NEW DISPLAYS FOR THE SPACE SHUTTLE COCKPIT

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Color is critical in reducing workload and enhancing situation awareness for shuttle astronauts.

THE SPACE SHUTTLE WAS DEVELOPED in the 1970s using technology that was advanced for its time. The recent upgrade, called the Multifunction Electronic Display System (MEDS), helped to remedy the obsolescence of the original cockpit components, but MEDS did not resolve the human factors drawbacks of the legacy cockpit displays. To address these deficiencies, the National Aeronautics and Space Administration (NASA) initiated a usability-oriented modification called the *cockpit avionics upgrade*. The goals were to redesign the displays to improve situation awareness, reduce workload, and improve performance.

In this article, we describe the human factors principles that guided the redesign.

DRAWBACKS OF THE ORIGINAL DISPLAY DESIGN

Astronauts on a space shuttle mission access information about the vehicle through a variety of sources, including electromechanical gauges, paper documents, and computer-generated displays. The latter were originally available on monochrome CRT screens, as shown in Figure 1. During the launch or entry flight phases, the three CRTs in the forward section of the flight deck were visually accessible by the pilot and commander. The fourth CRT, in the aft section, was accessible by one of the mission specialists.

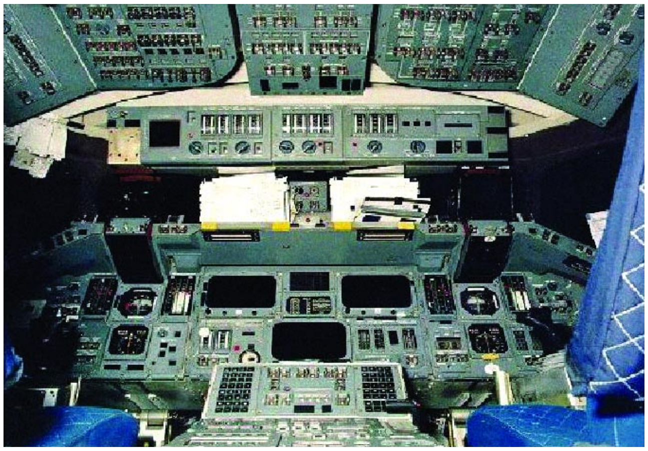
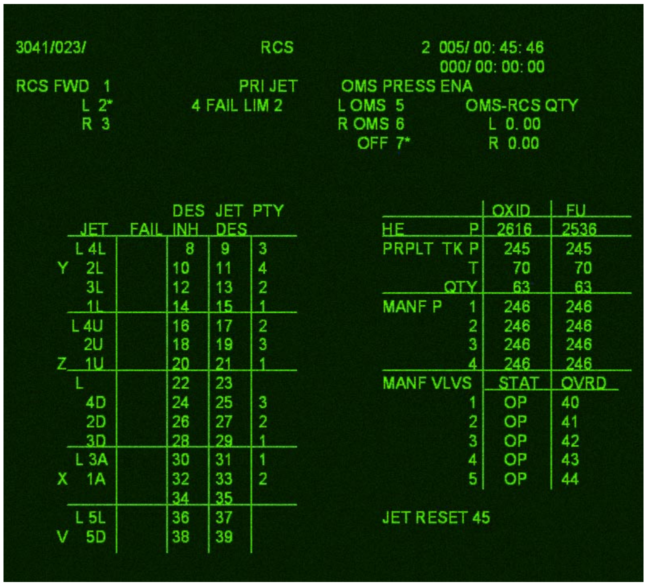


Figure 1: Original space shuttle cockpit. Three of the CRTs are in the forward section of the cockpit, as shown here. The fourth CRT is in the aft section of the cockpit.

The information on each CRT was presented in a display format, a window that filled the screen with a specific type of data. For example, following liftoff, the crew might select a display format called "Ascent Traj 1," which showed the flight path trajectory of the shuttle during the first stage of powered flight (prior to solid rocket booster separation). Once the shuttle was in orbit, the crew no longer needed information about the ascent trajectory and might instead view a display format providing information about the robotic arm. During entry, the crew might select a display format showing information on the position of the flight control aerosurfaces, such as the rudder. Several dozen display formats were available for the crew, and an example is shown in Figure 2.

FEATURE AT A GLANCE: During a spaceflight mission, astronauts in the space shuttle obtain much information from cockpit displays that convey critical details, such as the status of the main engines and the electrical systems. In the original design of the space shuttle, the displays contained simple monochrome graphics with dense arrays of numbers. In the proposed upgraded cockpit, the displays contain a better layout of information through enhanced graphics and color. The goal is to reduce the time necessary for an astronaut to interpret and analyze key information about the vehicle.

KEYWORDS: interface, situation awareness, space flight, cockpit, displays, human factors



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3041/023/                    RCS              2 005/ 00: 45: 46
                                                000/ 00: 00: 00
RCS FWD  1             PRI JET      OMS PRESS ENA
      L 2*          4 FAIL LIM 2    L OMS  5        OMS-RCS QTY
      R 3                           R OMS  6          L  0. 00
                                      OFF  7*         R  0.00


                   DES   JET  PTY                  | OXID  |  FU
       JET   FAIL  INH   DES         HE           P| 2616  | 2536
      L 4L       |    8 |  9 | 3     PRPLT  TK P|  245  |  245
   Y    2L       |   10 | 11 | 4                 T|   70  |   70
        3L       |   12 | 13 | 2              QTY|   63  |   63
        1L       |   14 | 15 | 1     MANF P     1|  246  |  246
     L 4U        |   16 | 17 | 2                 2|  246  |  246
        2U       |   18 | 19 | 3                 3|  246  |  246
   Z    1U       |   20 | 21 | 1                 4|  246  |  246
      L          |   22 | 23 |       MANF VLVS    |  STAT | OVRD
        4D       |   24 | 25 | 3                 1|  OP   |  40
        2D       |   26 | 27 | 2                 2|  OP   |  41
        3D       |   28 | 29 | 1                 3|  OP   |  42
      L 3A       |   30 | 31 | 1                 4|  OP   |  43
   X    1A       |   32 | 33 | 2                 5|  OP   |  44
                 |   34 | 35 |
      L 5L       |   36 | 37 |       JET RESET 45
   V    5D       |   38 | 39 |
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Figure 2: Typical display format shown on the CRTs in the cockpit.

The display formats on the CRTs in the original space shuttle design (and still used in Space Shuttle *Endeavour*) have a number of human factors drawbacks.

- The original CRTs are monochromatic, so all graphics and text are green on a black background.
- Most of the information on the displays is in digital form and is frequently arranged in closely spaced rows and columns, making it difficult to localize and process key sources of information such as off-nominal readings.
- System and subsystem information is often poorly organized from the viewpoint of the end user. Information about one system or even one flight parameter is sometimes scattered across two or more display formats, not all of which can be viewed simultaneously.
- On any single display format, information about one system sometimes occupies a region adjacent to a region containing information about a completely separate system. This seemingly haphazard structure is driven in part by the limitations on processing speed and memory in the general-purpose computers that provide both the flight control and flight management functions for the orbiter.

THE INITIAL COCKPIT UPGRADE

The MEDS upgrade (Figure 3) replaces many of the obsolete electromechanical gauges and all four CRTs with color LCDs, thereby improving the reliability and maintenance requirements of the original screens and instruments. Because the upgrade was driven by concerns over hardware obsolescence and maintenance, few human factors limitations of the original design were addressed. For example, although the MEDS screens have full-color capability, only minor color changes were introduced (such as making the alert symbols yellow).

The display formats shown in the MEDS cockpits are largely copied versions of the formats designed for the original cockpit. In many cases, MEDS displays are merely "painted" versions of the electromechanical instruments they replaced. The MEDS display hardware is an adaptation of the technology used for cockpit displays in the Boeing 777 (McCartney & Ackerman, 1994). This upgrade was first flown in the Space Shuttle *Atlantis* in 2000.

PROPOSED COCKPIT UPGRADE

Under the cockpit avionics upgrade project based at NASA Johnson Space Center, each of the dozens of legacy display formats was redesigned by teams that included astronauts, human factors scientists, engineers, programmers, mission controllers, and astronaut trainers. The project includes installation of a separate set of high-power computers allowing for much-improved supplemental calculations to be utilized in the development of vehicle displays and controls.

Designers of the cockpit avionics upgrade displays were able to make sweeping changes to the legacy formats, in many cases replacing them completely.

A fundamental issue in developing the new display formats was the application of human factors usability principles to ensure that the new formats would provide information that is intuitive and quickly comprehended. The challenge is that despite the MEDS and cockpit avionics hardware upgrades, there are still strong design constraints. For example, the display

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 are in the aft section of the cockpit.

size of each screen is only about 6.7 × 6.7 inches. The user interface is restricted to three identical 32-key keypads (with no mouse or trackpad available), plus six so-called edge keys at the base of each display to provide a means for crewmembers to navigate through different display formats. Although we briefly considered modifications of these characteristics (such as adding more edge keys), they were not used in the final approved design because of cost constraints. Nevertheless, designers of the cockpit avionics upgrade displays were able to make sweeping changes to the legacy formats, in many cases replacing them completely.

Color principles for the proposed cockpit upgrade. One of the biggest underutilizations of the LCDs in the MEDS cockpit is the limited use of color. The proposed display formats use color in a systematic fashion to enable the crew to differentiate classes of data and information, particularly during off-nominal conditions (defined as malfunction cases such as coolant leaks). Recommendations on the appropriate number of colors on a single display vary from source to source, with most authors preferring no more than six colors (Stokes, Wickens, & 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, in a human factors analysis, Spiker, Rogers, and Cicinelli (1985) used 12 colors in a computer-generated map to help military personnel differentiate features such as roads, streams, and bridges.

> Each color was specifically chosen based on balancing display constraints with usability principles.

For the updated display formats in the cockpit of the space shuttle, the proposed number of colors is 10. A key rationale behind using such a high number is that not all colors appear on the display format simultaneously (which otherwise may produce a somewhat overwhelming, cluttered appearance). On most displays, the number of colors is typically no more than 6. In addition, not all colors apply to dynamic digital data; a number of colors apply to static parameters such as background color and separator lines.

In addition, the relatively high number of colors aids the crew in differentiating the characteristics of such an intricate vehicle. The space shuttle is the most ambitious flying machine ever built. It operates as a rocket during launch, a spacecraft during orbit, and a glider during entry. The complexity of the systems needed to support these functions imposes large mental demands on the crew to maintain situational awareness of systems mode and status. Distinct color-coding is intended to aid the crew in maintaining that awareness.

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 article may be subject to modifications after additional design work). Although actual displays would be unlikely to contain so many colors (caused by a large number of failures), this figure does provide an example of most of the color-coding conventions.

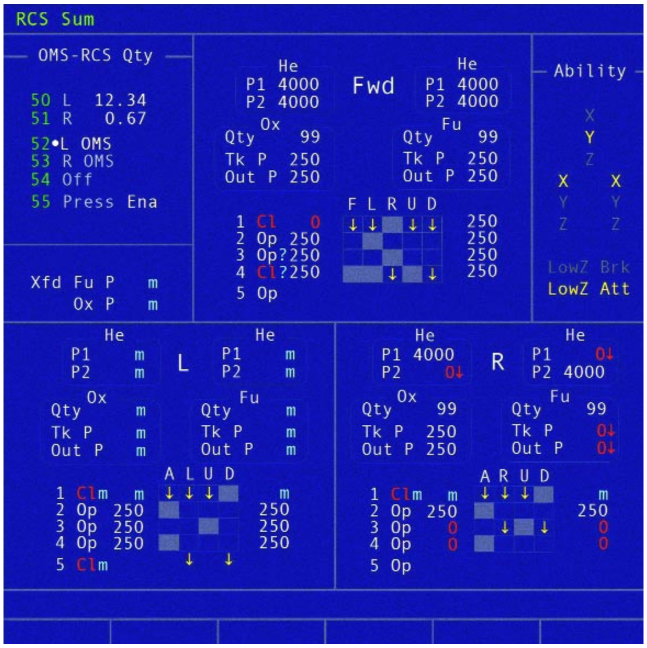


Figure 4: Proposed display format showing a large number of colors because of many simultaneous failures of onboard systems.

Each color was specifically chosen based on balancing display constraints with usability principles. For example, the ideal background color of a display would maximize the contrast between the background and all foreground hues and colors. On the shuttle LCDs, however, even when all three of the LCD color channels (red, green, blue) are set to their lowest setting (a value of 0 to 15), the color of the display screen appears dark blue, not black. Dark gray is similar to the background and is therefore reserved for noncritical elements such as separator lines.

We chose light blue-gray as the color of display labels to make them distinctly visible but not as salient as data being driven by a dynamic source, such as main engine chamber pressure, which are normally 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 white, not green. Magenta, which also appears bright and noticeable, is reserved for commanded messages, such as action alerts, which are critical for the crew to read. Light green is reserved for the display title and navigation as well as highlighting data fields that can be changed by the crew.

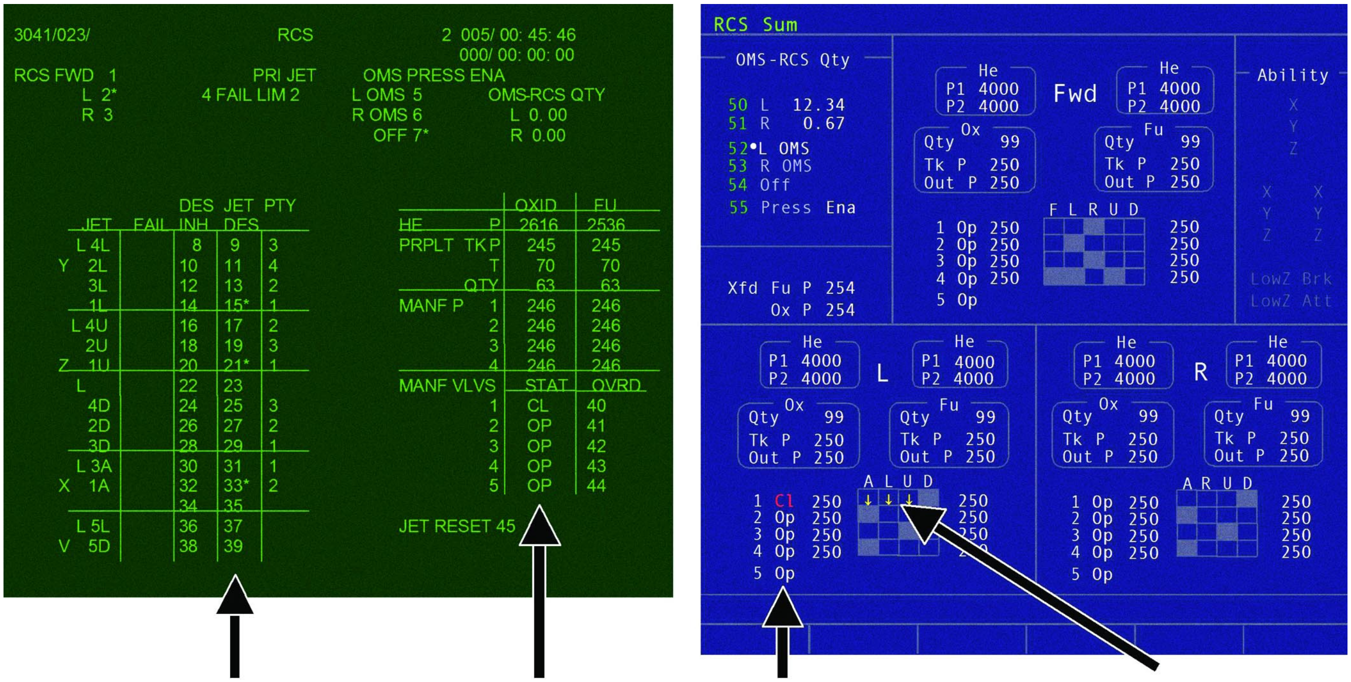
Four colors are used to represent off-nominal (failure) conditions: red, yellow, orange, or cyan (blue). The critical colors of red (warning) and yellow (caution) correspond to the conventional meanings for these colors (Krebs, Wolf, & Sandvig, 1978). The purpose of conventional coding for the caution and warning colors is to draw attention rapidly, as suggested by Stokes and Wickens (1988). Orange represents a unique condition in which the onboard primary and backup computer systems produce different outputs (for example, to indicate that the primary computer system would control the engine thrust to a different level than the backup computer system). Cyan represents cases in which data are unavailable for display because, for example, a sensor has failed.

Graphics principles for the proposed cockpit. Graphics on the updated display formats are constructed from simple but effective symbologies representing components such as valves, pipes, and tanks. Familiar but salient symbols are often used to indicate component failures. 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. The yellow arrow forms a color singleton (i.e., a distinctly colored item) that is highly effective at capturing visual attention (Turatto & Galfano, 2000). Pipes that contain a fluid that is flowing (such as Main Propulsion System propellant during ascent) are white. Pipes that contain either stationary or no fluid (such as downstream of a closed valve) are gray. Valves themselves are depicted by circular icons superimposed on the pipes. Small bars within the icons change orientation depending on whether the valve is open or closed.

A key goal in designing the overall display layout was to match it with the operator's mental model (and sometimes physical implementation) of system structure and system functioning. An example is the Reaction Control System (RCS), a collection of 44 jets that provide propulsive forces primarily to control the attitude and maneuvering of the shuttle in orbit. The pods containing these jets are located in three regions: forward, aft left, and aft right. Accordingly, the three regions on the RCS Summary 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.

> This consolidation reduces the workload required to build situation awareness of system functioning and capability.

The logic behind designing displays that correspond with the user's mental model (and, in this case, the actual physical implementation) of the depicted system is described by Cooper (1995). Consolidating the information from all three pods in a single display format is an improvement over the current arrangement, which distributes RCS pod information



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3041/023/                    RCS                2 005/ 00: 45: 46
                                                  000/ 00: 00: 00
RCS FWD  1              PRI JET      OMS PRESS ENA
      L  2*          4 FAIL LIM 2   L OMS 5         OMS-RCS QTY
      R  3                          R OMS 6           L 0. 00
                                      OFF 7*          R 0.00

                 DES  JET  PTY                       OXID    FU
      JET  FAIL  INH  DES           HE           P   2616    2536
      L 4L          8    9    3     PRPLT  TK P      245     245
    Y   2L         10   11    4                T      70      70
        3L         12   13    2              QTY      63      63
        1L         14   15*   1     MANF P     1     246     246
      L 4U         16   17    2                2     246     246
        2U         18   19    3                3     246     246
    Z   1U         20   21*   1                4     246     246
      L            22   23          MANF VLVS        STAT    OVRD
        4D         24   25    3                1     CL      40
        2D         26   27    2                2     OP      41
        3D         28   29    1                3     OP      42
      L 3A         30   31    1                4     OP      43
    X   1A         32   33*   2                5     OP      44
                   34   35
      L 5L         36   37          JET RESET 45
    V   5D         38   39
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RCS Sum
 OMS-RCS Qty          He                    He          Ability
                    P1 4000      Fwd      P1 4000          X
 50 L   12.34       P2 4000               P2 4000          Y
 51 R    0.67           Ox                    Fu           Z
 52•L OMS          Qty     99            Qty     99
 53 R OMS          Tk  P   250           Tk  P   250     X     X
 54 Off            Out P   250           Out P   250     Y     Y
 55 Press Ena                 F L R U D                  Z     Z
                    1 Op 250                 250
                    2 Op 250                 250
                    3 Op 250                 250
 Xfd Fu P 254       4 Op 250                 250       LowZ Brk
     Ox P 254       5 Op                               LowZ Att

      He                 He                 He                 He
   P1 4000     L      P1 4000            P1 4000     R      P1 4000
   P2 4000            P2 4000            P2 4000            P2 4000
      Ox                 Fu                 Ox                 Fu
  Qty     99         Qty     99         Qty     99         Qty     99
  Tk  P  250         Tk  P  250         Tk  P  250         Tk  P  250
  Out P  250         Out P  250         Out P  250         Out P  250
                A L U D                              A R U D
   1 Cl 250     ↓ ↓ ↓       250          1 Op 250               250
   2 Op 250                 250          2 Op 250               250
   3 Op 250                 250          3 Op 250               250
   4 Op 250                 250          4 Op 250               250
   5 Op                                  5 Op
```

Asterisks in this column indicate a malfunction.

"CL" in this column indicates a malfunction.

Red "Cl" in this column indicates a malfunction.

Yellow arrows indicate a malfunction.

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.)

across three different display formats. This consolidation reduces the workload required to build situation awareness of system functioning and capability, as suggested, for example, by Wickens and Carswell (1995).

COMPARISON OF CURRENT AND PROPOSED DISPLAY FORMATS

The redesign of the RCS display format is a good example of how the application of human factors principles can improve the salience of off-nominal information. An example of an off-nominal situation occurs if an RCS manifold valve fails closed. In that case, the associated jets will be unable to fire. Detecting that loss of capability becomes easier with the proposed display formats compared with the original display format, as shown in Figure 5.

> The designers have confidence that users will comprehend the significance of the different types of graphical symbology on the display interface.

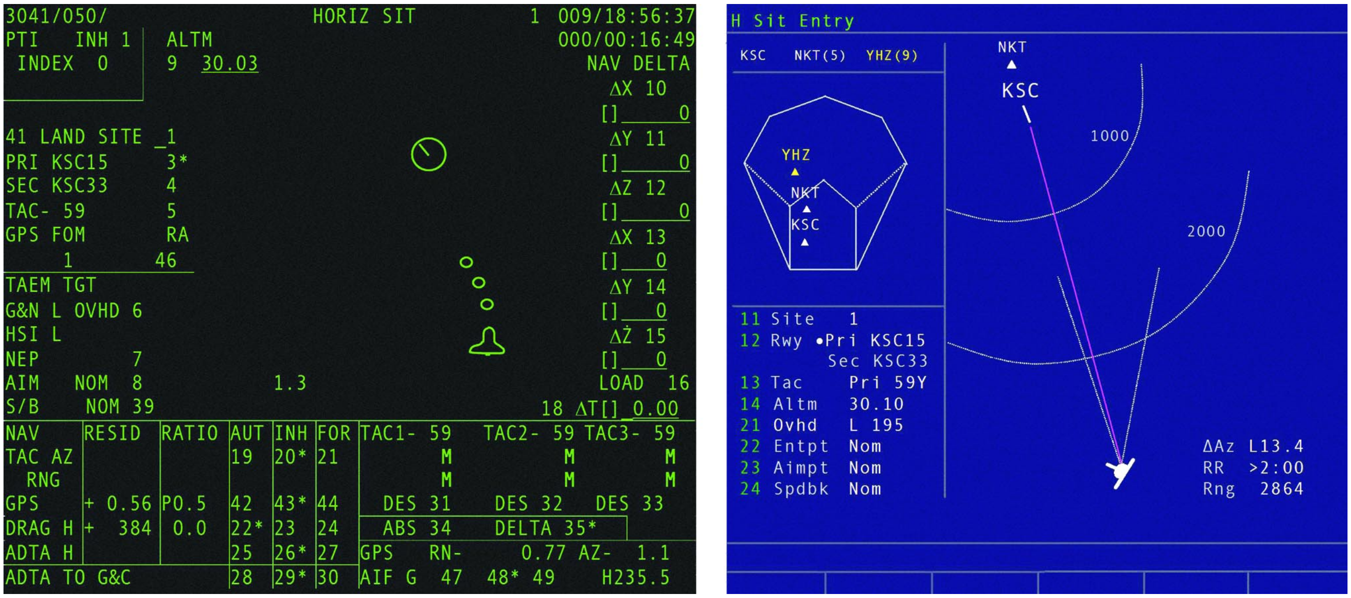
With the current display format, the crew can detect the failed jets only by locating asterisks next to the corresponding jets in the "JET DES" (for jet deselect) column, as well as a "CL" (closed) notification next to the manifold valve. In the proposed display format, this information is made more noticeable by coloring the "Cl" notification red and inserting 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.

A second example showing a current versus proposed display format is illustrated in Figure 6. The Horizontal Situation display depicts a top-down view of the space shuttle relative to the landing site during entry. It illustrates how the shuttle would appear when viewed from directly above as it approaches the runway. In the current display (left side of Figure 6), the runway is depicted by the circle with the line through it. The shuttle is depicted by the small graphic symbol. Noticeably absent is any indication of whether the shuttle has enough speed and altitude to actually reach the intended landing site.

The cockpit avionics upgrade display format (right side of Figure 6) shows this information in the form of an "energy footprint." This footprint displays information on what runways are achievable based on the shuttle's velocity, altitude, and distance from the landing site. The center portion (which looks like an inverted home plate) is the nominal energy region. Runways that appear in this section are achievable using nominal flight commands. Sites just outside the center portion are achievable only with more risky flying techniques that minimize energy loss during the entry profile. Sites that are in the nominal footprint are white (the nominal color) and sites in the low-energy footprint are yellow (indicating they are an off-nominal condition). Sites that are outside the nominal and low-energy regions are red, marking them as unobtainable. This design visually clarifies the capabilities of the shuttle, providing the crew with situation awareness not provided on the current display.

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



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3041/050/                  HORIZ SIT          1  009/18:56:37
PTI    INH 1 | ALTM                              000/00:16:49
 INDEX  0    | 9  30.03                             NAV DELTA
                                                       ΔX 10
                                                    []_____0
41 LAND SITE _1                                        ΔY 11
PRI KSC15      3*                                   []_____0
SEC KSC33      4                                       ΔZ 12
TAC- 59        5                                    []_____0
GPS FOM        RA                                      ΔX 13
     1         46                                   []___0
TAEM TGT                                               ΔY 14
G&N L OVHD 6                                        []___0
HSI L                                                  ΔŻ 15
NEP           7                                     []___0
AIM    NOM  8             1.3                        LOAD  16
S/B    NOM 39                                   18 ΔT[]_0.00
NAV     |RESID |RATIO |AUT |INH |FOR |TAC1- 59   TAC2- 59 TAC3- 59
TAC AZ  |      |      |19  |20* |21  |        M         M       M
  RNG   |      |      |    |    |    |        M         M       M
GPS     |+ 0.56|P0.5  |42  |43* |44  |  DES 31    DES 32    DES 33
DRAG H  |+  384| 0.0  |22* |23  |24  |  ABS 34    DELTA 35*
ADTA H  |      |      |25  |26* |27  |GPS   RN-      0.77 AZ-  1.1
ADTA TO G&C           |28  |29* |30  |AIF G  47  48* 49     H235.5
```

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H Sit Entry
KSC   NKT(5)  YHZ(9)

11 Site    1
12 Rwy  •Pri KSC15
         Sec KSC33
13 Tac     Pri 59Y
14 Altm    30.10
21 Ovhd    L 195
22 Entpt   Nom
23 Aimpt   Nom
24 Spdbk   Nom
                        ΔAz  L13.4
                        RR   >2:00
                        Rng   2864
```

Figure 6: Horizontal Situation Display format showing a top-down view of the space shuttle during entry. The current display format (left side) is monochrome with limited graphics. The proposed display format (right side) shows a graphical indication of which landing sites are reachable.

usability principles. Because of inherent constraints in the shuttle, not all recommendations made by the Human Factors Team were accepted. For example, electronic checklists were rejected as not feasible given the computational limitations on board. Instead, the crews rely on conventional paper checklists as part of the Flight Data File. Ideally, training would be available in the shuttle during orbit for crewmembers to practice reentry scenarios. In other words, the shuttle should have the capability during orbit of simulating entry. That type of simulation ability is also not feasible given the shuttle's hardware constraints. Similarly, the possibility of using voice cues for critical action alerts (such as "Pull up") was rejected.

The International Space Station (ISS) also relies on a number of displays to provide information to the crew. However, the ISS maintains distinct differences in its operation and hardware. It contains hundreds of display formats, as opposed to the dozens available on the shuttle cockpit screens. The cockpit avionics upgrade project was constrained by 11 fixed computer screens in the cockpit, whereas ISS allows for more flexibility with its laptop computers.

The goals of this project are being met in a unique environment in which the number of users is low – there are fewer than 200 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 have confidence that 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 and provide them with an environment for flawless vehicle control, thereby maximizing safety. By taking into account the recommendations of usability consultants, astronauts, and others, NASA has successfully developed an improved set of display formats for the space shuttle.

POSTSCRIPT

In late 2004, the planned implementation of cockpit avionics upgrade project displays was canceled because of budget constraints. Fortunately, the principles associated with the proposed designs remain valid and should be applied to the next-generation spacecraft.

As discussed in "The Vision for Space Exploration" (2004), NASA intends to develop a crew exploration vehicle to carry astronauts back to the Moon by 2020. Such a vehicle, flying about half a century after the astronauts last journeyed to the Moon in 1972, will undoubtedly incorporate a host of technologies more advanced than those used in the *Apollo* era. Infusing these technologies will require clear user interface principles, such as those used in the cockpit avionics upgrade project, to ensure that the crew understands the status of the vehicle and their environment.

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