UPGRADES TO THE CAUTION AND WARNING SYSTEM OF THE SPACE SHUTTLE

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During a Space Shuttle mission, astronauts are alerted to off-nominal conditions via a Caution and Warning System that often generates a myriad of auditory and visual alerts. A key component of this system is the Fault Summary display, which contains text messages describing the malfunctions. The display often becomes cluttered with extraneous messages, increasing the difficulty of diagnosing a malfunction. In an effort to improve the crew's diagnostic performance, increase their situational awareness and reduce their workload, the Caution and Warning System is being improved as part of the Cockpit Avionics Upgrade. In the first phase of the upgrade, the Fault Summary display is being redesigned with a more logical task-oriented graphical layout and multiple text fields for malfunction messages. In the second phase, the text fields will indicate only the source (i.e., root-cause) of the malfunction to prevent non-operationally useful messages from appearing on the display. These and other aspects of the upgrades are based on extensive collaboration among astronauts, engineers, and human factors scientists. This paper describes the human factors principles applied to upgrading the Caution and Warning System in the presence of inherent limitations associated with legacy manned spaceflight vehicles.

1. OVERVIEW OF SHUTTLE COCKPIT UPGRADES

The Space Shuttle was developed in the 1970s using technology that was quite advanced for its time, including fly-by-wire components and multiple computer screens in the cockpit (Figure 1). Although the electro-mechanical gauges and cathode ray tube (CRT) screens soon became dated, no major upgrades were made to the cockpit for two decades. Part of the reason was simply that the original equipment is extremely reliable. However, it is also bulky and expensive to maintain.

The first major upgrade to the shuttle cockpit was implemented in Space Shuttle Atlantis in the late 1990's. Called the Multifunction Electronic Display System (MEDS), it replaced the original set of CRTs and many electro-mechanical gauges with color liquid crystal displays (LCDs). Although these LCD screens made possible many display design options that were unavailable in the original cockpit, the new MEDS displays (Figure 2) are mostly copies of the original display formats and electro-mechanical gauges.

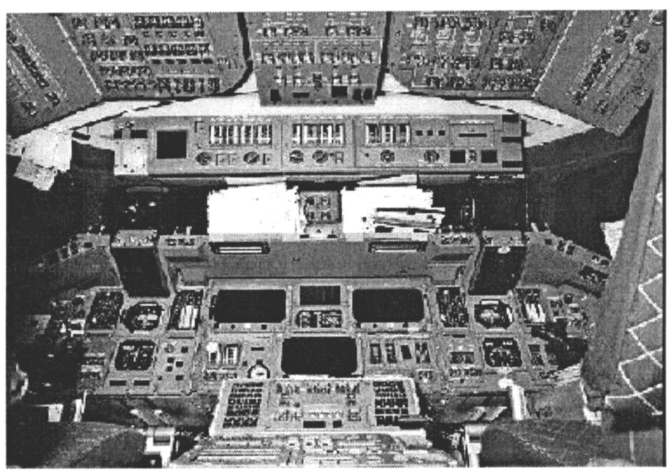

Figure 1: Original cockpit of the Space Shuttle.

From a human factors standpoint, several features of the original display formats are problematic. For example, information pertaining to a particular vehicle system is often scattered across several distinct displays. This forces the crew to navigate among these displays in order to work malfunctions, or even to acquire an integrated picture of systems health. In addition, information on the original displays is often poorly organized and highly cluttered, taking the form of narrow rows and columns of monochromatic (green) alphanumerics.

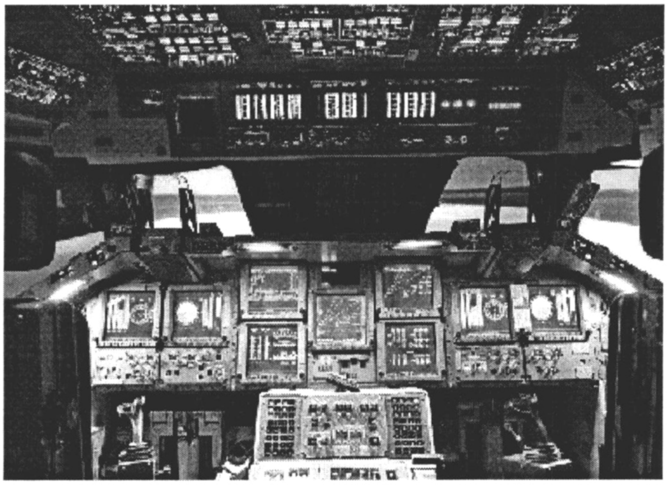

Figure 2: Upgraded cockpit with the Multifunction Electronic Display System (MEDS). As of June 2003, Space Shuttle Atlantis has completed its MEDS upgrade, Discovery is being upgraded, and Endeavour has yet to be upgraded.

Partly in response to these shortcomings, a new generation of cockpit display formats has been designed under the auspices of the Cockpit Avionics Upgrade (CAU) project, based at NASA Johnson Space Center. Scheduled for implementation in 2006, the upgrade is described by McCandless and McCann (2002). Three new PowerPC-based computers form the foundation of this upgrade. Whereas the MEDS upgrade was driven primarily by concerns over equipment obsolescence and maintenance, the CAU project has a human factors focus, targeting issues of crew workload, situational awareness, and performance. In particular, the goals of the CAU project are to simplify display navigation, reduce the time to acquire and process critical information, and provide improved computational capabilities.

Throughout the CAU project, fundamental tenets of human factors design have guided display designers. The choice of information to display to the crew was based on a formal task analysis to ensure that it is directly relevant to crew procedures. On-board computers will transform raw data into operationally useful information through calculations currently performed by the crew. A graphical layout (as opposed columns of numbers) for many display formats was implemented to more closely match the crew's mental model of the vehicle system design and functionality. Color-coding was used to guide visual attention and indicate different levels of criticality (such as warning indicators in red, caution indicators in yellow, and "information missing" indicators in cyan). Whenever possible, related information was consolidated on one display, reducing the need for the crew to navigate among multiple displays to acquire similar classes of information. For cases where navigation is still required, the process has been simplified by optimizing the use of "edge keys" at the base of each screen. In the MEDS cockpit, the crew has to call up most of the display formats by typing the number (requiring rote memorization) of the display format on the keyboard.

A related modification is that any display format can be called up on any of the nine forward LCD screens. In contrast, today's cockpit restricts the call-up of most display formats to three forward screens.

Even with these improvements, the crew will still be interacting quite frequently with the keyboard in the CAU cockpit. To make the process more efficient, the keyboard itself has been redesigned. For example, the MEDS version contains two similar keys that both provide an "enter" function, forcing the crew to remember which form of "enter" key is appropriate for the task at hand. On the CAU keyboard, a single "enter" key replaces the pair of existing keys.

One of the most important areas of human-machine interaction is the Caution and Warning System, which alerts the crew to systems malfunctions. As described below, the shuttle Caution and Warning System also has operational deficiencies, some of which have been addressed in the initial CAU upgrade. Approximately 18 months after the initial upgrade, the CAU Caution and Warning System is scheduled for a subsequent upgrade called the Enhanced Caution and Warning (ECW) System.

2. EXISTING CAUTION AND WARNING SYSTEM

The current Caution and Warning System alerts crewmembers to off-nominal conditions through four classes of annunciations, depending on the severity of the problem. The two most important classes are 1 and 2. Class 1 consists only of emergencies initiated by cabin smoke or cabin depressurization. By far the largest set of malfunctions fall into Class 2, which encompasses malfunctions that are generally not quite as time-critical as those associated with Class 1, but still may be life-threatening (such as an engine failure). The visual indications to Class 2 alerts are annunciator lights and fault messages. All fault messages are compiled together on a dedicated display format called the Fault Summary.

Nowhere is it more important to provide the crew with clear, easy-to-interpret information than that needed to work a time-critical malfunction. Unfortunately, the information provided by the Caution and Warning System is often confusing and difficult to process. In most cases the underlying software supplies direct links between individual sensor readings and alarm annunciations. If an individual sensor fails, and sends an out-of-limit value for its associated parameter, the caution and warning system will annunciate a malfunction, even if other sensors that redundantly sense the same parameter are reporting normal values. For this and other reasons, nuisance (false) alarms are quite common.

Visual indications to Class 2 alerts often require a considerable amount of crew effort and training to interpret. In many cases, the true cause (i.e., root-cause) of a subsystem malfunction is some outside source, such as a failure of an electrical distribution system that powers several distinct devices. Because each device failure annunciates separately, the system produces "a steady stream of fault messages and master alarms that may obscure other important fault messages" (Shuttle Crew Operations Manual, 2002, page 2.2-15), possibly including the message corresponding to the root cause itself. In fact, the crew can inhibit the affected parameter to eliminate nuisance alarms during some phases of flight. However, during ascent and entry, "the crew generally has to tolerate the extra alarms/fault messages and pay extra close attention to the fault summary display" (Shuttle Crew Operations Manual, 2002, page 2.2-15). This is because the crew is generally too busy monitoring critical systems (such as the propulsion and electrical systems) to spend time modifying the thresholds at which unwanted alarms are annunciated.

A specific example of the message proliferation problem is shown in Figure 3. Here, a failure of an electrical bus causes all of the mechanical components powered by the bus to stop operating. The first five messages in the FAULT column (THRM through AV BAY) are all the product of the bus failure. As Figure 3 shows, the Fault Summary display simply lists messages associated with all the failed components without providing an unambiguous indication of the actual source, or root-cause. The crew is forced to interpret the content of the messages by applying their knowledge of how the failed components link to the electrical power system, and "work back" to the root cause. For this reason, the Fault Summary display was one of the most important targets of the CAU Caution and Warning System upgrade. The following section describes the redesigned version.

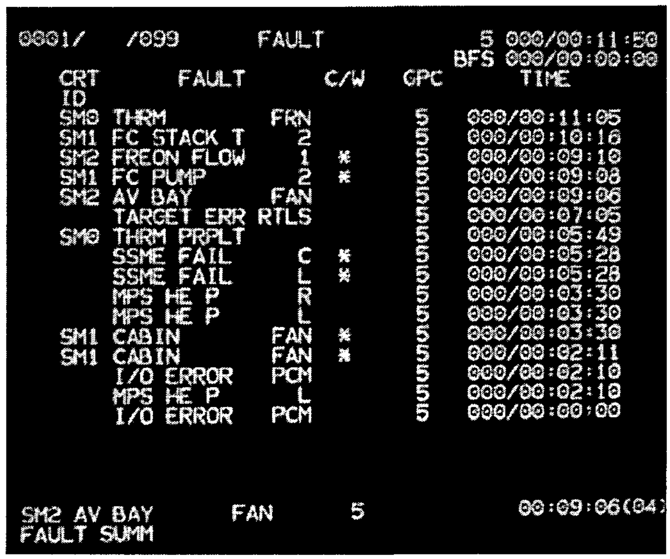

Figure 3: Current Fault Summary display (with sample messages).

3. INITIAL UPGRADE TO THE CAUTION AND WARNING SYSTEM

As part of the CAU project, the initial upgrade to the Caution and Warning System ameliorates some of the deficiencies of the current system. Because the current system so frequently overloads the crew with excessive information, and provides so little support for interpreting the information, the Fault Summary display in particular violates principles recommended by authors such as Hawkins (1987) by not presenting information in an effective manner. The upgraded Fault Summary display (Figure 4) is designed to function as a centralized single-point source for failure information and overall vehicle health, as opposed to the current cockpit, in which the crew must decipher panels of lights and displays across multiple regions of the cockpit. Each critical system on the shuttle has a small dedicated section on the display, providing key "at-a-glance" information about the health of each system. Perceptually grouping related information in this manner is a well-established means of reducing information processing difficulty (Man-Systems Integration Standards, 1995, section 9.6.2.6.1) and is recommended for visual displays (Department of Defense Design

Criteria Standard: Human Engineering, 1999, section 5.2.1.4.6).

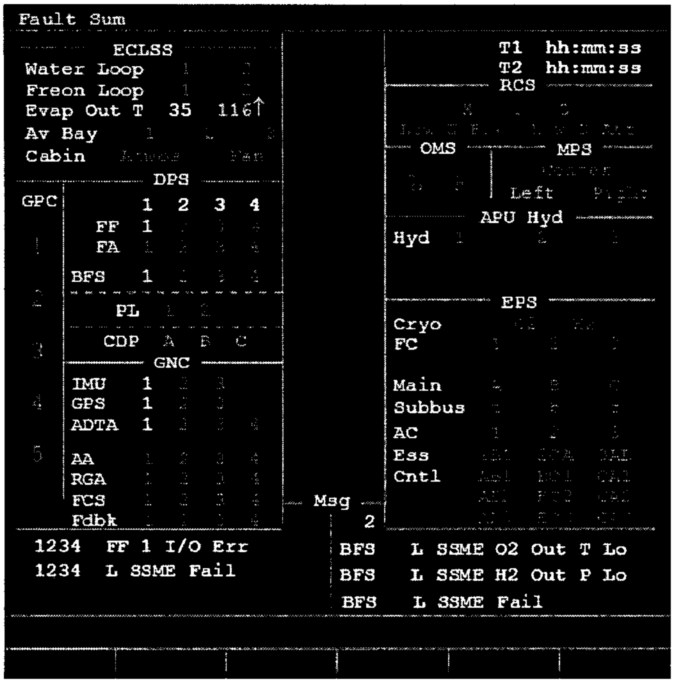

Figure 4: Initial Upgrade to the Fault Summary display.

The systems sections are also arranged in a logical manner to facilitate a more rapid determination of fault criticality. For example, the center section (the blank vertical region in Figure 4) is reserved for critical faults such as a detection of smoke, cabin depressurization, or a computer failure. There are several distinct regions reserved for brief text messages, such as "Fire/Smoke" or "dP/dt" (for cabin depressurization).

In the shuttle cockpit, the commander (who sits in the left seat) has physical access to a different set of mechanical switches than the pilot, who sits in the right seat. Hence, each crewmember is responsible for reconfiguration activities on a distinct subset of the systems. The redesigned Fault Summary display corresponds to the functional cockpit layout in that systems (switches) controlled by the commander are on the left (such as ECLSS, the Environmental Control and Life Support System), whereas systems (switches) controlled by the pilot are on the right (such as RCS, the Reaction Control System). In this way, each crewmember's reconfiguration responsibilities are cued by the particular spatial location of the systems sections.

Last but not least, the initial upgrade to the Fault Summary display employs the principle of "quiet/dark" to optimize the deployment of visual attention across the display. Nominal (meaning acceptable) parameters are displayed as dark gray, which is subdued enough not to attract the crew's attention while still being readable. If a parameter goes off nominal (out of acceptable range), it is color-coded. For example, the numbers 1 and 2 to the right of "Water Loop" in the upper left corner of Figure 4 are nominally dark gray. If water loop 1 fails, the associated number turns red. This kind of color-coding on the Fault Summary display should facilitate rapid switching of attention between the fault messages and the affected system section, helping the crewmember to more rapidly associate the fault with a particular vehicle system or subsystem. In turn, this should facilitate prioritizing tasks and navigating to the appropriate system detail display for further diagnostic activities.

These color-coding standards comply with many general recommendations in industry, such as coding qualitative (not quantitative) information (e.g., nominal information versus warning information) (Aerospace Recommended Practice, 1998) and ensuring the color is relevant to the task (Boff and Lincoln, 1988).

In summary, the upgraded Fault Summary design contains many improvements over the current Fault Summary display. Although the redesign addresses several limitations of the current Caution and Warning system, it will still require a high degree of training to recognize the failures and resolve the root-cause of those failures. The subsequent upgrade, described in the next section, attempts to resolve those remaining drawbacks.

4. SUBSEQUENT UPGRADE TO THE CAUTION AND WARNING SYSTEM

The primary goal of the Enhanced Caution and Warning System is to further improve the crew's ability to diagnose and resolve malfunctions. This improvement will be most evident in the lower region of the Fault Summary display, which contains text messages describing malfunctions.

The text message region will be improved in three key ways. First, ECW will incorporate rule-based logic to resolve a multiple signature failure down to its operationally relevant (root-cause) level. Therefore, only root-cause problems will be shown in the message region, allowing the crew to focus quickly on the source of the malfunction rather than its extraneous effects. This should greatly reduce the workload needed to diagnose a failure.

Second, root-cause messages that are not critical to the relevant task at hand will either be inhibited (meaning they will never appear) or suppressed (meaning they will appear at a later, more appropriate time). For example, towards the end of a mission, messages associated with main engines would be inhibited since the engines are off during that portion of flight. This principle of designing the display for the most probable case (that is, showing the crew only the information they really need) complies with human factors standards such as those described by Cooper (1995).

Third, the message area will no longer be divided into distinct regions for the classes of software systems. Instead, the left side is devoted to failure messages, and the right side to critical system alerts.

5. DISCUSSION

The proposed modifications to the Caution and Warning System are based on collaboration among several groups, including astronauts, astronaut trainers, flight software experts, Mission Control operators, and human factors scientists. Although this team is competent in designing cockpit displays, further improvements beyond these modifications will undoubtedly be possible.

It is important to realize, however, that the space shuttle cockpit is a unique environment that precludes certain upgrade paths that human factors specialists in other environments might expect to be pursued. For example, a case could be made that an upgraded Caution and Warning System would derive considerable benefit from an alternative input device (such as a mouse or trackball) instead of a keyboard. However, the turbulence or weightlessness felt by the crew during various phases of a mission make such precision devices difficult to operate. In addition, during ascent and entry, crewmembers wear fairly thick gloves, which restrict fine motor control. Another example would be to incorporate a natural voice-recognition interface to reduce the need for manual forms of display navigation. Once again, the turbulence and noise during critical flight phases (e.g., ascent and entry) reduce the feasibility of such an interface. Moreover, the limitations of the onboard computers preclude the computationally demanding requirements of a voice-recognition system.

As a result of these and other factors, the options for improving the Caution and Warning System are more limited than one might first expect. Nevertheless, careful consideration of available capabilities revealed several targets of opportunity for improving the system. These modifications rely on established design guidelines and standards.

Human factors scientists provided guidelines and standards while working with system experts as well as the actual users (i.e., the astronauts). Presumably, a human factors consultant could work only with the end-users (in this case, astronauts) to determine the appropriate methods for modifying the user interface. However, because of shuttle-specific restrictions (such as limited onboard computational processing), a number of other types of participants were needed to make feasible and constructive upgrades to the Caution and Warning System. In working on such a massively complex system such as the Space Shuttle, a single type of participant would be unable to fully provide the relevant competency for designing effective operational displays. This principle applies towards other projects as well. A human factors consultant should ensure that the design of a system carefully takes into account all limitations and restrictions that might otherwise be overlooked.

As a means of quantifying whether or to what extent the CAU project has reached its goals, a formal evaluation of the modified cockpit is being planned for 2003 and 2004. This evaluation will measure the crew's workload, situational awareness and performance with the current cockpit compared with the modified cockpit.

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