DESIGN TO COST METHODS TO LOWER THE AVIONICS COST FOR NASA COMMERCIAL CREW EFFORTS

S85-2010-5000-0802-006-1.0

Mitch Fletcher[1]
Honeywell International, DSES - Human Space, Aerospace, Glendale, AZ, 85308

Over the past decade, as a leading avionics supplier, Honeywell has been investigating novel ways to reduce the acquisition and life cycle costs of equipment while simultaneously improving the quality and performance of avionics systems for the NASA manned spaceflight missions. The initial results of these studies was a space rated derivation of a commercial avionics system used in the Boeing 787 aircraft that was first proposed to NASA as a TA-3 response to the Space Launch Initiative. Over the past year, due to the results of the Augustine Commission and the subsequent release of the President's 2011 budget request for NASA, the importance of commercialization of launch services to Low Earth Orbit (LEO) has increased. Honeywell has long been a provider to the commercial space market (e.g. Atlas Launch Systems, Direct TV, cell phone constellations, etc.) of commercial space equipment. Even though this is for the commercial space market, the requirement on these devices has often exceeded NASA requirements (for example, the part derating requirements of MIL-STD-1547 are more stringent than the NASA MIL-STD-975 requirements). Commercial satellites requirements remain high because they are insured by Lloyd's of London. Even with these high reliability and harsh radiation requirements, Honeywell design to cost efforts has resulted in a reduction of reaction wheel pricing. We now offer our product for ¼ the past price 15 years ago. As part of the Commercial Crew Launch Efforts, Honeywell has a wide range of experience that will allow solutions ranging from vibration isolation of low cost Off the Shelf (OTS) commercial aircraft avionics to full Fail-Op Fail-Op systems such as the original avionics proposed for Orion. This paper will discuss several methods for implementation of avionics for Commercial Crew missions, both in the crew capsule and the launch vehicle and the design to cost methods allowing these avionics to meet the reduced pricing that the commercial satellite industry has enjoyed for the last decade.

Nomenclature

SLI = Space Launch Initiative
RLV = Reusable Launch Vehicle
OSP = Orbital Space Plane
ISS = International Space Station
LEO = Low-Earth Orbit
ISHM = Integrated System Health Management
I/CSCS = Integrated Cost Schedule Control System
DODAF = Department of Defense Architectural Framework
CMMI = Capability Maturity Model Integration
SSPP = Standard Space Parts Program
OTS = Off the Shelf
FOM = Figures of Merit
SWaP = Size, Weight, and Power
IMA = Integrated Modular Avionics
LET = Linear Energy Transfer

---

[1] Chief Engineer, Electronic System Engr & Apps, 19019 N. 59th Ave./2S12, AIAA Senior Member.

I. Introduction

OVER the past decade, as a leading avionics supplier, Honeywell has been investigating novel ways to reduce the acquisition and life cycle costs of equipment while simultaneously improving the quality and performance of avionics systems for the NASA manned spaceflight mission. This has been stimulated by the NASA desire to replace and/or supplement the Space Shuttle. These efforts started in earnest with the VentureStar development and its 1/3 scale prototype, the X-33 with the NASA selection of Lockheed Martin Skunk Works in July of 1996. The next step in NASA's evolution was the Space Launch Initiative (SLI). According to Art Stephenson, director of NASA's Marshall Space Flight Center, Huntsville, Ala., "The Space Launch Initiative [was] a comprehensive R&D effort that provides technology developments that dramatically increase the safety, reliability and affordability of space transportation systems. Through [the SLI] initiative, NASA's mission requirements will be met more efficiently, the US launch industry can better compete in the international launch market, and our nation's leadership in space will continue to grow in the new century." The strategic goals of SLI were to develop concepts and the technologies to allow creation of a next-generation Reusable Launch Vehicle (RLV). One of the goals of this RLV was to reduce the cost of delivering payloads to low-Earth orbit to less than $1,000 per pound. In addition the RLV would be designed such to reduce the risk of loss of crew to approximately 1 in 10,000 missions. The leap-ahead technologies envisioned included crew survival systems, advanced fuel tanks and airframe structures, long-life rocket engines, and thermal protection systems. In early 2003, the NASA refined their vision and funding to better support the SLI vision as shown in Figure 1. As part of this change, the broad SLI was split to focus on both short term and long-term solutions. The short-term solution became known as the Orbital Space Plane (OSP) concept. The OSP was to focus on a system capable of providing crew rescue from the International Space Station (ISS) as early as 2008 and crew transfer in the 2010 time frame.

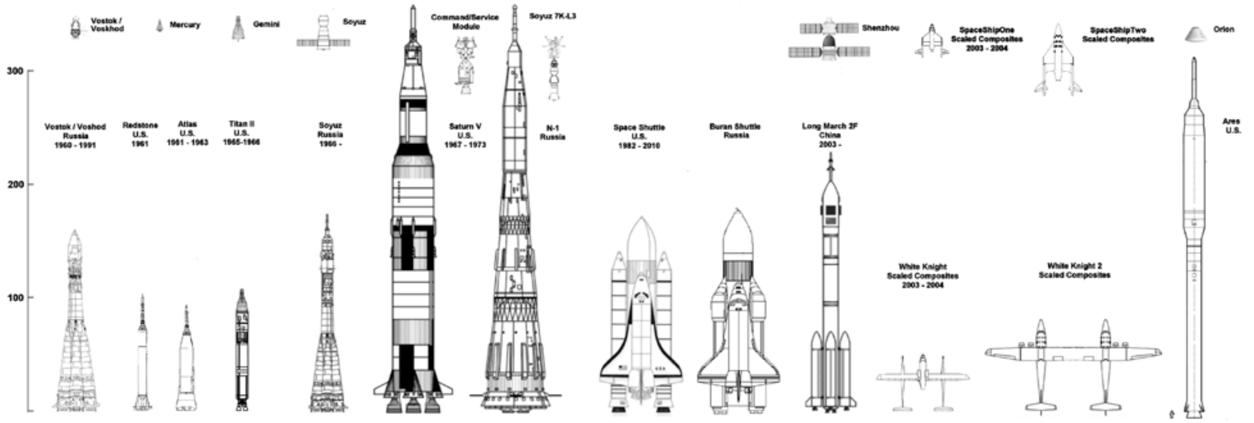
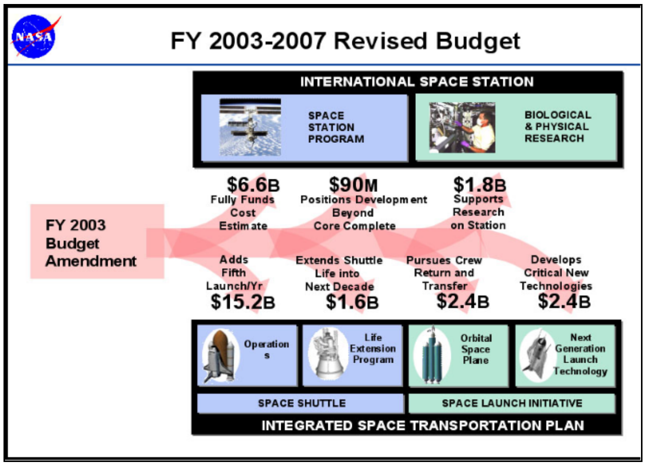


Figure 1. Scaled comparison of manned spacecraft[1]. *The Human Space community has created a large number of launch vehicles and crew vehicles over the years. In addition to the vehicles shown that have human space flight operational hours, there have been many false start vehicles including the X-20 Dyna-Soar, VentureStar (and its 1/3 scale prototype X-33), the X-37 Spaceplane, the X-38 Crew Return Vehicle, and the Orbital Space Plane.*



FY 2003-2007 Revised Budget

INTERNATIONAL SPACE STATION

SPACE STATION PROGRAM

BIOLOGICAL & PHYSICAL RESEARCH

FY 2003 Budget Amendment

$6.6B Fully Funds Cost Estimate

$90M Positions Development Beyond Core Complete

$1.8B Supports Research on Station

Adds Fifth Launch/Yr $15.2B

Extends Shuttle Life into Next Decade $1.6B

Pursues Crew Return and Transfer $2.4B

Develops Critical New Technologies $2.4B

Operations

Life Extension Program

Orbital Space Plane

Next Generation Launch Technology

SPACE SHUTTLE

SPACE LAUNCH INITIATIVE

INTEGRATED SPACE TRANSPORTATION PLAN

Figure 2. NASA Five Year Budget. *The Space Launch Initiative became focused with administrator O'Keefe's vision of an Orbital Space Plane and the five year budget to support its development.*

The Space Shuttle Columbia accident caused the administration to reconsider the aging Shuttle and thus added a new focus to the progression of crew vehicles. On January 14, 2004, President Bush announced a new vision for space exploration. The vision focused upon safety first with a reduced emphasis on mission cost. The Exploration Vision focus was also on a focused mission goal of returning to the moon and exploring Mars and beyond. Cost reduction was outlined by the Exploration Systems Architecture Study through a mission design model by implementing a simple and safe human launch vehicle utilizing a single four stage solid rocket booster with a single liquid engine upper stage later named the ARES I vehicle. This policy presented three goals:

- Complete the International Space Station by 2010 and focus our future research aboard the station on the long-term effects of space travel on human biology.
- Develop and test a new spacecraft, the Crew Exploration Vehicle, by 2008, and to conduct the first manned mission no later than 2014.
- Return to the moon by 2020, as the launching point for missions beyond.

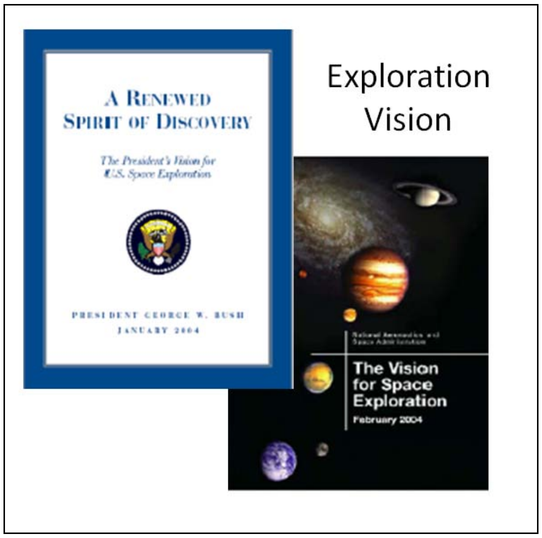
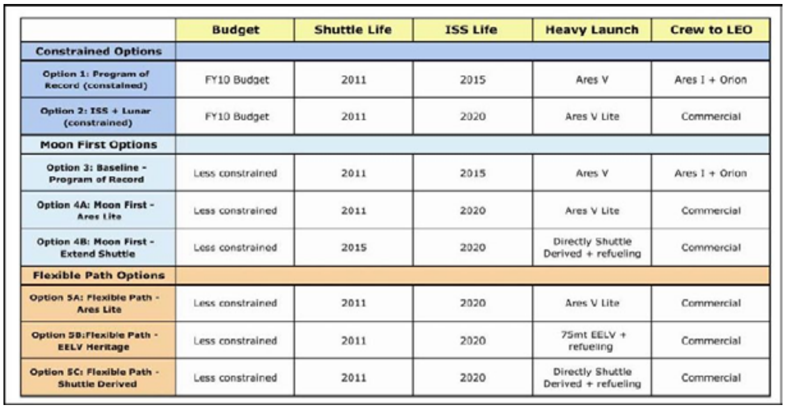


Figure 3. President Bush's Space Exploration Vision. *The Space Exploration Vision took away the previous 20 years of focus on creating a low cost launch capability and replaced it with an "Apollo Style" focused mission.*

Included within these goals are the retirement of the Space Shuttle Fleet at the end of ISS complete and a series of robotic missions to the lunar surface, starting no later than 2008, to research and prepare for future human exploration. The ultimate goal of the new vision is to embark on human missions to Mars and to worlds beyond. The complete vision was summarized on a White House policy directive shown in Figure 2.

The latest evolution in the architecture of a national space policy started with the Augustine Commission. Today, budget questions continue to dominate the human spaceflight debate. In the 37 years since humans last ventured beyond Low-Earth Orbit (LEO), and five years after announcement of the Vision for Space Exploration, consensus is still lacking about what is feasible and affordable in the future course of U.S. human spaceflight. This review of the Constellation Program concluded that any human exploration beyond low-Earth orbit is not viable with the money NASA is expected to receive under the budget for 2010 and beyond. The Committee developed five alternatives for the Human Spaceflight Program. In reviewing these, it found:

- Human exploration beyond low-Earth orbit is not viable under the FY 2010 budget guideline.
- Meaningful human exploration is possible under a less-constrained budget, ramping up to approximately $3 billion per year in real purchasing power above the FY 2010 guidance in total resources.
- Funding at the increased level would allow either an exploration program to explore the Moon First or one that follows a Flexible Path of exploration. Either could produce results in a reasonable timeframe.



	Budget	Shuttle Life	ISS Life	Heavy Launch	Crew to LEO
Constrained Options					
Option 1: Program of Record (constained)	FY10 Budget	2011	2015	Ares V	Ares I + Orion
Option 2: ISS + Lunar (constrained)	FY10 Budget	2011	2020	Ares V Lite	Commercial
Moon First Options					
Option 3: Baseline - Program of Record	Less constrained	2011	2015	Ares V	Ares I + Orion
Option 4A: Moon First - Ares Lite	Less constrained	2011	2020	Ares V Lite	Commercial
Option 4B: Moon First - Extend Shuttle	Less constrained	2015	2020	Directly Shuttle Derived + refueling	Commercial
Flexible Path Options					
Option 5A: Flexible Path - Ares Lite	Less constrained	2011	2020	Ares V Lite	Commercial
Option 5B:Flexible Path - EELV Heritage	Less constrained	2011	2020	75mt EELV + refueling	Commercial
Option 5C: Flexible Path - Shuttle Derived	Less constrained	2011	2020	Directly Shuttle Derived + refueling	Commercial

Figure 4. Augustine Commission Recommendations. *One of the Augustine Commission recommendations was to create a Commercial "Crew to LEO" option in order to reduce costs and to let NASA focus on technology and exploration beyond earth orbit.*

In response to the Augustine Commission report, the administration released their 2011 five year budget recommendation. This budget focused on Commercial Crew to LEO and NASA technology development. Because this budget included the cancellation of the Constellation Program, it was met with fierce opposition by both houses of Congress. Currently an apparent compromise between the administrations' budget and the congressional authorization bills maintains the Orion capsule, Heavy Lift capability from the Constellation Program, and adds the Commercial Crew to LEO outlined by the Augustine Commission. This continues to warrant the design and implementation of low cost avionics; in fact, more than ever because there is both a commercial implementation and a NASA implementation to be considered.

Throughout all this evolution of the NASA space human rated crew vision, one requirement has remained constant, the need for a flexible and re-configurable computing platform to host, control, and manage the systems that will enable the envisioned missions. The need for flexible and re-configurable avionics is a key element to keep both the initial acquisition costs and the life cycle costs minimized in order to avoid a future finding that the next steps are unaffordable.

Honeywell has provided long-standing support to NASA for Human-rated systems, which started with the Mercury program and continued through our major avionics role on the Space Transportation System, International Space Station Programs, and the Orion capsule. This progression of avionics started with the Shuttle design studies, the Space Station architecture, Shuttle Upgrades, throughout the SLI TA-3 Avionics architecture study proposal. Honeywell has completed studies ranging from early OSP studies through Orion architecture design, Altair LDAC-1 avionics evaluation, and the Lunar Surface System avionics study. In fact, Honeywell has completed commercial airplane to Human-rated avionics transitions for both the Shuttle Multifunction Electronic Display System (derived from the 777-cockpit display system) and the transition of the 787-flight computer to the Orion vehicle management computer. In addition, Honeywell is the world's leading commercial aircraft avionics provider which has been leveraged to evaluate avionics architecture and make recommendations to NASA and prime contractors for the implementation of high quality, Human-rated, low cost, Commercial Crew avionics options.

Throughout the evolution from SLI to project Constellation, the need for a computing platform has evolved from simple vehicle level avionics control to a system of systems control architecture for both transportation and habitats. The initial goals of a flexible, expandable, and easy to re-configure electronics system have only grown in importance. In addition to simple vehicle control, the computing platform must now host autonomous operation, enable system level operational reconfiguration, and support a higher level of Integrated System Health Management (ISHM). Due to longer mission times, all of these functions must be hosted with an ever-increasing demand for a composite of integrity and availability. Even with this additional functionality, the initial cost to implement, and the cost of ownership for the computing platform, must remain affordable. In fact, the cost of the computing platform, including hardware and software must be drastically reduced from the costs incurred by the Space Shuttle and ISS programs.

II. Commercial Space

In addition to the over forty years of NASA human rated flight avionics experience, Honeywell has been a provider of navigation sensors and effectors and avionics solutions to the commercial market since its inception. Honeywell has been a provider of systems in the Atlas commercial launch booster, most direct TV satellites, and throughout the Iridium satellite constellation as noted in the purple branch of the Honeywell space flight heritage tree (see Figure 5). Over 80% of all Honeywell Reaction Wheels are sold to the commercial market and have over 80 Million hours of operation. No Honeywell commercial product (in fact no space product) has been the cause of a mission to be terminated early.

Even though the products shown in Figure 5 below are produced for the commercial space market, the requirements imposed on these devices have often exceeded NASA requirements. For example, the part de-rating requirements of MIL-STD-1547 are more stringent than the NASA MIL-STD-975 requirements. The required qualification level operational junction temperatures of the integrated circuits are limited to 105ºC in MIL-STD-1547 while MIL-STD-975 allows junction temperatures of up to 125ºC for similar devices. Parts requirements, radiation test requirements, material certifications and mechanical fatigue margin factors are all similar for the commercial market deliveries as they are for the NASA market. This leads to several questions relating to the Commercial Crew implementation that is currently on the proposed NASA policy path.

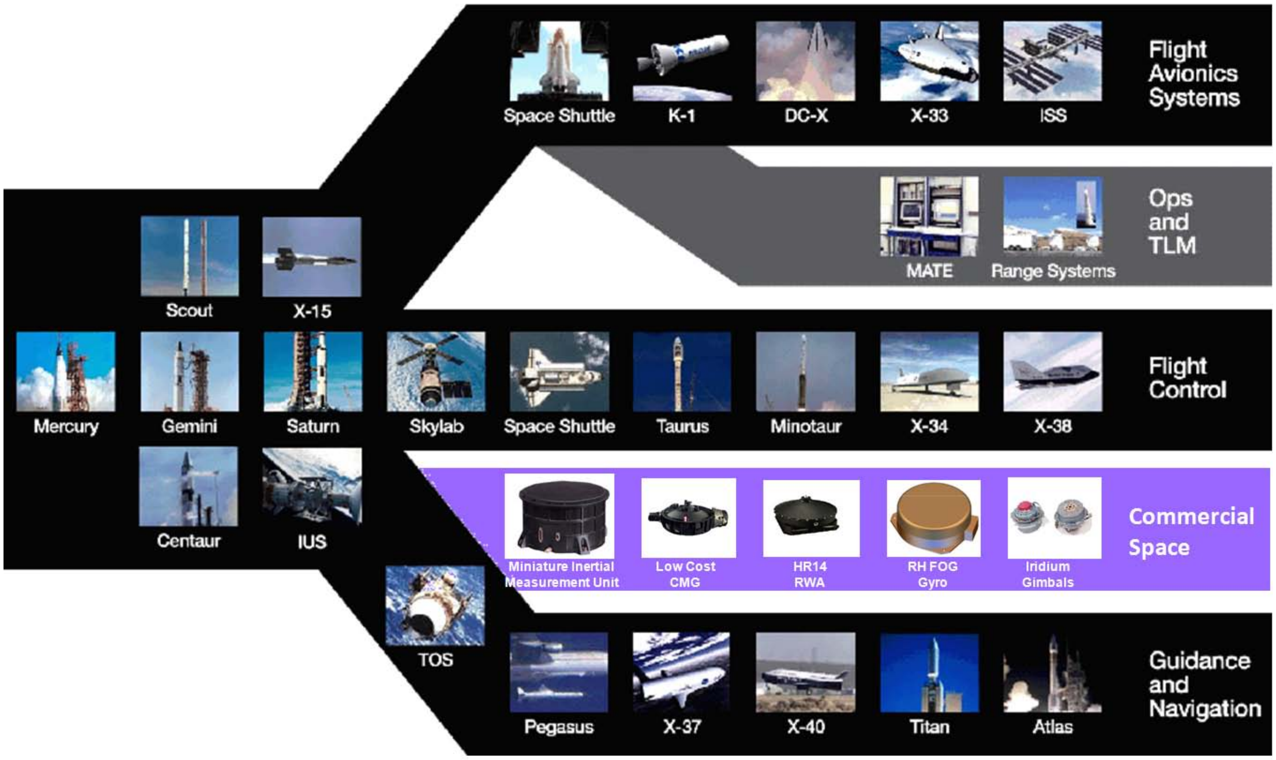


Figure 5. Honeywell Space Flight Heritage. *Honeywell has over four decades of supplying high quality, low cost products to the commercial space market. Over 80% of all Honeywell Reaction Wheels are sold to the commercial market and have over 80 Million hours of operation. No Honeywell commercial product, NASA, or DOD has been the cause of a mission to be terminated early.*

The questions raised by this perceived requirements parity are:

- Why are the requirements for commercial space products the same or more stringent than NASA human space requirements?
- Why do commercial satellites cost less than their government counterparts?
- Is the acquisition cost of commercial satellite components really less than government satellites?
- How do commercial suppliers keep their prices down?

There are some factual answers to these questions and some speculation. As to the speculation; the probability of success of any mission is controlled by the mean time between failures of the components within that satellite. If requirements are relaxed (lower quality parts, minimized design margins, low sigma design margins, etc.) it is obvious that the lambda of the system would increase resulting in a lower probability of success. A shorter mission life or a loss of mission would be a cost either to the prime contractor or to the insurer. In fact, Lloyd's of London is a driving reason for some requirements levied on commercial satellites. As to the acquisition cost of satellite components; Honeywell sells components to the government at the best price available; however, the government very rarely will purchase a catalog item for space. This results in commercial items costing less because commercial satellites do not always require the absolute OPTIMUM technical solution and can settle for the lower cost catalog item. In addition, catalog items have the advantage of “economy of scale” and can leverage lot buys and sales stock items to decrease cost.

Another method for commercial suppliers to keep their costs down in commercial pricing. In a commercial pricing model, the development of a product is done using the supplier’s investment capital. The price is the fabrication cost of an item plus the amortized development cost spread out over the anticipated number of units to be delivered. Because a supplier can sell the same catalog item to various prime contractors, this amortized cost can be low compared to the NRE cost associated with a one-off design.

Because there is significant savings associated with larger quantities of deliverables, commercial suppliers will do lifecycle cost trades to optimize cost amortized over deliveries to several customers. As NASA implements a commercial crew program, it will be important to develop a flight schedule that allows the industry to make these types of trades to gain the cost benefits that are anticipated. NASA will not see the anticipated cost savings if the assumption is that savings will be because the existing prime contractors have inefficient bloated execution systems. If fact the existing prime contractors have years of lessons learned that should make them more efficient on the whole than the new upstart companies. In fact, the continuous improvement design to cost efforts programs at Honeywell, while addressing these high reliability and harsh radiation requirements, have resulted in a reduction of reaction wheel pricing. We now offer our product for ¼ the past price 15 years ago.

The last element that improves cost performance is the commercial model itself. While any good company implements an earned value system for both fixed price and cost type jobs, the level of reporting can be tailored for a catalog price item to concentrate on performance-based metrics. When Integrated Cost Schedule Control System (I/CSCS) is implemented in government contraction, the procurement office does a blanket level of reporting. A tailored approach can result in cost improvement.

III. Cost Drivers; Anti design to cost

NASA is currently in the process of developing requirements for the commercial crew architecture implementation. As part of this effort, NASA has issued document CCT-1001 (CHRP) and through Request for Information NNH10ZTT005L asked for industry its evaluation of this document. This document contains a mixture of architecture, requirements, and oversight. While these are all important, it is Honeywell's experience that the amount of oversight and allowing the efficiencies of the internal processes are the primary cost drivers in delivery of space rated equipment for the commercial satellite market. NASA has recognized this and recently released a white paper documenting these findings. The paper concludes with recommendations for implementation of crew safety requirements.

According to NASA 469245, Government Insight/Oversight for Commercial Crew Transportation[3]; Projects will utilize tailored versions of the NASA governance (e.g. NPRs 1000.1, 7120.5 & 7123.1) as key tenets in the design, development, test and operations of commercial crew vehicles. These policies, once tailored, have provided an effective and successful process for maximizing programmatic and technical success of programs and projects through their full lifecycle. They have successfully supported the full spectrum of vehicle developments, from simple, inexpensive robotic spacecraft to complex human spaceflight vehicles. This is accomplished through judicious tailoring of the requirements, to support the specific vehicle development and the insight/oversight model proposed. This also includes the plan to perform key milestone reviews (SRR, PDR, CDR, mate review, etc) and the method used to independently review and critique the system at these milestones.

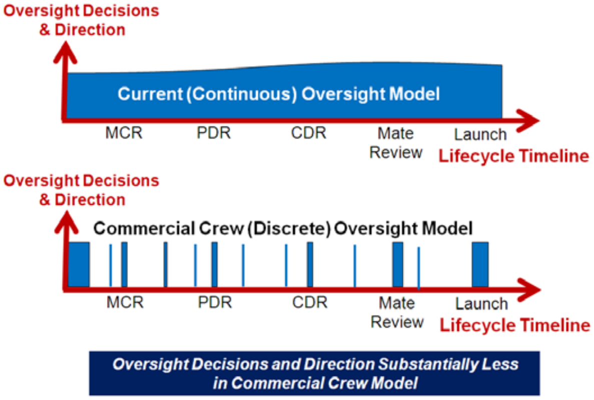


Figure 6. Government Oversight Models. *A recent release of a NASA evaluation of government oversight has just been released for public review. The document presents NASA insight into the intended level of government insight and will be a key component in evaluation the cost of future NASA Commercial Crew vehicle costs.*

Honeywell has over four decades of delivering architecture, systems, and components for human rated vehicles, military satellites, and commercial satellites. In addition to this, Honeywell has the same level of experience with architecture, design, and delivery for commercial airplanes, ranging from the largest wide bodies to the smallest personal jets. From this, Honeywell has lessons learned regarding design oversight that will continue to be drivers. Some of these cost drivers, but not all have been captured in the following paragraphs.

A. Requirements Churn

Among one of the most expensive elements of a development program (NASA or Commercial Airline) is requirements churn and requirements creep. Both commercial and military industry have developed and refined detailed Architectural Framework (AF) processes to help control this phenomena. The most recent generation of AF is the Department of Defense Architectural Framework (DODAF). The NASA System Engineering process as documented in NASA/SP-2007-6105 (Section 4.3) is based on DODAF and is recommended as a control model for system engineering development if the supplier does not already have an institutionalized architectural framework process.

Once implemented, a rigorous management of this AF process is necessary to assure highest reliability, lowest cost, and shortest schedule. To control creep and churn, it is necessary to assure that any physical or architectural “requirement” be traced and validated as necessary to implement an necessary “function” of the commercial crew vehicle. It is also necessary to verify and validate that any function is require by an operational requirement. Failure to do so results in creeping elegance and the inclusion of many “requirements” that are actually wants and not needs of the implementing staff (both NASA and commercial implementer).

Another benefit of adhering to a rigorous Architectural Framework process is within the framework of a CMMI process, this will allow for better planning of engineering skill set mix throughout the program. The AF process will identify the need for system engineers’ decomposition of functional requirements in the first stages of the program. The need for detailed hardware and software architects will be identified in the later stage of requirements development and program deployment. This careful process will limit the want to place the “marching army” on the development program from day one.

B. Corporate Tools and Process

Corporate America has invested heavily in the last ten years in process improvements designed to improve productivity and quality performance. These programs have included Total Quality Improvement, Malcolm Baldrige, Six Sigma, and Velocity Product Development. Foremost among these improvements has been the implementation of Capability Maturity Model Integration (CMMI) for development (software and system engineering). These programs have been implemented using best practices benchmarked from both internal and external sources. To achieve a CMMI level 5 certification, a company needs to demonstrate continues improvement.

While the NASA processes are well proven by many years of experience, they are not always the exact process that industry has incorporated into their CMMI process models. It is a large impact and a significant cost and schedule driver to replace existing corporate processes with NASA processes. When a Commercial Crew provider and/or their sub-tier teammates and suppliers have reached CMMI level 3 or higher certification, it is recommended that the NASA along with the Commercial Crew provider evaluate these processes and incorporate those that meet the intent of the NASA requirements. NASA benefits by incorporation of industry best practices that meet the intent of the NASA documents and the improved cost and schedule benefits of the continued improvement associated with a CMMI process model.

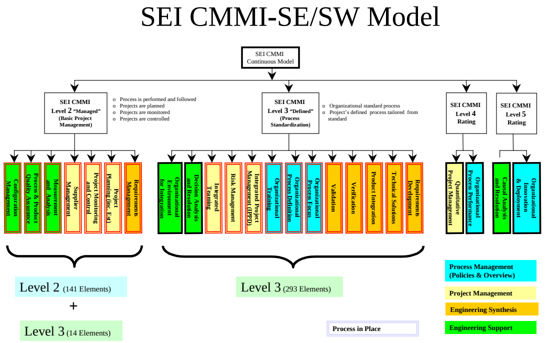


Figure 7. Honeywell CMMI Model. *Honeywell internal engineering process applies the discipline of its existing CMMI tailored to the new NASA architecture framework process to assure success in the architecture synthesis.*

As an example of this, Honeywell has studied and implemented an Engineering Process Model for both System Engineering and Software development. In considering architectural options, Honeywell will draws upon our domain avionics architecture experience gained through the programs referenced previously herein. Honeywell analyzes Avionic Subsystem Architecture needs, including design to cost elements, using processes from our CMMI process model (see Figure 7) as tailored to align with the newly released NASA system engineering process. To be cost effective, Honeywell must be allowed to trade and evaluate advanced avionics concepts for use in the next generation human rated commercial crew space vehicle. We draw on experience from other similar systems, such as the Boeing 777, Boeing 787 Flight Controls, and Orion along with legacy implementations from other avionics suppliers to recommend architectural concepts for the Commercial Crew Subsystem Architecture.

Under guidance of the CMMI Process Model, synthesis of the architectural concepts are optimized by a solution subset of the CMMI process that Honeywell refers to as the 3-View Systems approach as tailored to conform to the newly released NASA architecture framework. Honeywell's 3-View approach is a derivation of the government C4ISR and DODAF processes for system engineering. Use of the 3-View systems approach will provide for a design to cost optimized offering for Commercial Crew avionics needs.

The 3-View system approach focuses on "artifacts", not documents, and uses the views of the system to organize the artifacts and allow complete requirements allocation and management. The basic organization is shown in Figure 8. It is designed to approach system engineering from the three aspects as defined below, managed by a management control plan defined within the CMMI process. Looking at the system from these three aspects will lower the cost and risk to any future Commercial Crew development program independent of the eventual future winner because the requirements are clearly allocated and the likelihood of significant changes later in development is substantially reduced.

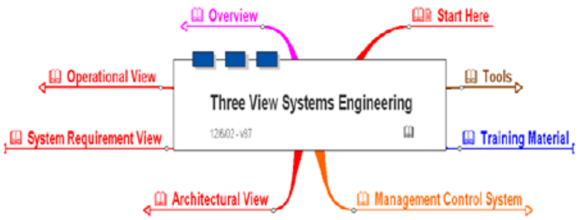


Figure 8. 3-View Architectural Framework. *The 3-View system solution approach focuses on an Operational View, a Systems Requirement (or Functional) View in addition to an Architectural View approach to assure all aspects of a customer's system needs are addressed and satisfied.*

C. Avionics System Architecture

The most important aspect of human rated avionics architecture is an implementation that provides the highest probability of mission success while guaranteeing the lowest possibility of loss of crew. This also needs to be completed within an affordable lifecycle cost, including both initial acquisitions, recurring production, logistics support, and sustaining costs. This is not only true for NASA systems, but is equally true for commercial airplane avionics ranging from the largest wide and narrow bodies through the regional jets to the smallest corporate jets.

NASA documentation has sometimes become overly prescriptive on avionics implementation over the last decade and thus has eliminated innovative implementations that could produce a lower loss of crew while simultaneously improving cost and schedule. As requirements are developed for the Commercial Crew vehicle, great care should be exercised in defining "what" must be done, not "how" to get it done.

D. Parts Program

Parts programs have historically been the one of the most costly elements of a space program. This has been driven by the requirement for grade 1 parts by many of the space programs. While this was necessary in the 1960s and 1970s, when electronic parts were in their infancy and the screening provided by the Joint Army Navy (JAN) parts program was the only means to achieve reliability. Today, the reality is there are only a handful of JAN parts and the electronics parts suppliers have been forced to implement Qualified Manufacturing Line (QML) processes to be cost competitive in their industry. A Grade 1 parts program based upon Qualified Part Line (QPL) parts is almost unaffordable in today's environment. It results in choices of not just more expensive parts, but greater quantity of parts, parts requiring higher power, and designs that are prone to obsolescence.

In response to this concern, Honeywell has developed and deployed an internal parts program over the past decade. This program fully meets the intent of MIL-STD-QPL programs at a fraction of the cost. The Honeywell Standard Space Parts Program (SSPP) utilizes Six Sigma Concepts and Lean Practices to achieve a lower parts defect rate while simultaneously reducing both cost and schedule. This parts program addresses the mutual concerns that NASA and NASA suppliers have in these areas:

- Cancellation of Government Specs/Standards
- Subsequent Loss of HI-Rel Space & Military Parts/Suppliers
- Well-Documented, Configuration Controlled Process Based on Extensive Human Space & Satellite Program Experience
- Shorter Development/Production Schedule

The SSPP program utilizes heritage practices for procurement and testing. These are developed from heritage QPL and QML practices. Requirements are established by part type. Two levels (ERA and SRA) for parts requirements generally aligned with MIL-STD-217 for Class B and Class S parts.

- ERA: Enhanced Reliability Assurance (Class S)
- SRA: Standard Reliability Assurance (Class B)

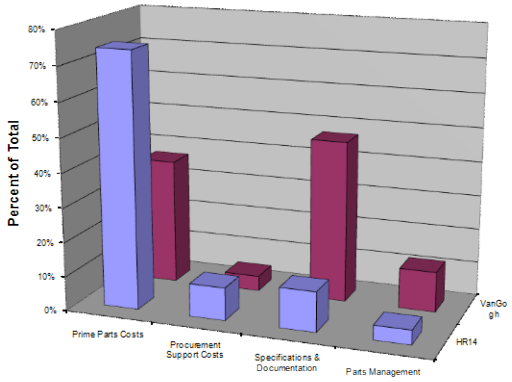


Figure 9. SSPP Program Cost Savings. *The individual cost reduction percentages by program element for two programs (HR14 & VanGogh) using the SSPP parts show where the savings occur using the SSPP program instead of using a MIL Grade 1 parts program.*

The requirements level is selected with customer based on program requirements. The program contains five equivalent approaches for procurement and inspection. The appropriate approach for each part is determined based on cost, schedule, and availability. This program has In-Process and Field Data since 1996 and shows that SSPP parts are as reliable as Class S/JANS. Historically, SSPP up-screened parts showed a failure of ~2PPM while Class S/JANS have showed a historic failure rate of ~4PPM.

The success of an alternate parts program is tied to the avionics architecture. The use of “rack and stack” commercial off the shelf boards create systems that do not have predictable failure modes. These failures are multiplied when alternate parts programs are applied to a design. For example, a parallel data bus will have 64 times the failure rate and un-predictability as compared to a serial data bus. All elements of an architecture must be able to be analyzed for failure modes. A system that can have fault isolation zones that “babble” upon entering failure modes will be increasingly difficult to certify. The system has to have additional cross-strap signals and voting actuators to account for these types of failures. A “fail passive” system where any failure cannot result in a change in state of an avionics output can be certified in conjunction with a reduced parts program. These architectural principals have contributed to the proven flight history for programs using the SSPP program.

A second area for concern is that NASA provides a balanced evaluation of cost associated with both hardware and software elements. Many times a focus is placed on hardware that results in a magnitude increase in software costs. The 1980’s philosophy that software can fix any hardware errors has resulted in numerous schedule slips and cost overrun programs. Many times the “hardware fix” will be more cost effective in both the short term and long term than the software fix”

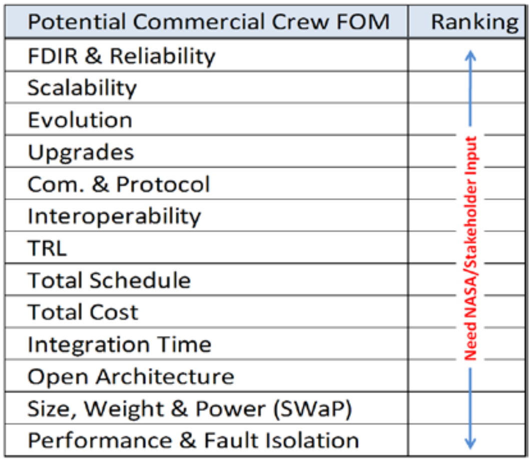
IV. Requirements; Not Implementations

Efforts, Honeywell has a wide range of experience that will allow solutions ranging from vibration isolation of low cost Off the Shelf (OTS) commercial aircraft avionics to full Fail-Op, Fail-Op systems such as the original avionics proposed for Orion. These following paragraphs discuss several methods for implementation of avionics for Commercial Crew missions, both in the crew capsule and the launch vehicle and the design to cost methods allowing these avionics to meet the reduced pricing that the commercial satellite industry has enjoyed for the last decade.

As stated in Section III, paragraph C above the most important element to control (and lower) cost of the Commercial Crew vehicle is to assure that “what” must be done is defined, not “how” to do it. Experienced suppliers, like Honeywell, have had a continuous stream of programs that place them in a unique position to understand the detailed operation of their domain system (in Honeywell’s case, avionics systems ranging from the Shuttle, ISS, X-33, and Orion). Honeywell worked closely with Draper Laboratory to complete trade studies of current avionics architectures and thus has gained a unique understanding of the Draper Laboratory Network Element approach and its implementation on the X-38 vehicle.

Industry should be allowed to use this knowledge base as our basis of response to Commercial Crew architectures. In Honeywell’s case, a response includes avionics architecture system engineering, heritage design capability, space commercialization efforts, and a comparison of various system implementation options. This is the same knowledge base used to evaluate the CEV RFP and implement a winning architecture described as a discriminator in the Orion win.

Also discussed herein (Section III, paragraph A), Honeywell recommends strict adherence to an architectural framework process such as documented in NASA/SP-2007-6105. In this process, NASA should be responsible for defining the Operational Environment; what needs to be done. The commercial supplier responsible for the vehicle should create the function required to perform all the tasks in the Operational View. System partners and classic suppliers should assist in the creation and validation of these functions and then complete the functional implementation (e.g. the architecture implementation). In addition to the operational requirements, the NASA/Industry team should identify and rank the critical to quality Figures of Merit (FOM) as shown in the table associated with Figure 10. Chief among the NASA comments describing the Honeywell proposed CEV avionics include such phrases as “great potential for reducing CEV project risk and life cycle cost”, “effective re-use of commercial/military hardware designs and architecture”, “increase probability of success”, and “lower design risks”. These FOMs form the basis for implementation trades throughout the program.



Potential Commercial Crew FOM	Ranking
FDIR & Reliability	Need NASA/Stakeholder Input
Scalability	
Evolution	
Upgrades	
Com. & Protocol	
Interoperability	
TRL	
Total Schedule	
Total Cost	
Integration Time	
Open Architecture	
Size, Weight & Power (SWaP)	
Performance & Fault Isolation	

Figure 10. Potential Commercial Crew FOMs. *Honeywell has spent the last decade doing avionics trades for both commercial avionics and human rated space vehicles. These FOM are repeated throughout the various studies and should be considered in the initial Commercial Crew definition.*

Allowing this level of flexibility, the industry supplier can propose their most cost effective solution, not a specified solution that may favor a specific supplier. As an example in avionics, Figure 11 shows five possible avionics architectures. Each of these has advantages and disadvantages in Size, Weight, and Power (SWaP) and cost (both initial implementation hardware and software costs in addition to life cycle costs.

Figure 11. Prior Avionics Architectural Views. *These views illustrate various architectural implementations of the flight vehicle system using five different heritage avionics system approaches. Allowing this type of trade will be essential in the effort to keep Commercial Crew cost minimized*

As a cost saving measure, it is important to be able to trade different architectures for different mission models. For example, the graph in Figure 12 illustrates that there is a significant difference in the reliability of a single string voting system as compared to a fail passive system. While this might be a highly rated FOM for the Orion program with its six-month duration, this is a nearly non-measurable for a Commercial Crew five day mission and even less important for an eight-minute human rated launch vehicle.

Another cost saving measure that must be considered is the amount of interconnect and cross strapping that can be implemented in an avionics implementation. As shown in Figure 13, there are multiple ways to gain the same interconnectivity in a system. These interconnects will result in varying probability of success for the implemented system. As discussed above for the reliability trades between a Triplex Integrated Modular Avionics (IMA) system and a quad voting system, the fact that the Commercial Crew mission will be much shorter that the beyond LEO Orion missions will allow a simplified implementation, which could reduce cost for a commercial system. In order for NASA to realize these benefits, they need to define the "what needs to be done" and work in a partnership with industry to define the "how to do it" to allow optimum priced implementations of the REQUIRED performance.

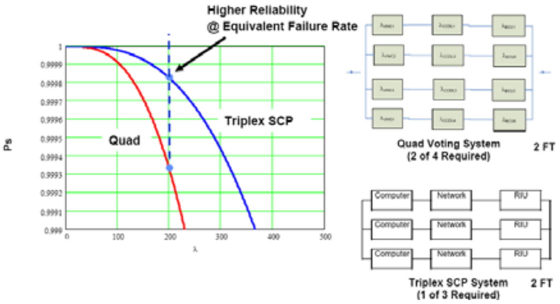


Figure 12. Reliability of Fail Passive IMA vs. Quad Voting Avionics Systems. *Although a triplex self-checking pair IMA architecture results in higher mission reliability at an equivalent failure rate, this may not be a cost driver in a Commercial Crew system to nearly the extent it is in a system designed for beyond earth orbit such as Orion.*

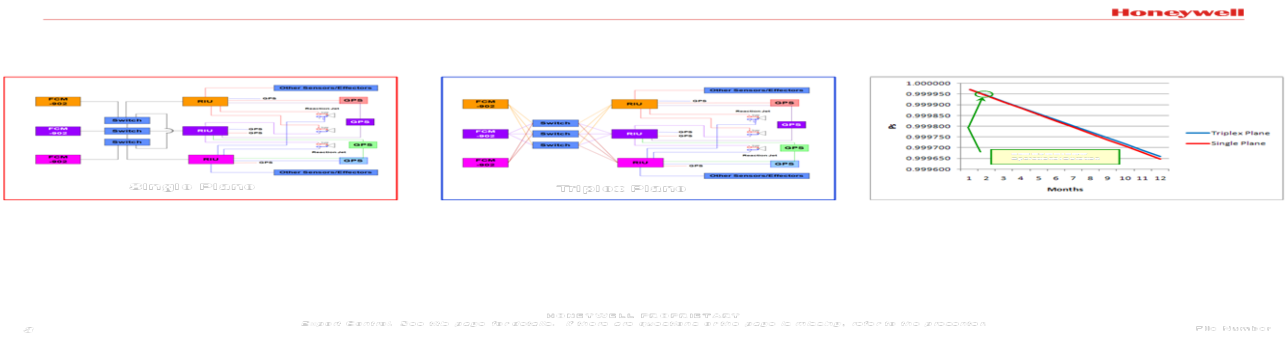


Figure 13. Interconnect Cross Strapping Reliability. *The reliability of an avionics system is dependent upon the amount of interconnect as well as the mission duration. Both of the interconnects shown here satisfy the fail-op fail-op criteria. The single plane requires switches with fewer ports making this a lower cost implementation. Because of the short mission duration, the Commercial Crew program may be able to take advantage of this.*

Options for radiation environment levels will have a large impact on the cost of implementing a Commercial Crew system. Although the existing Shuttle and ISS requirements are written to require 36 MeV heavy ion survivability, there is a contingent of radiation experts lead by William Culpepper at JSC that high-energy proton testing at 200 MeV (roughly translating to 14 MeV LET spectrum seen in Low Earth Orbit. Although this is not currently universally accepted, there are flight critical elements of the ISS that currently fly plastic components with a maximum survivability lever of approximately 20 MeV heavy ion (non compliant to the 36 MeV ISS requirement) exposure. Since electron testing can be done without de-lidding parts, there is a large potential cost reduction to allow 200 MeV proton testing as the LET spectrum for the Commercial Crew program. In fact Honeywell has evaluated the catalog item 787 Flight Control Processor (which has a current July 2010 catalog price of $75K) and determined that 80% of the components would meet the 200 MeV proton requirement. Since this is nearly the identical function of the Orion self-checking pair processor (currently projected to cost the Orion program $250K), it is worthwhile for NASA to investigate this possible cost savings opportunity.

The final consideration discussed herein is the trade between SWaP and cost as it applies to anticipated launch vibration levels. Historically space products have designed optimum mechanical housings to meet the high levels of launch vibrations. A new approach was taken with the Orion Pad Abort Test avionics equipment. An available off the shelf, commercial avionics, high integrity, commercial self-checking pair flight control computer was chosen for the PA-1 system. To meet the intended vibration environment, this commercial computer was mounted in an vibration isolation chassis as shown in Figure 14. This allowed the use of a much lower price flight computer with proven operating system software. It also allowed the immediate development of software to meet the quick turn schedule required for the PA-1 test. The power and weight of this unit are almost two times that of their Orion counterpart, but if power and weight are available to trade, this implementation could provide an immediately available high integrity flight control module for Commercial Crew architectures.

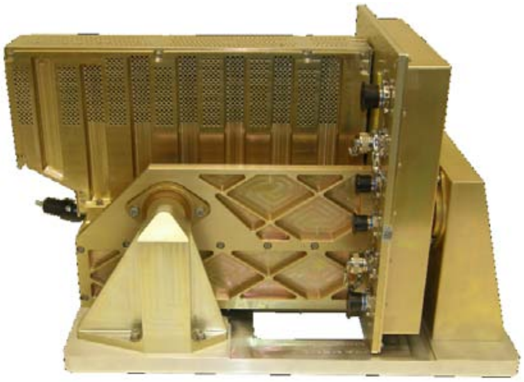


Figure 14. PA-1 Flight Control Module Isolation System. *The PA-1 flight test used an off the shelf 787 Flight Control Module as the main avionics control. In order to meet the near 20G random vibration environment with a unit only qualified for 4G, an isolation system was used.*

V. Conclusion

As presented in this paper, there are many ways to reduce the cost of the Commercial Crew program ranging from oversight of requirements, architectural decisions, and cost reimbursement models. What Honeywell has presented is proven methods to achieve reduced cost for a Commercial Crew launch system. These methods utilize the same high level standards that have been applied to previous human space endeavors. Cost reduction is not accomplished by replacing incumbent suppliers with new suppliers that may not have the process or lessons learned to produce six-sigma performance results over multiple launches and decades of operation. Cost savings is achieved by using the optimum design for cost choices and important lessons learned.

VI. Contacts

Mitch Fletcher, Chief Engineer
Honeywell International Inc.
Defense & Space
19019 North 59th Avenue
Glendale, Arizona 85308-9650
Telephone: (602) 822-3158
Cell: (602) 284-1715
Fax (602) 822-3680
mitch.fletcher@honeywell.com

Ed Banas, Sr. Program Manager
Honeywell International Inc.
Defense & Space
19019 North 59th Avenue
Glendale, Arizona 85308-9650
Telephone: (602) 822-4375
Cell: (602) 432-8040
Fax (602) 822-3680
ed.c.banas@honeywell.com

References

[1]Wikimedia Commons
http://commons.wikimedia.org/wiki/Main_Page

[2]Augustine, Norman, atla. “Seeking a Human Spaceflight Program Worthy of a Great Nation,” NASA 3960930, 2009.

[3] Wayne Hale & Frank Bauer, “Government Insight/Oversight for Commercial Crew Transportation,” NASA 469245, 2010.