Development of New Displays for the Cockpit of the Space Shuttle

Jeffrey W. McCandless, Ph.D.
Robert S. McCann, Ph.D.

Contact Information:

Jeffrey W. McCandless, Ph.D.
San Jose State University Foundation and NASA Ames Research Center
Address: Mail Stop 262-2, NASA Ames Research Center, Moffett Field, CA 94035-1000
Phone: 650-604-1162
Fax: 650-604-3323
Email: jmccandless@mail.arc.nasa.gov

Robert S. McCann, Ph.D.
NASA Ames Research Center
Address: Mail Stop 262-4, NASA Ames Research Center, Moffett Field, CA 94035-1000
Phone: 650-604-0052
Fax: 650-604-3323
Email: rmccann@mail.arc.nasa.gov

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Abstract

During a Space Shuttle mission, astronauts in the cockpit can view any one of dozens of display formats containing vehicle and mission-critical information. During launch, for example, the crew may view a display format showing tank pressures associated with the main engines. During orbit, the crew no longer needs main engine data, and might instead call up a display format containing details of the robotic arm that controls the payload. In the original cockpit, display formats were viewed on four cathode ray tubes (CRTs). In part due to the limitations of the CRTs, the display formats were monochrome and mostly text-based, with almost no graphical content.

Currently, the cockpit of each Space Shuttle is being upgraded. A key aspect of the upgrades is the replacement of the four CRTs with 11 color liquid crystal displays (LCDs). The new LCDs have greatly expanded graphics capabilities compared to the CRTs. However, the display formats presented on the LCDs are largely identical copies of the original display formats. Now that the LCDs have been proven in flight to be reliable and effective, NASA is exploiting the expanded color and graphics capabilities of the LCDs to design a new generation of more user-friendly display formats. The proposed formats make systematic and logical use of color. For example, a critical parameter may turn red when the value is off-nominal. In addition, the proposed formats make expanded use of graphics to provide a closer match to the crewmember's mental model of the system being depicted. These changes will enable the crew members to acquire systems information "at a glance", thereby reducing workload and increasing situational awareness.

1. Introduction

During a Space Shuttle mission, the astronauts onboard access information through a number of means, including electromechanical gauges, paper documents, and computer screens. The computer screens in the cockpit were originally designed to be four monochrome cathode ray tube (CRT) screens, as shown in Figure 1. Three of the CRTs are in the forward section of the cockpit and the fourth is in the aft section.

Figure 1: Original Space Shuttle cockpit. Three of the CRTs are in the forward section of the cockpit, as shown here. The fourth CRT is in the aft section of the cockpit.

One of the key classes of information shown on a computer screen is a display format, which is a window that fills the screen with a specific type of data. For example, during launch, the crew may view a display format showing the flight path trajectory of the Space Shuttle. Once the Space Shuttle is in orbit, the crew may view a display format showing information about the robotic arm. During entry, the crew may view a display format showing information on aerosurfaces such as the rudder. Several dozen different display formats are available for the crew. Because the CRTs have limited graphical capabilities, the display formats are primarily text, as shown in Figure 2.

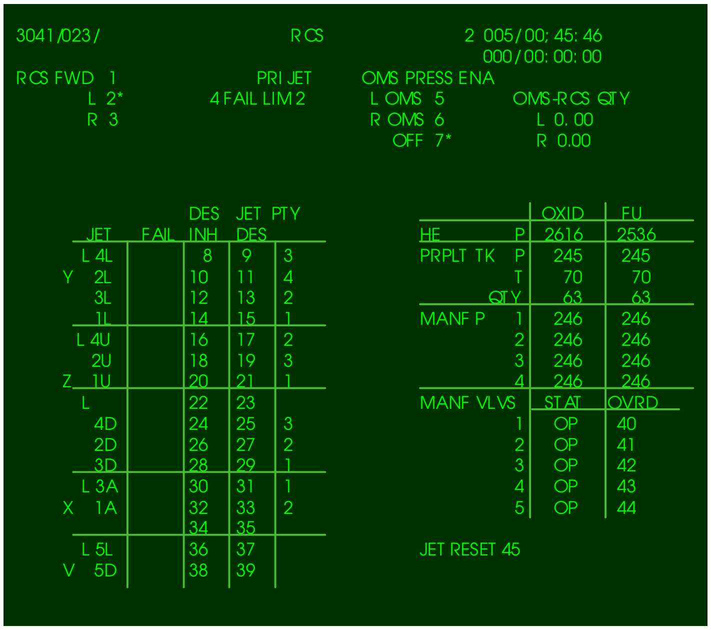

Figure 2: Typical display format shown on the CRTs in the cockpit.

The four CRTs in each of the Space Shuttle vehicles are being replaced with 11 color liquid crystal display (LCD) screens. The new LCDs have the same characteristics as those in the Boeing 777 aircraft (McCartney and Ackerman, 1994). The new system, produced by Honeywell Space Systems, is known as the Multifunction Electronic Display System (MEDS). As of the end of 2001, two of the four Space Shuttles had been upgraded with MEDS, shown in Figure 3. Key benefits of the new displays are lower cost and greater reliability.

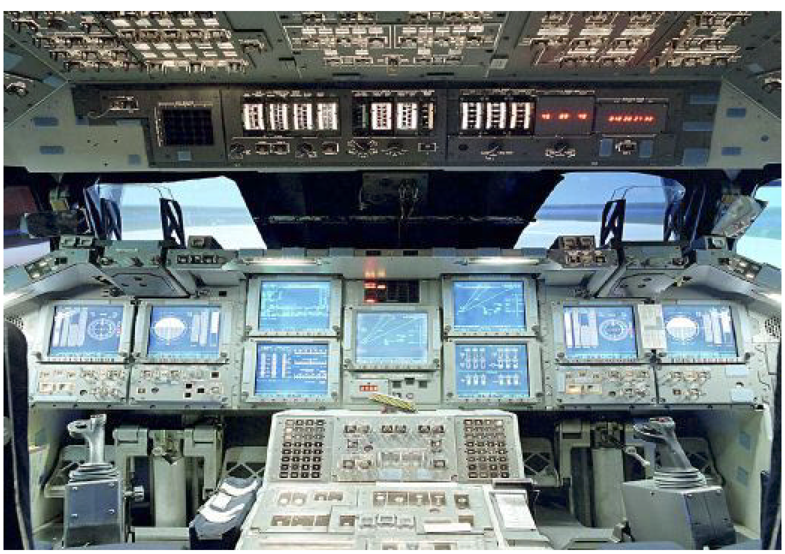

Figure 3: Updated Space Shuttle cockpit with LCD screens. Nine of the LCDs are in the forward part of the cockpit, as shown here. The remaining two LCDs are in the aft section of the cockpit.

Although the new LCDs have greater graphical and color capabilities than the original CRTs, the display formats shown on them are largely identical copies of the older display formats. Currently, NASA is developing new display formats that take advantage of the graphical and color possibilities of the LCDs. Under the Cockpit Avionics Upgrade program based at NASA Johnson Space Center, each of the dozens of display formats is being redesigned through a collaborative effort that includes astronauts, usability consultants, engineers, programmers, mission controllers, and astronaut trainers. Usability consultants provide a necessary input because a fundamental issue in developing the new display formats is the application of usability principles to ensure that the new formats are an efficient means of transmitting information to the crew. The challenge in such a task is the design of effective displays within the constraints imposed by factors such as limitations of the onboard computers and software. In many cases, compromises in usability and display design are required because of these limiting factors. Nevertheless, the modified display formats represent a significant improvement compared with the current display formats that are primarily monochrome and text. The updated display formats are anticipated to be implemented in all four Space Shuttles in approximately 2005.

2. Color and Graphics Standards

The purpose of color on the proposed display formats is to enable the crew to differentiate the varied classes of data and information, particularly during off-nominal conditions. Recommendations on the appropriate number of colors on a display vary from source to source, with most authors preferring no more than six colors, as noted by Stokes, Wickens and Kite (1990). However, this number depends on the type of display being considered by the designer, and in appropriate cases the number may be higher. For example, Spiker, Rogers and Cicenelli (1985) used twelve colors in a computer-generated topographic map. For the updated display formats in the cockpit of the Space Shuttle, the proposed number of colors (as of 2002) is 14, as shown in Table 1. (The final number of colors may vary depending on further prototyping.) A key rationale behind using such a high number is that not all 14 colors appear simultaneously on the same display format. In addition, the crews are highly trained on the significance of each color.

Table 1. Colors specified for the upgraded display formats.

	Color Name	**Typical Conditions**	**Typical Use**
1	dark blue	nominal	background of the display format
2	dark gray	nominal	lines that separate regions of the display format
3	light gray	nominal	labels adjacent to the data
4	white	nominal	nominal data
5	orange	off-nominal	discrepancies between the two software systems
6	red	off-nominal	warnings
7	yellow	off-nominal	cautions
8	cyan	off-nominal	missing data
9	magenta	nominal	commands to the crew

10	light green	nominal	title of the display format
11	dark green	nominal	item numbers corresponding to some labels
12	blue	nominal	special (occasional) use
13	pink	nominal	special (occasional) use
14	brown	nominal	special (occasional) use

An example of a proposed display format with a representative class of failures is shown in Figure 4. (This display format and others in this paper may be subject to additional modifications after prototyping.) Although the display would be unlikely to appear with so many colors (caused by a large number of failures), this figure does provide an example of how most of the colors listed in Table 1 would be implemented.

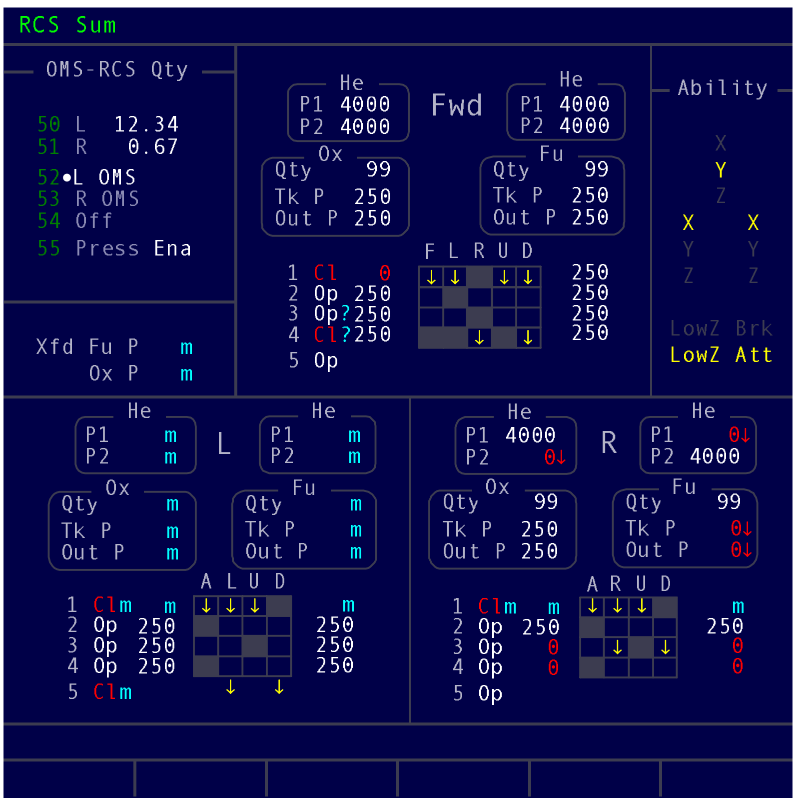

Figure 4: Proposed display format showing a large number of colors due to many simultaneous failures of onboard systems.

Each of the colors was specifically chosen based on display constraints and usability principles. For example, dark blue was constrained to be the background color of the displays. Even when all three of the LCD color channels (red, green, blue) are set to their lowest setting (a value of 0 out of 15), the color of the display screen appears dark blue, not black. Ideally, the screen would be black in that case, however, limitations of the display hardware prevent a truly black background. Dark gray color is similar to the background and is therefore reserved for non-critical elements such as separator lines. Light gray was chosen as the color of display labels to make them visible, but not as salient as the dynamic data, which are normally colored white. Although green is generally associated with an item that is acceptable, the goal for the shuttle displays was to maximize the contrast between the nominal data and background, even at the expense of violating a general color convention. For that reason, nominal data are colored white, not green. In off-nominal cases, the data (and associated messages) appear orange, red, yellow or cyan depending on the type of fault. The critical colors of red and yellow correspond to conventional meanings (red equals warning and yellow equals caution), as recommended in sources such as Krebs, Wolf and Sandvig (1978). The purpose of conventional coding for caution and warning colors is to draw attention rapidly, as suggested by Stokes and Wickens (1988). Magenta, which also appears bright and noticeable, is reserved for commanded messages, which are critical for the crew to read. Light green is reserved for the display title as well as highlighting of some display regions being changed by the crew. Dark green, which is not as vivid as light green, is used for less critical information. In particular, it is used to color the item entry numbers next to the labels and data. The three remaining colors (blue, pink and brown) have limited use.

3. Graphics and Layout Standards

Graphics on the updated display formats are based on simple yet effective symbology to indicate components such as valves, pipes, and tanks. Simple symbols are often used to indicate failures of onboard systems. For example, if a jet in one of the propulsion systems cannot fire, a yellow down arrow may be shown to represent that it is unavailable. Prior studies have shown that focal attention can be captured automatically with a unique salient object (Turatto and Galfano, 2000). Similarly, a yellow arrow is a color singleton (i.e., a distinctly colored item) that draws attention rapidly.

A key goal in designing the overall display layout is to match the layout with the operator's mental model (and sometimes physical implementation) of how the system is organized. An example is the Reaction Control System (RCS), which provides propulsive forces to control the motion of the Space Shuttle by firing propellant through 44 jets. The pods containing the RCS jets are located in three regions of the Space Shuttle: forward, aft left and aft right. Accordingly, the three regions on the display corresponding to those pods are upper (for the forward pod), lower left (for the aft left pod), and lower right (for the aft right pod). The logical principle of designing displays to correspond with the user's mental model (and in this case the actual physical implementation) is described by Cooper (1995). Placing information from all three pods is a related improvement compared with the current RCS displays, which required the user to bring up a new window for each pod. The new approach reduces the information access cost, as suggested, for example, by Wickens and Carswell (1995).

4. Comparison of Malfunctions Under Current and Proposed Display Formats

The display format for the RCS is a good example of how human factors principles can improve the salience of off-nominal information. An example of an off-nominal situation occurs if a RCS manifold valve becomes closed. In that case, the associated jets will not be able fire. Detecting that condition becomes easier with the proposed display formats compared with the original display format, as shown in Figure 5.

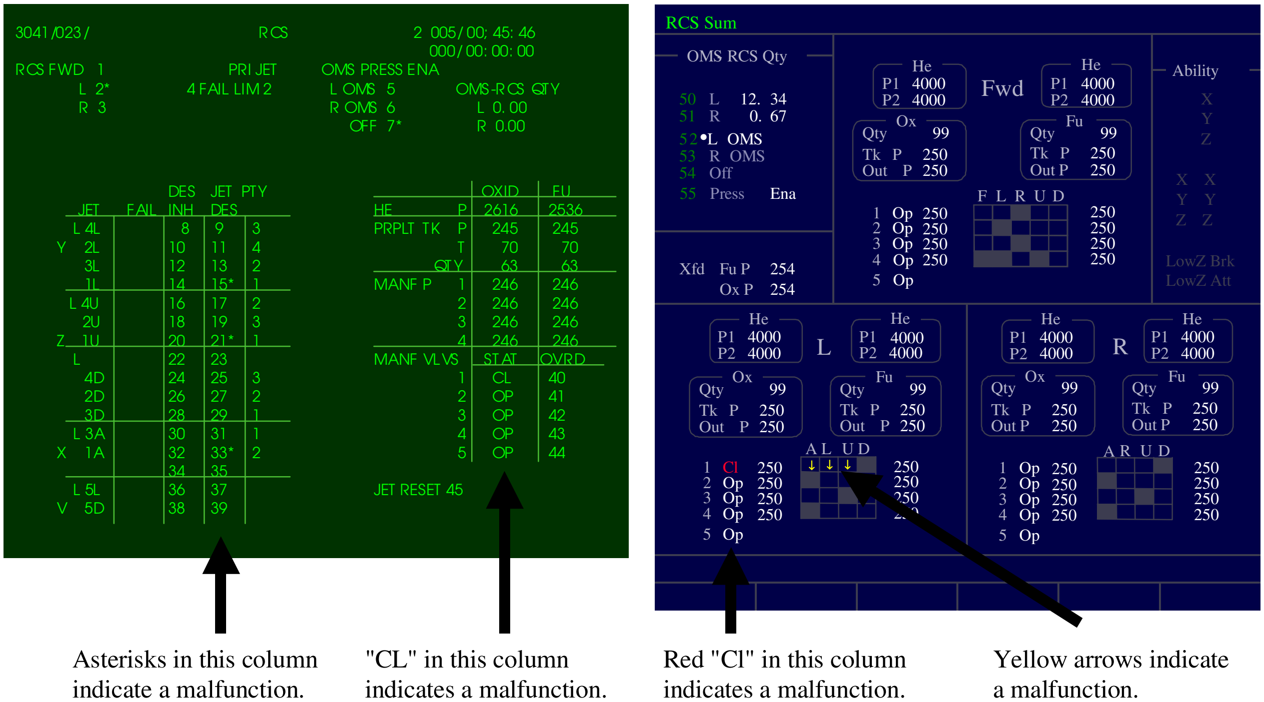

Figure 5: Display format for the Reaction Control System showing a malfunction caused by a closed valve. With the current display format (left side), the malfunction is indicated by asterisks in the column corresponding to jet deselect and the letters "CL" (for closed) in the column for valve status. With the proposed display format (right side), the malfunction is easier to detect because of color coding and symbology (red "Cl" and yellow down arrows.)

With the current display format, the crew would detect failed jets by locating asterisks next to the corresponding jets in the "JET DES" (for jet deselect) column, as well as a "CL" notification next to the manifold valve. With the proposed display format, this information is more readily shown through red "Cl" singleton and yellow down arrows next to the associated jets. Such a design is a more effective means of drawing a crewmember's attention to the malfunction.

5. Discussion

The new display formats for the cockpit of the Space Shuttle are designed to improve situational awareness and reduce workload by incorporating fundamental human factors and usability principles. These goals are being met in a unique environment in which the number of users is low (there are only about 150 astronauts). As a result, the abilities and characteristics of the users are well known, making some aspects of the design process straightforward. For example, the designers do not have to wonder whether the users will comprehend the significance of the different types of graphical symbology on the display interface. Because astronauts train for at least two years before their first mission, they fully understand how to use the display formats. Nevertheless, such experience and training on the part of the users does not reduce the necessity of having user-friendly displays. In such a critical and potentially dangerous environment as spaceflight, display formats must be designed to clearly present information to the crew, thereby maximizing safety. By taking into account the recommendations of usability consultants, astronauts, and others, NASA is developing an improved set of display formats for the Space Shuttle.

Appendix A: References

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Appendix B: Acronyms

CRT	Cathode Ray Tube
LCD	Liquid Crystal Display
MEDS	Multifunction Electronic Display System
NASA	National Aeronautics and Space Administration
RCS	Reaction Control System