AN EASY-TO-USE, OFF-THE-SHELF SPACECRAFT ARCHITECTURE FOR "SHORT-TIME-TO-SPACE" SATELLITE MISSIONS

B. Altan [a]*, Y. Segal [b]

[a] Space Exploration Technologies
1310 East Grand Avenue, El Segundo, CA 90245
[b] Stanford University, Graduate School of Engineering, Department of Aeronautics and Astronautics,
Durand Building, 496 Lomita Mall, Stanford, CA 94306-4035
bulent@spacex.com, ylan@segal-family.com

KEYWORDS: Space, Spatial, Small, Design, Development, Cost

ABSTRACT:

Today many industries are realizing that without increasing usability, miniaturization and expanding the customer base to industries other than those which are directly related, profits will be low and the cost for every end-user of such products very high. Computers, electronics, telecommunications and other high-tech industries have already reacted to this trend and introduced their products into everyday life and business. Indeed, without the aid of high tech gadgets like PCs and cell phones, daily life would be hugely inconvenient and business very wasteful. Yet one of the most sophisticated and high-profile industries, the space industry, has never reached a point where it is essential to many other businesses. Although the global telecommunications network would not exist without satellites, as would neither intelligence nor warfare, the customer base for these types of missions is very limited and the cost for these projects astronomical. Many customers today fear going into space-based business because of the high risk involved, and universities avoid using space technologies in their research because of the long development times and the high costs. With this paper we want to show that the current proceedings in space technology together with the right steps taken in the space industry make it possible to bring spatial resources to many researchers and businesses not directly associated with space. We will show that more can be done with less money and development times can be shortened by removing some of the decades-old legacy systems still in place at many government space agencies and large aerospace corporations, that can benefit the remote sensing industry by enabling them to build small satellites easily almost like buying parts for a computer in a store and putting it together.

1. INTRODUCTION

At the dawn of the space age, when the Soviet Union sent Sputnik into orbit or when the United States sent their astronauts onto the moon, the world was a much different place and therefore the way we conducted space research, the so called "Space Race" was quite different, too. At these times two things were of importance: national interests and military applications. Since these motivations coincided with the birth of the space technology we are using today and set the standard the way we things are done when accessing space, the resulting space industry targeted itself to these types of applications, government-funded and military-robust. When the first commercial users of space technology wanted to go into space, they had to adopt practices associated with these military-grade satellite systems, in order to not reinvent the wheel. Today, this legacy can still be seen in the aerospace industry, when you consider that most of the standards and testing and qualification requirements come from military sources. Although these standards are still vital for those applications, they make it harder for smaller industries to join using space as a resource

Today more and more disappointed customers of the space industry are confronted with high-cost, long lead components of space systems or big aerospace corporation prices for their satellites and therefore we are seeing the slow but steady emergence of new companies willing to cover this demand for cheaper access to space. What is the key to making the space business for the not-so-fortunate industries and sciences, like agriculture, city planning, oceanography and disaster management, that do not generate the type of income from a satellite that a broadcasting or telecommunications company can generate?

The key is re-standardization and streamlining. We have to standardize the way we access space, how we build satellites and produce in masses for smaller missions. We have to streamline these standards through mass-production and generate more and more similar or identical hardware to bring unit-costs down. We should also generate more and more space hardware using open research institutions and universities to enable the free flow of information and flight hardware to peaceful and scientific missions. Once that is done, we can see that the use of satellites for business will get to be as common as the use of computers. And do not forget that computers were in the same place that the space industry is today. When you look at the quote from the IBM CEO Thomas Watson from 1943 where he says "I think there is a world market for maybe five computers," we can see that many industries have fallen into the same pitfalls, yet later established themselves as industrial and economical strongholds.

2. THE COST OF A SPACE MISSION TODAY

The cost of a space mission today is the sum of many factors. There is the cost for R&D for the non-standard payloads and subsystems, the cost of acquiring the hardware, the integration costs, the cost of the launch system and the cost of operations. In many cases the potential industry customer can control the costs of development, integration and testing yet has almost no control over the cost of operations or launch. These are factors that have spacecraft size, weight and the amount of autonomy of the spacecraft as parameters and can only be made smaller by changing the design of the satellite. In most cases the cost per weight ratio stays the same for the customer. Therefore the first area of improvement is the development and the hardware procurement itself.

3. A STANDARD ARCHITECTURE

3.1 Solutions for Structures

The structures subsystem supports all other spacecraft subsystems and its design must satisfy all strength and stiffness requirements imposed on it. Traditionally, the structures subsystem design process follows the following iterative procedure (Wertz and Larson, 1999):

1. Identify requirements
2. Develop packaging configurations
3. Consider design options
4. Chose test and analysis criteria
5. Size Members
6. Check if requirements are met and iterate as needed

The structure design must account for loads exerted in all mission phases: manufacturing and assembly, transportation and handling, testing, pre-launch, launch and ascent and mission operations. In most cases, the critical loads that drive the primary structure design are those found during the launch phase of the mission:

- Steady-state booster acceleration
- Vibration and acoustic noise during launch and transonic phase
- Vibrations from the propulsion system engines.
- Transient loads during booster ignition and burn-out, vehicle manoeuvres, propellant slosh and stage and payload separation
- Pyrotechnic shock from separation events

For a given set of satellites that have comparable masses, altitude and launch vehicles, the requirements imposed on the structures subsystem are very similar and a set of enveloping conditions and loads can be defined. A standard structure that meets these enveloping requirements can be designed and tested. This structure would incorporate a “best-practice” approach and would also include interfaces to different launch vehicles. The use of such a structure would reduce the number of design iterations needed for the satellite design not only for the structures group, but also for other subsystems. The result would be a reduction in design time and cost. On the flip side, the resulting spacecraft would have a structure that is not optimal for the mission and has more mass than actually needed, leaving less mass for other sub systems.

3.2 Solutions in On-Board Data Handling

In the area of on-board data handling big savings in design can be made. Not only does cheaper hardware lower overall satellite costs, but well-written software and new technologies in computer science and electronics engineering make it possible to operate the spacecraft more autonomously, thus reducing the cost of operations.

First of all, we have to realize that electronically speaking, a satellite is not the most complex system in the world. Actually the amount of work the command system of a satellite has to do given a time frame would not come close to the amount of work done by other commonplace applications, like a game console or a high-end PDA, yet, compared in cost, the systems in satellites are far more expensive than the $200 system sitting right underneath the television.

Terrestrial computer systems and electronics have it easy on our planet. They don’t have to deal with the harsh atmosphere outside of our atmosphere. As a result they are not right out-of the box usable for space programs where radiation, vacuum and atomic oxygen might affect their reliability and life-time. So what is the way to shield our satellite computer against these environmental hazards? In the past, the thing to do was to put a big (huge in satellite terms) heavy shield around the computing system of the satellite and keep the board voltage and the energy density high on the board itself. These measures then quickly contributed to the overall mass of the satellite as well as the power consumption, leading to more solar cells, bigger batteries, more heat and therefore, active thermal management.

Today many other critical industries use a far better approach to the computer systems that are exposed to hazards that can bring down a computer system. The key concept in this particular case is “tolerance” as opposed to “shielding”. It is far easier to build systems today that are tolerant to the effects of the space environment then to shield them completely against these. With just a mere fracture of the weight of a shielding system of the on-board computer system, two more CPUs and two more memory chips can be installed and thus create the ability of an election system where the results of all three systems are compared to each other and if one deviated from the other two, that result being discarded. Such systems are easily implemented and a lot of research has been done in computer science on the area of parallel processing to enable to use of certain algorithms to ensure data quality in case of a single event upset of one of the computers. With the added tolerance the energy volume needed on the printed circuit boards can be reduced thus actually decreasing the overall power usage. This tolerance also can enable the use of more up-to-date computing products cheaply available on the market to be used in spacecrafts and thus alleviate the computing power on-board.

In certain cases there have been also advancements in the suppliers' side of these computing systems. Recently Xilinx Corporation, manufacturer of field-programmable gate arrays, has released their Virtex-II Pro series of FPGA chips, which not only is an FPGA but also a simple PowerPC processor bundled in one chip not much bigger than a thumbnail. These chips enable not only the use of advanced PowerPC processing capabilities in a very small area and with low power consumption, but also give the manufacturer the tool to customize the abilities of a designed and complete on-board computing system for a different mission without having to customize the PCB and its interfaces to the new mission thereby reducing development cost. In the case of Virtex-II Pro, Xilinx must have seen the opportunity to supply the spacecraft industry with the computing system they need, so they actually brought out a version of their system that has been targeted exactly for space applications and is not only flexible like its industrial counterpart but also radiation tolerant.

The second problem of spacecraft computers is the lack of the operator standing nearby. With modern day computers we are all far too familiar with the CTRL+ALT+DEL combination that saves our computer from a lock-up and sometimes and there is no other way of getting that computer running again other than rebooting by flicking the switch. This is a luxury many satellites don't have. The solution again is the use of more than one processing unit. One can monitor the output of the second and should there be more than a glitch in the output of the second CPU the first one can instruct the power subsystem to recycle the power on the first CPU's backbone. This capability, combined with a regular watchdog timer to look for software glitches causing endless loops and an external software patching mechanism to reprogram the CPUs in case a fault is discovered on the on-board computer, would be as reliable as the more than million dollar expensive systems available on the market and can be developed in-house at the satellite building industry or at educational institutions for everyone to use on their satellite.

3.3 Solutions in Communications

Communications is one of the tougher of the systems to simplify and streamline than command and data handling. First of all, the basic laws of communication have not changed and laws of physics governing losses over distances will stay the same regardless of technological advances as long as we continue using RF links to transmit information. This does not mean however that simplifications can not be achieved or technological advances in other areas can not be put to use in communications subsystems. In the modern wireless world, power and space usage in RF link transceivers have been optimized and advances have been made in employing higher frequency data carriers that enable the use of smaller antennas. The use of wireless communication for voice and digital data has made many advances in terms of algorithms for error correction and data encryption and brought out commercial digital communication devices that would have taken years to produce for one small satellite system.

Today, one can buy a wireless transceiver for as little as $700 from Microhard Corporation with output power as much as 1W, and with the proper authorization these devices can be modified to have even more output power and gain antennas can be used to deliver much better link margin results. Most of these devices will come with all the extra features that sometimes even the really expensive data transmission devices from aerospace companies will not offer. In case of the $700 Microhard radio you will get data encryption, multi point networked communication and relay capabilities, and error correction built-in right into the system. And with 2.4 GHz or 900 MHz frequency allocations these devices require much smaller antennas then their lower frequency counterparts. In addition these devices, not even 6cm wide and 9.5 cm long and 2.5 cm high, take up almost no space in a satellite. Most of these devices are transparent to the command and data handling system and can be hooked up to any serial port of the command system of the satellite and treated no different than transferring data between your computer and your PDA.

Miniaturization through newer advances in communications technology have yielded smaller and smaller patch antennas that not only are less massive and do not require big and expensive deploy mechanisms, but also provide better gains. They probably do not have enough high-bandwidth to provide communication capabilities for bigger links; however they can be used for telemetry and housekeeping antennas. In regard to the payload, a bigger antenna might be selected for the larger payload data generated. The receiving antennas for these smaller patch antennas can be made to be higher gain antennas with the appropriate authorization from the ITU and its national subsidiaries and whatever is lost in power dissipation on the spacecraft through miniaturization can be compensated for in the ground.

3.4 Solutions in Power Systems

Power systems are still considered to be one of the bigger parts of a satellite in terms of mass and thermal requirement generators. Not only are the batteries bulky and heavy but they also require a narrower range in temperature to operate efficiently. Most of the satellite surface is devoted to solar cells and when that surface is not enough today's satellites have to rely on heavy mechanical systems to deploy their solar arrays. In this respect smaller satellites have an advantage over larger ones: when scaling down a satellite, the ratio of projected area to inner volume is much increased and since the power consumption of the electronics remains proportional to their mass and volume the power generation needs of smaller satellites can be generally satisfied without the need of deployable solar cells (Wertz and Larson, 1999).

Some progress has been made to achieve higher power densities in batteries enabling them to store more in less space and weight. The following table gives a good estimate on how some of the newer technologies like lithium-ion and nickel-hydrogen batteries compare to the older systems.

Type	Wh/kg	Wh/l	Voltage	Cycle Life
Lead-acid	35	80	2	400
Nickel-Cadmium	35	80	1.2	>1000

Nickel-Hydrogen	55	60	1.2	>10000
Li-Ion	150	300	>3.6	>2000

Table 1. Different battery technology capacities

We can clearly see that using the Li-Ion batteries a program can save quite a lot on the mass and volume properties of a satellite. In the early days of the Li-Ion development, these batteries were considered a risk and had not been tested in flight conditions. Also since their recharge and power consumption requirements were quite strict, designer tended to shy away from the use of Li-Ion cells for development. But with the extended use of the Li-Ion type batteries and the development of monitor and charge electronics, assembling a battery usage circuit has become significantly easier. Today a cell phone battery, which uses prismatic cell structures, can power a store-and-dump type of satellite almost through its whole life cycle.

There have also been some breakthroughs in solar cell efficiency. Through the introduction of multiple junction cells like triple junction solar cells, efficiencies of up to 27.5% have been achieved.

Yet besides these innovations and breakthroughs in solar cell and battery technology, the power subsystem is a very tricky area, still filled with areas of "black magic." Designs with improvements in these areas come rather from the industry than educational or non-profit institutions and therefore the price is set by these companies. The price of this subsystem can not be brought down just through an initiative by universities by building such hardware in-house and free flow of information. The end users and research institutions have to be innovative when getting the required solar cells and batteries. In many cases the aerospace-rated batteries have a terrestrial application counterpart; by thoroughly testing these in vacuum and thermal chambers some of these terrestrial batteries can be used on space missions. For the acquisition of solar cells, institutions can contact solar cell manufacturers for "reject" high-grade cells that have not met very strict constraints but still are efficient enough for small programs.

Of course, the best design strategy in building a small power subsystem is to bring down the power consumption of other subsystems as well as to keep the number of voltage levels required by the whole satellite to a minimum. This can be achieved by having a technology comparison meeting at the start of the project and deciding on components for each subsystem that require as little power as possible but also share a common supply voltage. This way the amount of bulky DC-DC converters on board can be kept to a minimum, which also keeps the thermal household more stable.

3.5 Solutions in Mission Operations

Mission operations, although neglected in many small satellite development projects, is one of the bigger contributors to the overall mission cost of a project. Mostly, ground stations do not come cheap and the amount of coverage one can get out of only one ground station is so limited that the satellite has to incorporate means to store and transfer larger amounts of data, which transfers to the project as added communication and command and data handling costs. However, mission operations is also a field where cooperation can be easily achieved and major cost savings can be accomplished.

However, the first initiative before achieving cooperation between institutions and countries is to establish communications hardware standards. The reason for establishing such standards is more to establish frequency and networking standards rather than to provide a shorter list of communications equipment. The goal is to make every ground-station capable of establishing a link with any satellite and through the use of the internet, route the data to the end user without having to reconfigure the ground station's hardware or software.

To accomplish the use of multiple ground stations by multiple users, a network of ground stations can be connected to a resource manager website, where the operators of the satellites have individual accounts. Through this website the operators can enter in their orbital parameters and desired contact times. Then the resource manager can allocate ground station time based on these parameters, as well as other parameters such as the occurrence of a critical event in orbit, satellite status (Nominal, Safe mode, Deployment) and also fairness. In this manner, a true world-wide ground station network can be established and become greater than the sum of its parts.

Through the use of TCP/IP for communication, not only between the ground stations but also between the spacecraft and the ground station, the hardware and maintenance costs of ground stations can be minimized since there are widely available TCP/IP hardware and software solutions.

3.6 Solutions in Software

Software is one of the first areas where projects today can and are saving money since the development of software requires less expensive hardware than the other subsystems and is only intensive in labor which many research institutes and schools can provide easily in form of research assistants and students.

This does not mean, however, that software comes completely free and one can not accomplish cost savings in that field. Today many satellites run on either commercial real-time operating systems or custom written firmware. The wide-spread use of embedded linux applications has brought a new possibility for the satellite designer. This new operating possibility is not only completely free, but also comes with a big community of software developers and libraries that can be employed when putting together the software for the spacecraft. These systems similarity with desktop linux systems also means that software developers will be in known territory, programming with a system familiar to them which in turn reduces development times.

The use of TCP/IP in the communication scheme between ground station and spacecraft, as suggested earlier, also has the added benefit of minimizing the required software development. Once the driver has been written to put TCP/IP on the physical communication link between the satellite and the ground-station, the rest of the software is a trivial piece that has already been solved and the communication between the two nodes is not much different than bringing up a website on your home computer. In case of our suggested communication hardware, the Microhard MHX, this driver could easily be found for the device and embedded linux.

3.7 Solutions in Payload Integration

The payload in a satellite is the combination of hardware and software that is there specifically for the purpose of accomplishing the mission. Payloads are the reason that missions are flown in the first place and are typically unique to each mission. The purpose of the rest of the spacecraft, known as the spacecraft bus, is to accommodate the payloads and keep it operating within requirements.

The interface between spacecraft bus and payload is usually a source of considerable costs, since it involves requirements from several subsystems. For example, the structures subsystem is typically concerned with the mechanical attachments and load transfer from payload to bus, the electrical power system is concerned with the payload’s power consumption and the C&DH subsystem is concerned with flow of information between bus and spacecraft.

As suggested previously, the development of a standard structure can bring added benefits outside the structures subsystem proper. A standard structure can lead to a standard interface between bus and payload that incorporates mechanical, electrical, and thermal and data needs into a ready-to-use solution that fits most missions.

As an example, we examine the CubeSat program. Developed jointly between the California Polytechnic State University San Luis Obispo and Stanford University’s Space Systems Development Laboratory, the CubeSat program sets standards for pico satellites in terms of size, volume, mass, shape and the interface to the orbital deployer they are launched from (called the P-POD). Since the P-POD can accommodate three CubeSats stacked on top of each other, there are some missions that have taken advantage of this and built satellites that use the space of two or three CubeSats. Taking this concept a little bit further, it is conceivable to create a standard way for CubeSats to interface with each other, so that one CubeSat becomes the bus and another the payload in a given mission. The result would potentially make CubeSats even more popular, making it easier for different groups to cooperate on projects.

A similar idea can be scaled for use in small satellites but not quite as small as CubeSats. Creating a standard structure, with a standard interface between payload and bus can bring enormous savings, promote the cooperation between different organizations and even the creation of a commercial niche for standard spacecraft buses and payloads that can “plug and play” with each other, in the same fashion as PC components are mixed and matched today.

4. THE COST OF LAUNCH

The cost of a space mission lies not only in the building and the operation phase only though. For one part of the mission every small satellite builder has to go to a bigger company and that is the launch vehicle that will deliver the finished satellite into orbit. Right now there are not that many launch vehicle companies in the world and most of the launches are quite expensive for the small satellite industry. Most of these launchers employ complex systems and are based on heritage technology and require complex procedures to build, maintain and operate which keeps the overall cost per weight ratio very high.

February small satellites were dealt another blow when the loss of the space shuttle Columbia and immediate grounding of the remaining fleet put at least a temporary end to free rides for even the smallest hitchhiker payloads.

Yet even in the launcher business there have been some improvements over the last couple of years which the satellite industry can count on for the future. One of the mainstays of the small launch business is Orbital Sciences Corp.'s Pegasus rocket. At prices of $15 million and up, the Pegasus is often beyond the reach of experimenters with satellites for small institutions, yet still can be of use for slightly larger projects. The European Space Agency plans to spend more than 300 million euros on the development of the Vega small-satellite launcher. The development is being led by ELV, a joint venture of FiatAvio of Colleferro, Italy, and the Italian Space Agency.

The three-stage rocket will be operated from Guiana Space Center in Kourou, French Guiana, beginning in 2006 and will be capable of placing a 1,500-kilogram satellite into a 700-kilometer low Earth orbit.

But the real news is coming from new entrepreneurial companies opening up in this new business. SpaceX, an El Segundo, California-based small company of approximately 50 engineers, where the author is also working, is about to finish their first launcher, the Falcon-I, to be placed in service later this year. The company, founded by Elon Musk, a 32-year old serial-entrepreneur who made his fortune on the Internet, looks forward to offering 450kg LEO launches for no more than $6 million followed by a medium-sized launcher the Falcon-V, which will deliver up to 9200 pounds to LEO with a fairing diameter of 4 meters. This vehicle will be also capable of launching missions to geostationary orbits and the inner solar system or carring supplies to the ISS with the addition of a lightweight automated transfer vehicle. With a successful launch, SpaceX could be providing 10 times the cost efficiency to the customers of its rockets.

Yet SpaceX is not the only company to enter this new business. Microcosm Inc., of El Segundo, California also is seeking to enter the small launch market. Robert Conger, Microcosm's executive vice president, said the company's proposed Sprite Small Expendable Launch Vehicle would carry 700 pounds to orbit for $2.5 million. Development of Sprite, however, is on hold until Microcosm secures government funding.

In the meantime, other private efforts, while not aimed explicitly at the small satellite market, could be a boon for small satellite proponents. Two dozen private ventures have emerged to compete for a $10 million purse put up by the St. Louis-based X-Prize foundation, to be awarded to the first team to build a piloted vehicle and complete two suborbital flights within two weeks.

X Prize Chairman Peter Diamandis said that while the primary market for the suborbital spacecraft is tourism, some X Prize contestants see an opportunity to launch small satellites with their vehicles. Any development that promises to change launch economics would be a positive development for the small satellite community, according to Futron's Thrash.

5. CONCLUSIONS

Streamlining a design is a process that involves many bold steps. A designer, a committee or an organization that takes such steps should do so with great care. When setting standards, one can easily set them in such a way that eliminates innovation for the next generations and prevents the use of many devices in future projects. In this sense, the standards can have the opposite effect of what is wanted and should be set with great care. Today’s standards could become the legacy systems of tomorrow.

Keeping these potential pitfalls in mind, we think that universities and research institutions are less likely to fall into these traps, since these organizations have a constant supply of new minds and ideas to keep older systems from getting anchored in the system too deeply.

However, in order for standard to be useful, they have to be accepted widely and incorporated into everyday use. The future of the space industry is surely being shaped by the decisions and actions taken today. Cooperation between government, educational organizations and industry can bring about a revolution in the space industry and make affordable, short time-to-space spacecraft a reality in the near future.

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