design, spacecraft design, manufacturing, and operation could be quickly evaluated. The STC also made use of the Internet to exchange information and connect designers in remote locations into interactive design sessions. The initial STC was reconfigured with more advanced equipment and is now operating as the second-generation STC II.

At JPL, two related elements were created: the Project Design Center (PDC) and the Flight System Testbed (FST). These facilities were constructed with a stated goal of "recrafting" the engineering design process. JPL began by reevaluating all internal processes, breaking them down into four areas: project planning and implementation; mission and system design, fabrication, assembly, and test; and validation, integration, and operation. (Smith, 1996, p. 4.)

The PDC, shown in Figure E.1, is dedicated to what has traditionally been called mission design, the refinement of a science concept into a viable engineering design. To encourage team involvement, the PDC consists of one large room with peripheral support areas. An assortment of computers throughout the area allows engineers to run a suite of software tools and models, many of which are commercial tools, and to project results on large screens. As fitting the mission-design role of the PDC, these tools are selected to allow the team to perform trajectory studies, assemble power and mass budgets, generate solid models of the spacecraft, and estimate resulting costs. JPL relies on an expert technical body called the Advanced Projects Design Team, or Team X, made up of senior technical personnel, to assist in the initial design of a mission. Team X makes extensive use of the PDC to ensure that such issues as cost and operability are included in the overall mission design.

SOURCE: JPL.

Figure E.1—Team X in the Project Design Center

The FST, shown in Figure E.2, is a functional, system-level simulation of a proposed spacecraft. It contains computer-based analogs for each of the primary systems on the spacecraft, including the instruments. Simulations of the ground-control systems and the data-communication networks are also provided. The goal of the FST is to deliver a ready-to-build design that can be produced at reduced cost and schedule risk. This form of advanced simulation also allows new technology to be evaluated in modes similar to what will be experienced on the spacecraft.

To the extent that designs exist only inside of a computer (the term “silicon spacecraft” is often used), a virtual design environment is possible, one in which team members need not be physically colocated. Lockheed Martin Missiles and Space Company’s Palo Alto Research Laboratory is pioneering this type of capability under the support of DARPA. What is called the Simulation Based Design (SBD) Laboratory is actually a geographically disperse collection of teams collaborating on the design of a product through Internet connections.

Members of the design team communicate electronically, making individual contributions to the overall design. High-performance computers render designs, perform structural analysis, calculate performance against objectives, and coordinate and update design information.

One of the principal challenges of such approaches has been the difficulty of linking together advanced design tools and simulation models into a single, in

SOURCE: JPL.

Figure E.2—Design Team in JPL's Flight Systems Testbed

teractive environment. Such linkage requires creating interface standards that allow disparate models to exchange information and operate interactively. Standards are emerging, such as the Common Object Request Broker Architecture (CORBA). Extensive use is also being made of current Internet standards, such as the HyperText Markup Language (HTML) and Virtual Reality Modeling Language (VRML), and interfaces that are familiar to a broad user community, such as WWW browsers like Netscape.

In the future, the SBD environment will likely be linked to data archives containing a common set of information on the parts and components used to build spacecraft. The result will be an enclosed design process where a complete spacecraft team can quickly close on a desired design solution and enter the fabrication and test phase with a high degree of confidence.

Many organizations are getting involved in the process of creating new design environments. NASA GSFC, for example, has recently established the Integrated Mission Design Center (IMDC). DARPA and the National Institute of

Standards and Technology are also funding extensive studies in manufacturing that are tied to virtual design environments.

Remaining Challenges

Advanced design processes are an important development in terms of helping builders deliver less-expensive, more-capable, and more-reliable spacecraft. Yet, these capabilities are costly to develop, and their availability could be a factor constraining use. Cultural factors must also be addressed to achieve widespread acceptance of the computer-based approaches.

The development of new design capabilities requires a level of investment that is likely to be beyond the means of many commercial developers of small spacecraft. JPL's management realized that smaller missions could not afford to contribute to significant improvements in the infrastructure needed to construct the PDC and FST. (Sander, 1997, p. 4.) The FST and PDC are, therefore, available at modest cost to in-house design teams. Pricing and prioritization policies for use by customers outside of JPL, however, have not yet been established.

Most small spacecraft programs have rapid development schedules and commensurately short design timelines. Facility priority is usually given to in-house projects; attractive pricing might, therefore, be of little use because of scheduling problems. A related example, access to test facilities, illustrates this point. A small spacecraft design team cannot usually accept uncertainty in the availability of a test facility and will often pay a premium for ensured access. To the extent that advanced design environments represent national assets, pricing and availability policies will need to be established.

The creation of new design facilities also requires the resources to experiment with alternative structures. The first incarnation of the PDC, for example, was found to be uncomfortable for design teams. Acoustics and lighting were poor, and the physical layout was not conducive to team operations. Subsequently, the PDC was moved twice to reach an arrangement that worked.

Finally, new approaches to design can encounter cultural barriers. When JPL's facilities were first opened in 1994, engineers used the new virtual environments as extensions of traditional practices, and their full potential was not realized (Smith, 1997, p. 3). Managers, too, can resist change. JPL project managers, traditionally able to select their own design approaches, faced standardization and the subsequent loss of autonomy (Smith, 1997, p. 4). Also, most programs still rely on mission-specific test beds for evaluating designs.[2] Design teams will likely require that new design environments demonstrate a clear advantage over mission-specific test beds before being willing to completely adopt them.

IMPLICATIONS FOR FUTURE SPACECRAFT

Virtual design environments are the state of the art, and spacecraft builders are only now starting to use them. As they gain acceptance, industry analysts predict significant cuts in design times and cost, while improving final component performance and reliability.

The ability of a virtual environment to help the engineer visualize the effects of design changes is the real advantage of working in a simulated environment. Feedback is rapid, and other team members are available to resolve problems and make the required trades. The goal of LMC's SBD system, for example, is to "reduce satellite design processes from months to days." (Graves et al., 1997, p. 7.) Such dramatic reductions are often difficult to achieve in practice, but there is ample reason to believe that large reductions in design times are possible. Intel, while achieving the quality and reliability targets reported in Appendix D, reduced the average component design time from 80 weeks in 1986 to 23 weeks in 1995. (Intel, 1996, pp. 1–8.)

The existence of computer-based design environments also offers an opportunity to integrate the factors described in Appendixes B and C. New test approaches, insights into sources of failure, and knowledge gained from research into high-reliability systems can be brought together in a central location that is coincident with the design effort.

SUMMARY

The design of space systems is a comprehensive process that is being reengineered to deliver less-expensive, more-capable spacecraft that perform better and offer greater reliability. In regard to space systems, cost is the primary driver for changing the design process, since the design phase is typically the most expensive cost element in spacecraft TMC.

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[2] Test beds are a synthesis of computer models and physical elements that simulate the operation of the spacecraft and its ground control network. As the development of the spacecraft continues, simulated systems are replaced by actual flight equipment, so the test bed serves as both a design and test tool. Test beds are often built specifically to meet the requirements of a mission. Advanced design environments seek to provide many of the capabilities of the mission-specific test beds, reducing or eliminating the need for them.

Builders of small spacecraft are especially pressed to minimize the length, and thus the cost, of the design phase. Some of the methods used to control design cost are

- Capping the design effort (design-to-cost) and focusing on testing
- Forgoing the use of engineering test units
- Reducing new technology in the design.

These methods can work against other goals, such as reducing design-related failures and increasing the performance of spacecraft systems. New design approaches seek to improve the cost and technical effectiveness of the design process.

One of the most important improvements has been a greater degree of collaboration within design teams. The traditional hierarchical design process, built around the work breakdown structure, has been largely replaced by a collaborative process. RAND found that most of the small spacecraft programs in this study have reflected this shift by experimenting with or wholly adapting concurrent engineering practices and the use of integrated product teams.

Design process improvement has been paralleled by gains in the performance of modeling and simulation tools. Initial developments in this area have centered around the creation of design centers in which engineers are immersed in a team environment, surrounded by the latest computer-based tools. JPL's Project Design Center and Flight System Testbed are representative of such developments.

A natural extension of such centers is to connect geographically disperse teams via the Internet. Such "virtual" design environments connect teams via high-speed, fiber-optic links. Engineers can quickly analyze aspects of the emerging design by accessing local or remote tools, make changes, and communicate them to other team members.

The emergence of a collaborative design process, supported by computer-based environments containing advanced modeling and simulation tools, is an important development in terms of reducing the cost and risk associated with space systems.