Int. J. Engng Ed. Vol. 24, No. 2, pp. 221–225, 2008
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Design Engineering Education and Space Exploration in a Flat World*

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Keynote Address, Sixth Biennial Mudd Design Workshop, Harvey Mudd College, Claremont, CA, USA, 23 May 2007

IT HAS BECOME A COMMONPLACE that we're living in a so-called 'flat world' in which people, goods and information travel around the globe with increasing speed and seamlessness [1]. While political scientists can debate the merits of this metaphor, there is no question that those of us working in the aerospace industry over the past few decades have witnessed a profound transformation in the way we do business. It is important to note, however, that this has been a two-way street. Even as changing market forces and rapidly advancing technology have reshaped our environment, we have simultaneously played a role in shaping the globalization of science and technology through our practice of working collaboratively across borders and sectors. The kind of collaboration that is characteristic of NASA—involving partners in the international community, industry, and academia—has been with us far longer than the current wave of globalization; it is a continuum, not a revolution.

Space exploration has always been an international phenomenon. Even before a manmade satellite ever orbited the Earth, the first space exploration initiative was built on the premise of cooperation among nations. In 1952, the International Council of Scientific Unions established the period from 1 July 1957–31 December 1958 as the International Geophysical Year (IGY). During the IGY, scientists around the world would conduct coordinated observations in 11 earth science disciplines. The IGY began with 46 participant countries, with 67 ultimately becoming involved [2]. On the eve of the IGY kickoff, President Dwight D. Eisenhower noted that ' . . . the most important result of the International Geophysical Year is that demonstration of the ability of peoples of all nations to work together harmoniously for the common good' [3].

The importance of cooperation was a key consideration for the United States' burgeoning civilian space programme. When NASA was founded in October 1958, its first Administrator, T. Keith Glennan, appointed a Director of the Office of International Cooperation as part of the new agency's management team [4]. Since then, the US has had well over 3,000 international partnership agreements [5].

NASA has a long history of international collaboration and partnerships, but it is also important to recognize that space exploration takes place in the larger context of politics and diplomacy. Throughout NASA's history, the balance between international cooperation and competition has shifted in response to political events, as it continues to shift to this day. In addition to big-picture foreign policy issues, NASA's partnerships are shaped by technical restrictions such as the International Traffic in Arms Regulations (ITAR), a set of regulations that govern the import and export of defense-related technologies and services [6].

While the IGY emphasized cooperation, the Soviet launch of Sputnik on 4 October 1957 locked the US and USSR into a competition of 'firsts': the first satellite, dog in space, man in space, woman in space, two-man crew, spacewalk, lunar orbit, planetary fly-bys, manned lunar orbit, and finally the first manned moon landing on 20 July 1969 [7]. The success of Apollo 11 effectively marked the end the space race.

Just two months after that historic event, NASA Administrator Thomas O. Paine wrote a letter to his Soviet counterpart suggesting greater opportunities for collaboration [8]. By 1971, there was general agreement between the two nations about the concept for the Apollo-Soyuz test flight. A new era of international collaboration—this time involving human space flight—had begun.

EVOLUTION OF SYSTEM ENGINEERING

The early space missions were relatively simple by today's standards: you attached a payload carrying a few instruments to a launch vehicle, and then you collected data from those instruments. Data systems and interfaces were rudimentary. With the emergence of complex programmes

* Accepted 13 January 2008.

such as the intercontinental ballistic missile (ICBM) and Apollo, there was a need for a more integrated and rigorous approach to engineering and engineering management. NASA hired senior leaders from the Air Force Ballistic Missile Programme to bring disciplined procedures to the manned space programme [9], and as a result system engineering and the system management approach achieved maturity through Apollo. NASA engineer Stephen B. Johnson, who is also a historian, has described system management as '. . . a set of organizational structures and processes used to develop a novel but dependable technological artifact within a predictable budget' [10]. Though we now take these practices for granted, they were engineering management innovations in their time.

Through Apollo and successful planetary missions such as Viking and Voyager, NASA developed a way of managing highly complex missions. It was not a model of perfect efficiency—a 1981 NASA study requested by Congress found that, '. . . several projects have experienced major cost increases without apparent forewarning' [11]. From the standpoint of technical performance, however, the project success rate under the mature system management approach was high.

THE CURRENT WAVE OF GLOBALIZATION

The next major shift on the government side of the space business came with the end of the Cold War. The abrupt transformation of our former adversary paved the way for far greater openness and international cooperation. High technology also took off, with exponential gains in computing power going hand in hand with rapidly falling prices for IT capability. The rise of the Internet and the availability of advanced products worldwide resulted in a huge shift of players in the space arena. There was massive consolidation in the aerospace industry, and at the same time it became a truly global marketplace.

Two NASA missions developed in the 1990s exemplify the globalization of science and technology. The first is the International Space Station. The space station concept had been considered for years, and there were a number of precursors, including the Soviet Salyut, Mir, and NASA's Skylab. But the International Space Station took the concept to an entirely different level, with five space agencies participating as full partners. It is one of the most ambitious construction projects ever attempted. ISS is the model for future cooperation in human space flight: it illustrates that technical excellence comes from all corners of the globe. There are now sixteen countries contributing innovative engineering, ranging from Canadarm 2, a 55-foot-long robotic arm from the Canadian Space Agency, to the station modules built by Russia and the European Space Agency [12].

Another mission that reflects the trend toward the globalization of science is the Earth Observing System (EOS). EOS has had nineteen launches since August 1997, with several more pending, and it has placed dozens of scientific instruments in orbit for long-term observation of the Earth's land, oceans, biosphere, and atmosphere. EOS is enabling an improved understanding of the Earth as an integrated system.

One example from EOS of a multinational, multidisciplinary mission is Terra. Terra involved partnerships between NASA and the space agencies of Canada and Japan. It has five instruments to observe the Earth in several wavelengths. All of the sensors were first of a kind, with many experimental capabilities. One of Terra's instruments, MODIS, had capabilities that evolved in an unexpected way to the benefit of humanity. Band 7 on MODIS is able to spot fires from space. It was envisaged as a research tool to aid in the understanding of aerosols emitted into the atmosphere from fires. However, early in the mission there were several severe forest fires in the US, and the Forest Service was unable to cover the large areas. Weather and smoke limited aircraft coverage, so NASA and Forest Service scientists recognized MODIS's ability to identify fire front lines. For this utility to be maximized, the data needed to be on the front line in a timely manner—within hours. No plan for this existed.

The solution to this required seamless interagency and international cooperation. Data were collected on the satellite and down-linked to the NASA facility in White Sands, New Mexico. Then Goddard Space Flight Center in Greenbelt, Maryland did initial processing, the result of which was sent to Europe for conversion to a product useful to the Forest Service. This was sent back to Goddard for quality checking and geolocation, and was then forwarded to the forest rangers located in the western US This was all done electronically, using the time zones to allow processing 24 hours a day, thus greatly helping to fight forest fires. Today this product is routinely used around the world, and now it is entirely automated. MODIS is just one example of how space flight projects enable the globalization of science in a way that makes a real difference in people's lives.

COMPLEXITY AND SYSTEM ENGINEERING

One of the key challenges that programmes like the International Space Station and EOS pose is the need for outstanding system engineering. System engineering has become a critical yet misunderstood field. The problem starts with the very definition of system engineering. Unlike electrical or mechanical engineering, if you ask five system engineers to define their discipline, you'll get five definitions (if not more). Another challenge in defining system engineering is determining the measurable outcome or product. An electrical engineer, for example, can design a box, which is a discrete product. With a system engineer, it's more elusive: how do you quantify the value of all the risk that a good system engineer removed from the project by anticipating and eliminating potential problems?

My definition is: 'A system engineer is a person who combines the science and the art of technology to achieve a goal within cost, schedule, and technology constraints.' I like to emphasize that phrase 'science and art'. System engineering requires multidisciplinary experience that can only be obtained on the job. A system engineer is grown, not trained.

In engineering there are many acceptable solutions to a problem. Look at the Soviet Vostok versus NASA's Mercury-Atlas, or the Soviet Soyuz versus NASA's Apollo. The common features are dictated by physics; those are the requirements that bound every design. The common language is math and science, which is the intellectual toolset engineers use to solve the design problem. The rest is dictated by the available resources and the vision of the designer. One need only look back in history to designers such as Filippo Brunelleschi and Leonardo DaVinci to see that ingenuity and vision are as crucial as math and physics to the development of successful solutions. Thomas Edison famously said that genius is 1% inspiration and 99% perspiration, but that last 1% is the critical difference between a visionary and a hard worker.

In addition to knowledge of different engineering disciplines, one of the key things system engineers bring to the table is engineering judgment. In the real world we often make decisions based upon incomplete information. We must make decisions, sometimes hard ones, based upon the information at hand. If we cannot explain our decision within the context of our scientific and engineering knowledge tempered by our experiences, we are looking for trouble, and will lack the ability to convince people of our actions. When using engineering judgment you are looking at the problem, looking at the data. All of the implications of the data may not be clear, but based on experience—the experience acquired over years—we can look at the data as it's presented and evaluate it and determine what the possible outcomes are, what the possible solutions are, what the possible consequences are if they're wrong.

Systems today require complex arrangements of technologies to meet the objectives of our missions, and as complexity increases, so does the need for system engineering to mitigate risk. At NASA this is further complicated by the fact that we usually build 'firsts' and 'onlies'. We don't design an airplane and then build 400 of them, so we can't refine a design once we go into production. We have to get it right the first time, and it's very difficult to predict what will work in a new environment.

Factor	Example
Organization	geographically distributed; multiple stakeholders
Technology	increased spacecraft autonomy; number of interfaces
Environmental uncertainty	solar activity; planetary landing site terrain

Fig. 1. Contributing factors to overall mission complexity.

GROWING SYSTEM ENGINEERS

Our young engineers and scientists need opportunities and training to reach the plateau of a system engineer. There is a critical need for talented system engineers, and NASA has undertaken a workforce training and development effort to address this. We've met with our counterparts in other government agencies and private industry to learn as much as we could about how other aerospace and high-reliability organizations develop their system engineers. We revamped our entire curriculum within our Academy of Program/Project & Engineering Leadership to address system engineering at each stage of a career, and to promote system thinking among all our technical personnel, regardless of whether they ever wear a system engineer badge. And many of the different NASA centres have system engineering professional development programmes that include mentoring, coaching and hands-on job rotations. The programme at Goddard Space Flight Center, where I worked for many years before moving to NASA Headquarters, calls its programme SEED: System Engineering Education Development. The acronym reinforces my point: system engineers are grown.

As the individual responsible for ensuring the technical readiness of NASA's engineers, I am often asked what makes a good system engineer. Technical skills, of course, are a prerequisite. A system engineer must have a breadth of knowledge of all the key engineering disciplines. Beyond that, a system engineer must have the ability to see the whole system and anticipate the effect that changes in one subsystem will have on the whole. System engineers also need to understand how a spaceflight project actually gets done from start to finish. Within the context of NASA, this includes how work gets authorized—the system of budgets, funding commitments, and organizational partnerships—as well as how designs get implemented once they enter the manufacturing process. Finally, communication skills are just as critical as technical expertise. In everything from technical reviews to continuous communication with team members, the system engineer has to be at the center of the technical conversation.

The best system engineers tend to share certain personality traits. They are tough-minded and unafraid to express dissenting opinions. They are intellectually driven by challenges. And they are always near the centre of the action—these are not the types who come to the office and shut their door so they can do their work.

NASA is facing a critical shortage of system engineering talent today, one that threatens both its ability to execute the Vision for Space Exploration and U.S. preeminence in aerospace in general [13]. This shortage is part of a larger international trend in education, in which the United States is not producing enough graduates in science, technology, engineering and math (STEM) [14]. The broader trend extends far beyond NASA, but its implications for the agency are clear: partnerships will be critical to our future.

CONTINUING NEED FOR COLLABORATION

Given the inherent difficulty and cost involved in what we're trying to do, it's to our mutual benefit to work collaboratively across borders and sectors. Our partners in other government-funded space agencies, academia and industry all contribute to our success in different ways. Governments, of course, determine the funding and the highest-level mission requirements for civilian space programmes based on national and international interests. (The European Space Agency, for example, is an international agency that reflects the collective priorities of its member nations.) Academia gives us scientific expertise, broad-based knowledge, and blue-sky thinking about our most complex scientific and technological challenges. Private industry enables us to implement and execute our missions by leveraging cross-program expertise in space systems design, development, deployment, and operations. The entire enterprise is international; academia has always worked that way, and our industry partners all now operate internationally.

Many of the questions we seek to answer are **shared** questions about the Earth's environment, microgravity, planetary science, astrobiology, and the origins of the universe. Collaboration is the most effective way to address these issues that are not zero-sum situations, where one space agency's gain is another's loss. From a resources standpoint, it is simply too costly for any one nation to try do it all alone. More than that, though, there is a great deal of expertise out there that can only be leveraged through cross-border collaboration. By its very nature, the scientific method demands that new discoveries be shared, critiqued, and improved upon. We at NASA don't have all the answers, nor do the Europeans, the Russians, the Japanese, or anyone else; working together, however, we can find them.

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