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Space Shuttle Avionics Upgrade: Issues and Opportunities

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Abstract

The Space Shuttle uses a complex set of software and hardware to guide, navigate and control it through all phases of flight. Five IBM AP-101B flight computers host a set of highly critical and complex programs. The current man-machine interface consists of a series of dedicated electromechanical instruments and switches combined with specialized displays with limited function. The exponential growth of microprocessor technology combined with the approaching obsolescence of the Space Shuttle cockpit avionics have driven NASA to explore a Product Improvement Plan for the Space Shuttle which includes the cockpit displays and controls.

The IBM Systems Integration Division (SID) in Houston is currently studying alternatives for upgrading the Shuttle's cockpit. Some goals of the upgrade include: Offloading of the main computers by distributing some of the avionics display functions, reducing crew workload, reducing maintenance cost, and providing display reconfigurability and context sensitivity. These goals are being met by using a combination of off-the-shelf and newly-developed software and hardware. The software will be developed using Ada, and must meet the timing constraints imposed by existing Shuttle Systems. Advanced active matrix liquid crystal displays are being used to meet the tight space, weight and power consumption requirements. These displays are tied to commercially available 80386 microprocessors.

On top of the challenges presented by the software and hardware development are programmatic constraints. These include: Transparency to existing Shuttle avionics and data processing systems, Integration into training facilities: avionics labs, simulators, aircraft, etc., Development of ground support systems: Software Development facilities, verification capabilities, systems integration environments, etc. and Installation into the operational Shuttle fleet without impacting current flight rates. Of course, this all has to be done within cost and timing constraints in a dynamic environment.

This upgrade holds promise for future improvements to the onboard avionics systems. An example is online storage and display of crew checklists and procedures. This and other potential growth paths must be accounted for in the design of this upgrade. The opportunities for laying the groundwork of a cohesive strategy for avionics in the nation's space fleet are many and the issues are complex but the technology has advanced far enough that significant benefits can be achieved by upgrading the current system making this a worthwhile if not mandatory task.

Introduction

Being designed in the early 1970's, the Space Shuttle's then state-of-the-art avionics seem outdated when compared to modern avionics systems. However, upgrading the Space Shuttle's avionics involves many complex issues when thoroughly analyzed. From ground systems to an orbiter's physical characteristics, the design and integration of a new avionics system affects much of the National Space Transportation Systems (NSTS) infrastructure. Today NASA is looking at ways to upgrade the shuttle avionics with an eye toward reducing maintenance and improving reliability while taking advantage of the improved avionics available in the marketplace today. IBM has been investigating various approaches to address the needs of the NSTS program.

Current Shuttle Avionics

The core of the current Space Shuttle avionics suite is comprised of five IBM AP101 series General Purpose Computers (GPCs). The AP101 line was originally developed in the 1970 time frame, and a version was adapted for use by the Space Shuttle with the designation AP101B. In recent years an upgrade program has been underway which will result in first flight of the AP101S version in 1990. The AP101B/S processor architecture is known by the name Multipurpose Midline Processor (MMP) and is programmed in HAL/S and assembler for the Shuttle Program. The GPCs are interlinked in a system which provides both hardware and software redundancy. Four of the processors run the primary software and are voted, while a fifth processor runs an independently coded backup software system which can be engaged by the crew. Communication between processors and with the rest of the shuttle systems is accomplished via twenty-four 1-megabit/second serial data buses connected to each GPC's I/O processor. Mass storage is provided by a redundant pair of tape units (Mass Memory Units - MMUs).

Wrapped around this core of processors are the devices which allow the crew to interact with the Shuttle. These I/O units fall into three major groups - (1) multifunction displays, (2) dedicated switches and indicators, and (3) dedicated flight instruments. These devices are discussed in subsequent paragraphs.

Multifunction Displays

In the forward cockpit area are three monochrome green Display Units (DUs), which are driven by three Display Electronic Units (DEUs) each of which is connected back to the GPCs via its own dedicated I/O bus (DK buses). Together with their keyboards and a fourth set in the aft crew station, this equipment forms the Multifunction CRT Display System (MCDS). The DEUs are semi-intelligent devices which contain an SP-0 integer processor (600 KIPs), 32K X 17 bits of core memory, and an analog stroke symbol generator. Processing activity at the DEU is limited to basic keystroke filtering, time maintenance, and health monitoring. The display screens are refreshed by cyclic execution (55 Hz) of chained Format Control Words (FCWs) in the DEUs memory by the Symbol Generator. The static portions of display pages are stored on the MMU and are called up and loaded into the DEU as required. There is also a set of pages ("critical formats") which are always resident in the DEU after initial load to allow rapid access. Dynamic data listed in a table associated with each active format is accessed by the GPCs, pre-processed, and fed to fixed locations in the DEU memory for display. It should be noted that although the DEU has a significant amount of graphics capability (line, circle, translate, rotate), the majority of displays are exclusively tabular text and data.

This method of generating displays has distinct advantages which were very important in the beginning of the program. For one thing, it is fairly efficient in terms of storage space requirements. Secondly, since all the display formats are formed ahead of time, verification of both the displays and the display effects on the real-time system is relatively simple. Once the structure of the display page is set, the storage space is fixed, and the maximum amount of processing required for a display page is known.

Unfortunately, the structured simplicity of the display system has many disadvantages when it comes to flexibility and maintainability. Now that increased processing capability and memory storage are available, and the operational constraints of the real-time redundancy management system are better understood, alternate techniques for display generation should be investigated.

Dedicated Switches and Indicators

The second major group of crew interface devices is the dedicated instruments and controls. These devices cover most of the cockpit area and (unlike the MCDS) are usually only significant during limited portions of a mission. These devices include vast arrays of switches.

Switch positions are in general sensed as digital inputs to the Multiplexer/Demultiplexers (MDMs) which are polled on the serial buses by the flight software in the GPCs. Programmable indicator lights are also in general connected to the discrete outputs of MDMs (via annunciator amplifier units) and set on or off under flight software control.

While some effort has been made to employ graphical aids to ease identification of switch function (i.e. switches located in flow control diagram for propellant system), extensive training is required for a crew member to be able to quickly locate and recognize the function of individual switches. Furthermore, especially in those cases where graphic representations are used, redefining switch functions means fabricating and installing new control panels.

While comforting to the human pilot by their physical reality, it should be noted that many of the switches on the front panel are in effect "virtual" in the sense that they perform no direct physical function. Unlike the light switches on your wall, they do not conduct current to the light bulbs on the ceiling - they merely represent ones and zeros to software which could just as easily adjust the cabin temperature as turn on the light if you so desired. Given this fact, the physical switches are a waste of both space and weight, and their etched labels limit the inherent flexibility of a software controlled user interface. Although in some situations dedicated switches are desirable, the increased flexibility of a software controlled interface is often advantageous.

Dedicated Flight Instruments

The major flight instruments - the Attitude Directional Indicator (ADI), Horizontal Situation Indicator (HSI), Alpha/Mach Indicator (AMI), and the Altitude/Vertical Velocity Indicator (AVVI) - are electromechanical instruments custom designed and built for the space shuttle application. These devices are driven by flight software via the Display Driver Unit (DDU). Two sets of these instruments (Commander and Pilot) are available forward, and an ADI is located in the aft area for on-orbit operations. Three DDUs supply drive to these instruments and power for the hand controllers at each of the crew flight stations. For redundancy, each of the DDUs may (by crew selection) be driven by any of four flight critical buses commanded by different GPC's. In addition to these mechanical instruments, a pair of Head-Up Displays (HUDs) are connected to the same buses and can display the same types of information.

The dedicated flight instruments do not suffer from the same interpretation difficulties as the numerous dedicated switches and lights. In most modes, the data they represent is clear and concise, and the format is quickly grasped. However, these instruments are a waste of four dimensional space - they occupy volume continuously on a timeline that has them covered over with procedure sheets for more than 95% of a mission. Replacement with devices which could perform the same functions when required and yet be useful (if only for storing and displaying those same procedure sheets electronically) for the rest of a mission would be desirable.

In addition to the temporal limitations of these instruments, maintenance issues must also be considered. These are mechanical devices, subject to wear and requiring periodic maintenance. Their manufacture and care has become a dying art with the advent of electronic equivalents in the commercial and military avionics fields, and the associated costs will rise exponentially in the future.

In each case, Multifunction Displays, Dedicated switches and indicators, and dedicated instruments, there are good reasons to consider upgrading or improving the existing system.

Operational Needs

As the shuttle program has matured, so have the operational needs. After almost a decade of use, the information needs of the cockpit have evolved along with the technology available to present it. Processor technology has come to a point where significant improvements in performance can be made by migrating to a more modern processor.

The Shuttle avionics system is now almost 20 years old. Reliability, maintainability, availability, and obsolescence are becoming significant factors. For example, the current Display Unit (DU) is failing every 8 flights. While this has not caused any real problems, it can be expected to get worse and repair and parts for this device are increasingly difficult to obtain. Maintainability is fast becoming a factor for all of the displays as parts and expertise become more and more scarce. Many of the onboard display devices are approaching their design lifetimes. All of these symptoms point to a growing obsolescence which typically means additional cost.

As the United States' manned space program grows, the need for compatibility across the fleet grows as well. The avionics for the Space Station Freedom are different from the NSTS system. This brings along with it different ground facilities, labs, and maintenance personnel. It will become more and more important to have as much compatibility across the spacecraft as practical to minimize costs by avoiding duplication of facilities and expertise. Any space avionics upgrade from now on needs to consider developments in collateral programs to insure maximum compatibility.

A positive result of the evolution of microprocessor technology is the ability to provide more function onboard a spacecraft. This means more flexibility can be built-in to provide more information to crew members onboard and to reduce the turnaround time and cost. One example, of this would be to store crew checklists and vehicle maintenance manuals in a display unit for reference as needed by the crew. Additionally, display software reconfiguration cost could be reduced by providing more "room" and processing power onboard.

In order to provide these improvements to the system, some fairly stringent physical requirements must be met. Since the front cockpit is subject to direct sun-shaft lighting, display devices must be readable in ambient light of up to 10000 foot-candles. Very few display technologies in general can meet such a requirement, and almost no color displays. Further, volume constraints imposed by the existing air-frame limit display unit depths in general to between 6-8 inches, eliminating conventional tube technologies.

In addition to having a high contrast, upgrade display units should have a fairly high resolution. Resolutions of 512 x 512 color pixels in a 6.25 inch square format have been demonstrated and appear to be adequate for most instrument representations and text output. Higher resolution would be desirable if applications such as engineering drawing databases were to be made available.

Finally, as in all space applications, power and weight are also at a premium. It is difficult, if not impossible to justify any upgrade to a system which reduces payload capacity or limits mission length. Therefore any proposed upgrade should stay within the bounds of the current systems weight and power consumption.

Technology Evolution

Shuttle Avionics Origins

As mentioned previously, both the AP101B and the MCDS are circa 1970 technology. It is often somewhat instructive when attempting to anticipate the future to first review history - toward that end we shall look back to this time frame briefly. The AP101B was designed initially with the then massive memory of 64K x 34 bits of core implemented on 16 pages. Having flown to the moon on a small fraction of this in 1969 who would believe this could be insufficient to the task. As soon as the technology became available, the density of the core memory pages in the CPU section was increased, giving the AP101B a total memory of 104K x 34 bits. The CPU and I/O Processor occupied two Airline Transport Rack cases and weighed approximately 120 pounds. The processor zoomed along at over 400 KIPS on 32-bit data while the IOP executed control sequences at a cumulative rate of 2 MIPS to support its 24 channels. These are fairly impressive achievements considering that the most complex IC available for the design was a 4-bit wide Arithmetic Logic Unit - after all, the hand-held four- function calculator was not even commercially available until the early 70's.

In the display world the CRT reigned supreme - an easy task, since the only conceivable competition was an array of seven segment LEDs for text display. Bit-mapped graphics was virtually a dream, considering the availability and the cost of the high density, high speed memory required to support it. Graphics demanded the use of a stroke written display, with an extensive analog design to achieve such features as rotation and translation using discrete transistors. Even so, as stroke writers go, the Shuttle DEU still provides competitive display capability in all areas except volume and power after 20 years.

Previous Upgrades

By the time the Shuttle first flew in 1981, its avionics system was already 10 years old. Even with the expansion, the ascent software had filled available memory and processing loads had grown to peaks of more than 75% of the CPU's capacity.

In an effort to head off the rising costs of software development in the restricted memory and processing environment, a computer upgrade program was initiated in 1982. The goal of the program was to produce a processor which would relax the system programming restrictions yet preserve NASA's extensive investment in developed and verified flight software. At the time, the only tenable solution was to provide a processor with object code transparency to the AP101B. Enhancements to the processor architecture were made in an attempt to reduce restrictions on memory utilization, and both processing speed and memory size were increased by approximately 2.5X the capacity of the original machine capacity. The result of this upgrade program was the AP101S, first field deployed in 1984, and currently scheduled for its first flight in late 1990. Once again, the avionics processors will be almost ten years old by the time they fly. This time lag is inherent in the highly critical nature of the processor's task and the extensive verification associated with it, and must be considered in all upgrade planning cycles.

State of the Art

In the 20 years since the start of the Shuttle Processing System design, radical changes have obviously occurred in the computing field. From the development of the hand-held calculator in the early 70s and the general advent of PCs at the start of the 80s, we have reached the mainframe on your desk state of the 486 and other similar processors.

When the Shuttle first flew, its CPU had many times the power of the available microprocessors at the time. The AP101S improved this margin for a short time. However, the exponential growth of microprocessor technology has outstripped the Shuttle processor. While no match for the custom I/O processing of the GPC, a commercial 386 chip with a 387 coprocessor running at 16 Mhz packs almost double the power of the AP101S in a few square inches of board space using a fraction of the power. 80486 machines running at over 30 Mhz are becoming commercially available which have more than 10 times the power of the AP101S.

These new processors have other advantages beyond raw speed. Their architectures provide hardware support for multitasking and memory management, and Virtual memories in the gigabyte range are planned into them. What is more important is the user community support for these microprocessor architectures and the associated manufacturing commitments. Operating Systems and High Order Language support are readily available for the major microprocessor families, and manufacturers have planned evolution paths to support the continued growth of processing power. New languages such as Ada combined with structured design techniques and enhanced development environments promise to reduce life cycle cost for software developed on these new processors. And while by Murphy's laws programs still expand to fill all available memory space, desk machines with 4-16 Megabytes (4-16 times the size of the AP101S memory) are available to make the task more formidable.

Display technology has also blossomed. The availability of cheap, fast, memory has caused graphic displays of over a megapixel resolution in 16 million colors to become commonplace. The CRT is no longer undisputed king - in fact its days may well be dwindling in some applications. Flat screen technology in both monochrome and color is now available. Active Matrix Color LCDs with 14 inch diagonals have been demonstrated. Prototypes of avionics grade color displays 6.25" x 6.25" with 512 x 512 color resolution and extremely high contrast even under intense illumination have been available since early 1988.

Of course, one must always be aware of the unique problems associated with the space program when evaluating new technology. Reliability, safety, power and volume constraints, high vibration and shock levels, temperature extremes, and high-energy radiation are all elements which separate space based processing from its commercial equivalents. For example, the 486 processor gains much of its processing speed from an on-chip cache memory. Unfortunately, this cache is not protected by parity in the present design, which makes it impossible to detect alteration of data or code by cosmic ray induced single event upsets once inside the cache. Given the criticality of most code run on space based processors, inability to detect what in space is a high probability error mode is unacceptable.

Application of Technology

Limitations of Current Technology

With all the currently available technology, why not take advantage of it all? Today! Many factors inhibit the introduction of new technology into a man-rated space vehicle. They fall into two basic categories: physical and operational.

Physical factors significantly limit what technology a program can realistically take advantage. First, a new technology must live within a power budget imposed by the existing vehicle's architecture. In the case of the NSTS, the existing avionics were selected for their optimum use of the available power. Many existing technologies (especially displays) use equivalent or more power than existing orbiter systems. Cooling also figures in here since that often requires an active system which also utilizes power. Weight and volume are less of a factor since most modern processors use highly integrated components. However, if a "glass cockpit" approach is used, a significant weight penalty might be paid for the additional displays. Finally, any new avionics system must fit within the existing space with as few structural modifications as possible. Ideally, a system with equivalent form and fit wherever possible is desirable. The current system's physical constraints limit what existing technologies can be used in the NSTS system.

While physical factors are internal to the system, operational factors are externally driven. When such a significant change is made to a complex operational system such as the Space Shuttle, impacts ripple through the entire infrastructure. As with any manned space venture, the NSTS program has trainers, development facilities, engineering labs, as well as vehicles to include in an integration strategy.

From a vehicle standpoint, any modification has to be factored in with flight and existing maintenance schedules. Current manifests indicate the orbiters go in for maintenance every 3 years for approximately 3 months. This means that an avionics upgrade would have to coincide with this downtime or require small enough increments of work that it could be accomplished during normal processing flows. Then other questions arise: Should all orbiters be converted as closely together as possible? Should a pathfinder vehicle be utilized? Should the avionics upgrade be accomplished incrementally or all-at-once?

Development facilities and engineering labs pose different issues. Typically, upgrades such as this are developed, tested, and verified in these facilities. These labs and facilities are also used for flight-to-flight reconfiguration and certification. With a mixed fleet, (some vehicles with the upgrade and some without) dual capability must be maintained.

An avionics upgrade affects training facilities/operations with both vehicle and lab impacts. The training facilities require vehicle upgrades early enough that crews can be given sufficient exposure to them before the first flight. Like the labs, trainers must maintain a configuration similar to the fleet so dual capabilities will likely be required.

All of these operational factors are far more complex and nebulous than the physical factors. Their effect is the same, however, in that they limit the current technology that can be applied to the Space Shuttle.

Solutions

One possible solution to the developing problems in the Shuttle avionics system is a phased infusion of new technology through a display system upgrade. Such an approach, if properly planned, would have the advantage of both immediately addressing one of the longest neglected (and most visible) segments of the avionics, as well as allowing a firm foundation for further system enhancements.

This upgrade plan would consist of several phases, designed to support needed improvements to the system and to integrate efficiently into the program flow. These phases are as follows:

Functionally Transparent Replacement

This first step in the program would involve replacement of elements of the crew interface with enhanced units that preserve maximum physical compatibility with the orbiter structure and absolute conformity to existing flight software. The initial step which we would propose would be the replacement of the Shuttle DEU with a highly intelligent processor programmed to emulate a DEU. Such a device, based on the Space Station Freedom (SSF) Standard Data Processor (SDP) has been developed and demonstrated in the SID lab in Houston. The selection of the SDP allows for maximum leverage of NASA investment in both hardware and software, since the development costs for the bulk of the system are already budgeted. The SDP, augmented by a prototype avionics color AM-LCD easily handles the emulation of the DEU/DU without impact to the flight software.

User Interface Enhancements

This enhanced processor would also allow the addition of numerous user support functions, without impacting flight software. Currently, any additions to display functions require modification of software intertwined by virtue of central processing with critical flight software. A multitasking operating system in the display device can allow the DEU emulation to coexist with other tasks such as online databases and expert systems. Other enhancements such as programmable edge keys, dynamic data highlighting, and out-of-range color highlighting are also possible without modification to flight software.

Migration

The final stages of the upgrade program would begin to involve the GPC flight software. First, functions such as display processing would be segregated from the rest of flight software and migrated out to the display processors using modern software technology. This would have several advantages: 1) It will allow increased flexibility in display generation; 2) It will increase maintainability of the display software; 3) It will offload the central processor, and 4) It will allow redefinition of the dedicated DEU bus protocols to allow for additional software migration. Following these changes, additional simplex functions can be rehosted out to the "display" processor. Eventually, only core Guidance, Navigation, and Control tasks which require the high degree of real-time redundancy management provided by the current flight system will remain in the AP101s. These functions need not change frequently and should be more easily maintained in the less restricted GPC processing environment created by the rehost.

As a consequence of these actions, a major portion of the shuttle processing can be migrated into a hardware and software technology which is common to other NASA Spacecraft. Program support and future upgrades may therefore support multiple programs.

Benefits

Upgrading the current Space Shuttle Avionics would provide benefits in many areas including, increased function, improved human factors, and lower operational costs. By providing more local processing power and storage, an upgraded avionics system could perform more functions than today. For example, checklists and procedures manuals which exist in hard copy today could be stored onboard in electronic form and called up as needed. This would reduce the amount of documentation carried onboard reduce the effort to maintain that documentation. Engineering or maintenance data could be treated similarly. In the area of human factors, many improvements could be realized. Color displays and and reconfigurable edge keys would improve the user interface to the Space Shuttle Data Processing System. Where most displays today are fixed function, a context-sensitive display system could be constructed to only show that data which is required at a given time. Avionics costs could be lowered across the board by reducing obsolescence and therefore maintenance costs, by providing higher-level, easier-to-maintain, software, and by reducing the flight-to-flight display reconfiguration required.

Summary

It is important to continue to address the upgrade of the Space Shuttle Avionics. As other "spacecraft" are added to the fleet (Space Station, Shuttle-derived vehicle, flight telerobotics servicer, Aeroassist flight experiment, etc.) the burden of an aging avionics and display system will continue to grow. The opportunities for laying the groundwork of a cohesive strategy for avionics in the nation's space fleet are many and the issues are complex but the technology has advanced far enough that significant benefits can be achieved by upgrading the current system making this a worthwhile if not mandatory task.