

Designing Functional Visualizations for Aircraft Systems Status Displays

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A number of researchers have observed that glass cockpit displays tend to be opaque and that this makes it difficult for the flight crew to develop accurate and comprehensive mental models of system functioning, thereby leading to errors in abnormal situations. However, few researchers have suggested how to create better functional visualizations of system behavior, and even fewer have provided examples of what such advanced displays might look like. This article describes how the principles of ecological interface design (EID), a framework developed in the context of process control, can be applied in aviation to design engineering systems status displays. A prototype EID interface for the fuel and engines of a Lockheed Hercules C-130 Model E-H aircraft was constructed using the VAPS prototyping tool. This study shows, for the first time, that EID can be meaningfully applied to aviation.

Designers have been turning toward computer-based technology for creating cockpit displays. The rationale for doing so is presumably to improve performance and safety, but research has shown that glass cockpits create new challenges for flight crews. The most studied example is the interface for flight management systems (FMS). Results have shown that such interfaces are opaque in that they do not provide a clear indication of what the FMS is doing (e.g., Sarter & Woods, 1994). Thus, pilots' mental models of FMS operation are incomplete or incorrect, leading to errors in abnormal situations. Researchers have suggested that the remedy to this problem is to create transparent interfaces that reveal system functioning. However, the literature is generally silent on how such interfaces should be designed. Also, very few examples of such interfaces have been developed. Therefore, al-

though there is a recognized problem with current glass cockpit displays, little progress has been made toward a solution.

In this article, we try to overcome this gap in the literature by making two contributions. In terms of theory, we propose that ecological interface design (EID), a framework for designing interfaces that was originally developed in the context of process control (Vicente & Rasmussen, 1992), can also be used to create transparent interfaces in aviation. Experimental research in process control has already shown that an interface based on EID can lead to better performance and better system understanding than an interface based on a traditional design approach (Vicente, 1997). Research on EID has also led to technology transfer to the nuclear industry (Itoh, Sakuma, & Monta, 1995), but it had not been applied to aviation before. In terms of implementation, we describe how EID was used to construct a prototype military aircraft systems status display for the fuel and engine systems on a Lockheed Hercules C-130 Model E-H aircraft using the VAPS prototyping tool. In addition to showing how EID can be applied to military aviation, this prototype provides a concrete example of an interface that was designed to visualize system functioning and to thereby allow users to develop an accurate mental model of the system. We believe that this research may also have relevance to commercial aviation.

First, a brief description of the EID framework will be provided. Second, the literature on aircraft system status displays is reviewed. Third, a systems analysis is presented to identify the information that should be displayed in an EID interface. Fourth, a prototype EID interface implemented in VAPS is described. Finally, the operating philosophy of EID is contrasted with the philosophy currently dominating commercial aviation to identify some obstacles for technology transfer of our work to industry.

EID

The EID framework is an exemplar of functional interface design (Lintern, Waite, & Talleur, 1999/*this issue*). The theoretical foundations of EID have already been described in detail in Rasmussen (1999/*this issue*) and elsewhere (Vicente, Christoffersen, & Hunter, 1996; Vicente & Rasmussen, 1990, 1992), so only a very brief treatment will be provided here.

To appreciate EID, two seminal concepts from cognitive engineering research must be introduced: the abstraction hierarchy (AH) and the skills, rules, knowledge (SRK) taxonomy (Rasmussen, 1986). The AH provides a framework for representing the physical and functional constraints in a particular work domain (e.g., the engineering systems of an aircraft). This multilevel representation describes how the work domain is structured and thus provides a normative basis that people can use to interact with that domain. The AH is defined by a *means-ends* relation

between adjacent levels which means that it can be used to describe technical, engineering systems in a psychologically useful way, supporting people engaged in goal-directed problem solving (Bisantz & Vicente, 1994; Vicente & Rasmussen, 1992). Although the AH describes the environment (i.e., the work domain), the SRK taxonomy postulates three qualitatively different ways in which people can interact with that environment. Skill-based behavior (SBB) consists of parallel, perceptual-motor control based on a dynamic world model and time-space signals from the environment. Rule-based behavior (RBB) involves a direct association between familiar perceptual signs in the environment and an appropriate action or goal, without any need for mediating deliberation. Finally, knowledge-based behavior (KBB) consists of serial, analytical problem solving based on a symbolic problem representation. The relevance of the AH and SRK to EID becomes apparent by examining the underlying goals embedded in EID.

The basic premise of EID is that, in complex sociotechnical systems, the unique role of people is to act as adaptive problem solvers who can engage in the flexible, goal-directed activities required to satisfy changing and unanticipated demands. To fulfill this adaptive role effectively, it is important that people have an accurate mental model of the work domain that they can use for reasoning. However, it is also important that people be able to deal efficiently with more routine task demands as well. If an interface is to support people in these two roles, then it must provide a functional representation of the work domain, and it must present this representation in a form that makes it easy for people to pick up information. This goal can be rephrased in terms of the SRK taxonomy: An interface should present information in a way that allows people to take advantage of the efficiency and effectiveness of SBB and RBB, while still providing the support required to engage in the more effortful and error-prone KBB that is required for novel situations.

To achieve this goal, EID suggests three design principles, each directed at supporting one of the levels in the SRK framework: (a) SBB, to support interaction via time-space signals, the user should be able to act directly on the display; (b) RBB, to provide a consistent one-to-one mapping between the work domain constraints and the signs provided by the interface; (c) KBB, to represent the work domain in the form of an AH to serve as an externalized mental model that will support problem solving. The example presented later in this article will add some concrete details to this brief and abstract theoretical description.

LITERATURE REVIEW

We reviewed the literature on aircraft system status displays to determine if EID has the potential to offer a unique contribution in designing more transparent interfaces that reveal system functioning, thereby improving the fidelity of users' mental models. Interestingly, the traditional approach to designing status displays in

aviation is identical to that in process control. In either case, data have been presented using a *single-sensor-single-indicator* (SSSI) approach (Goodstein, 1981), typically using analog, hard-wired "steam gauges." The limitations of this type of design are well-known (e.g., Vicente & Rasmussen, 1990), and consequently, several alternative approaches have been proposed.

One alternative that has received a great deal of attention in aviation is *pictorial displays* (Oliver, 1990). For example, Reising and Emerson (1982) designed pictorial status displays for the fuel, hydraulics, engines, and electrical subsystems. These displays are quite similar to the piping and instrumentation diagram displays that have been used extensively in process control. The pictorial approach may seem to be an attractive alternative in aviation because many of the quantities of interest have a meaningful physical referent (e.g., the view out of the cockpit, highways in the sky), whereas those in other domains frequently do not (e.g., energy, radioactivity, pH). However, in the specific context of engineering systems (as opposed to navigation or attitude), pictorial displays may not be sufficient even for aviation because they focus primarily on physical depictions of system components (e.g., fuel tanks). Higher order information (e.g., mass or energy flow) is typically not presented because such information may not have physical referents. As a result, it is difficult to depict functional information using a pictorial format. This is an important omission because there is mounting empirical evidence indicating that higher order functional information improves human performance beyond the level achieved through physical information alone, especially during problem-solving activities (Vicente, 1997).

An alternative approach that addresses this deficiency is known as *emergent feature displays* (Bennett & Flach, 1992). These displays try to overcome the limitations of SSSI and pictorial displays by presenting higher order functional information as well as low-level physical information in a single, integrated display. Furthermore, perceptual organization principles are used to present this information in a form that is easy and efficient for people to pick up. One of the earliest examples of this approach is Coekin's (1969) octagon "star" display in which the emergent feature of symmetry is mapped onto a higher order system property (normalcy). When the system is in an abnormal state, the emergent feature is violated, revealing a problem in a salient fashion. Moreover, the way in which the octagon deforms is intended to provide information as to the nature of the problem. This octagon display was adapted for aviation by Beringer and Chrisman (1991) but with equivocal results. Calhoun and Herron (1981) implemented emergent feature displays for engine and hydraulic subsystems in a cockpit simulator. Their results suggest that such displays allow pilots to identify engine parameter abnormalities faster and more accurately than conventional displays. The advantage of emergent feature displays arises because people do not have to mentally integrate individual data to determine the status of a higher order function; instead, they can see the status of the function directly.

There is no doubt that emergent feature displays are a useful and important contribution to interface design. EID tries to take advantage of this advance, as the following example will make clear. However, this approach does not provide any systematic guidance in identifying what information should be displayed. Research on emergent feature displays usually assumes that the lower order and higher order information to be presented have already been identified. However, in complex systems such as process control and aviation, it is usually not at all apparent what information is needed to get the job done, especially under unanticipated abnormal conditions.

Abbott's (1989, 1990) work on *task-oriented displays* integrates the advantages of emergent features with a systematic approach to information requirements identification. The goal of this approach is to identify the higher order information needed to perform specific tasks and then to present that information in a form that is easy to perceive. Using this approach, Abbott (1989) designed a new engines status display, known as engine monitoring and control systems (E-MACS). Instead of displaying raw engine data in a traditional circular gauge format, the E-MACS display normalizes these data with respect to the expected values for each variable, resulting in a set of deviation bar graphs. An empirical comparison of the E-MACS display with the engine indication and crew alerting system (EICAS) display that currently exists in many Boeing glass cockpits indicated that fault detection performance was much more accurate with the E-MACS display.

This initial result suggests that task-oriented displays can make a useful contribution to interface design. However, they too have their limitations. Specifically, such displays tailor information presentation to specific tasks, which means that they may not effectively support people in reasoning under situations that are different or unanticipated (Rasmussen, 1999/*this issue*). Task-oriented displays provide support for proceduralized activities (i.e., SBB and RBB) but not necessarily for the more discretionary and open-ended problem-solving activities (i.e., KBB). This claim can be supported by examining the E-MACS display. There is no visualization of a deep model of the engine. Instead, the display is based on nominal values for certain operating conditions. Thus, although the E-MACS display may support efficient pattern recognition (RBB), it may not support analytical problem solving (KBB). Because there is no explicit model of engine functioning, pilots are unlikely to develop an accurate and comprehensive mental model. Unfortunately, these conjectures cannot be tested against Abbott's experiment because fault diagnosis and fault compensation performance were not evaluated.

In conclusion, there seems to be a useful role for EID in designing aviation systems status displays. It seems to be the only unified, principled approach that (a) provides a systematic approach to identifying interface information requirements (the AH), (b) presents higher order functional information and lower level physical information, (c) takes advantage of the power of emergent features, and (d) provides a model-based visualization that can support problem-solving activities and

the development of more accurate mental models. We will make these claims more concrete by showing how EID can be applied to design military aircraft system status displays.

AH SYSTEMS ANALYSIS

The first step in developing an EID interface is to create a multilevel representation using the two-dimensional space illustrated in Figure 1: an AH progressing from functional to physical system models and a part-whole hierarchy progressing from the whole system to its individual components. This analysis was conducted for the engine and fuel systems of a Hercules C-130. The views that were adopted for the engine system are prefaced with the label *E*, and those for the fuel system are labeled with an *F*. Cells labeled with an *X* were not found to be useful for this particular system, and those labeled with *N/A* were not applicable (see the following).

Part-Whole Hierarchy

The part-whole hierarchy provides a mechanism for users to alter their focus of attention, moving between less-detailed views (e.g., subsystem) to more-detailed views (e.g., component). Five levels of resolution were adopted. Objects at the *component* level include valves, pumps, and heaters (see Figure 2). The next level, *subunit*, was created through a meaningful aggregation of components. For example, the various components that control the amount of oil stored in an engine's oil tank are grouped to form the oil tank subunit. When the subunits are aggregated, the *unit* level is obtained. For example, all the subunits that provide an engine with fuel are grouped together. The *subsystem* level is next, which for an engine is comprised of the oil, fuel, gearbox, compressor, combustion, and turbine. This aggregation leads to a less-detailed representation, shown in skeleton form in Figure 3. Finally, the *system* level, shown in Figure 4, represents the entire fuel system and each of the four engines as single objects.

AH

The AH is conceptually orthogonal to the part-whole dimension and consists of five levels of description, as shown in Figure 1. These levels identify what types of information should be included in the interface. The complete AH analysis is lengthy, so only a summary of the content of each level can be presented here (see Dinadis & Vicente, 1996, for the full detailed analysis, and Bisantz & Vicente, 1994, for a tutorial on the AH).

		Aggregation - Decomposition				
		SYSTEM	SUBSYSTEM	UNIT	SUBUNIT	COMPONENT
Physical - Functional	FUNCTIONAL PURPOSE	View E1 View F1	X	X	X	X
	ABSTRACT FUNCTION	View E2 View F2	View E3 View F3	View F4	X	X
	GENERALIZED FUNCTION	X	View E4	View E5 View F5	View E6 View F6	View E7 View F7
	PHYSICAL FUNCTION	X	X	X	X	View E8 View F8
	PHYSICAL FORM	X	X	N/A	N/A	N/A

FIGURE 1 The two-dimensional space used to represent the engineering systems. The views that were adopted for the engine system are prefaced with the label *E*, and those for the fuel system are labeled with an *F*. Cells labeled with an *X* were not found to be very useful for this particular system. Cells marked with an *N/A* indicate views within the problem space that could have been incorporated via video feeds but were omitted due to the specific nature of the system being designed for.

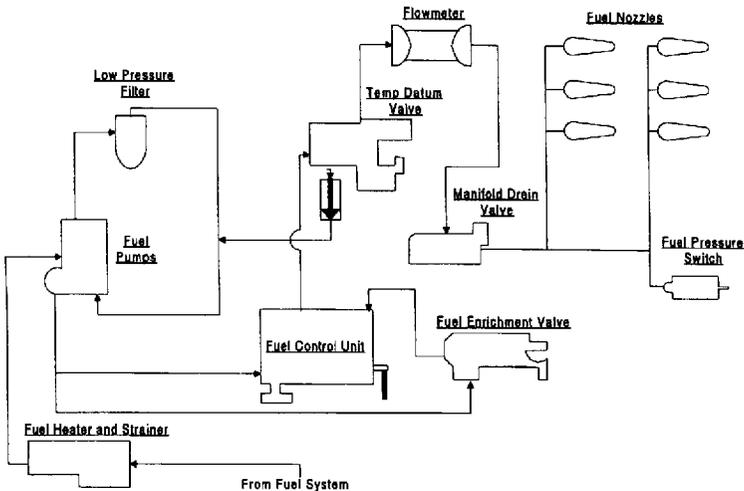


FIGURE 2 Example of the component level in the part-whole hierarchy.

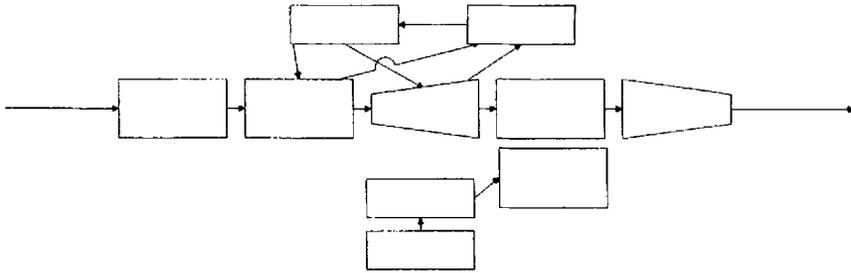


FIGURE 3 Example of the subsystem level of resolution in the part-whole hierarchy.

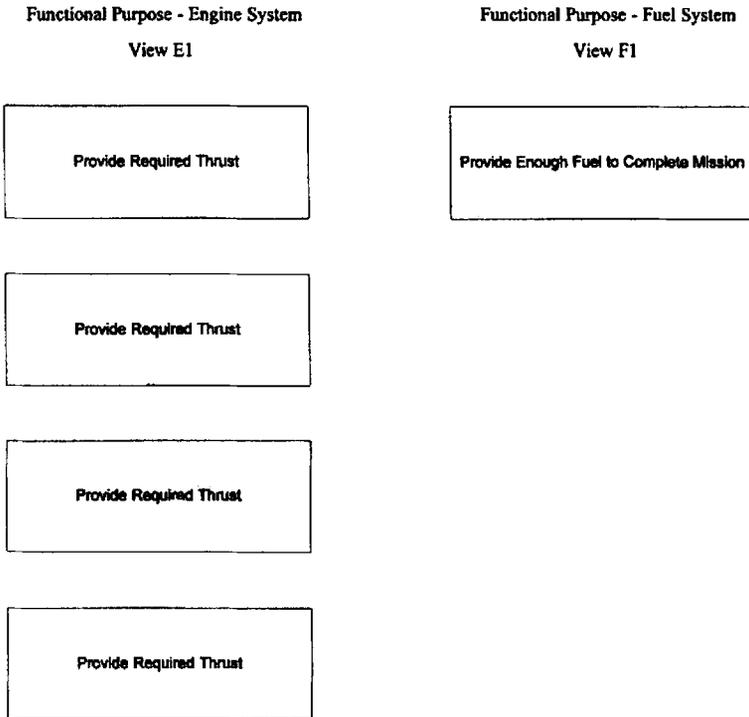


FIGURE 4 Views E1 and F1 (cf. Figure 1).

Functional purpose. Objects at this level of abstraction correspond to overall system purposes, as opposed to the functions or equipment that are used to realize those purposes. As shown in Figure 1 (Views E1 and F1), there is one main purpose for each of the fuel and engine systems. The fuel system's purpose is to provide enough fuel to fly to a destination, and the engine system's purpose is to provide sufficient thrust to safely fly the aircraft (see Figure 4).

Abstract function. This level describes the system in terms of conservation laws (i.e., mass and energy topologies), independently of the functions and equipment that realize these topologies. As shown in Figure 1, this level can be meaningfully applied at two levels of decomposition for the engine system (system and subsystem; E2, E3) and at three levels of decomposition for the fuel system (system, subsystem, and unit; F2, F3, F4). The most important benefit of the abstract function level is that it allows users to reason about the systems in terms of first principles. This is particularly important under abnormal situations, when reasoning based on the normal functioning of physical components is unreliable.

Generalized function. Flows and storage of different liquids, gasses, and heat are described at the next level of the AH. As shown in Figure 1, four levels of aggregation–decomposition were defined for the engine system: subsystem (E4); unit (E5); subunit (E6); and component (E7). Within the fuel system, three levels were defined: unit (F2), subunit (F3), and component (F4). This level describes the state of system functions (independently of the state of the equipment that materially instantiates those functions), which is useful for fault management.

Physical function. This level represents the state of the physical equipment itself. The resulting views, shown in Figures 5 (Engine) and 6 (Fuel), are familiar piping and instrumentation diagram representations of the two systems.

Physical form. The final level represents the systems in terms of spatial location and appearance of equipment (as opposed to just its physical state). This information could only be provided in computer form via a video camera, so we decided not to include this level of abstraction in our representation (see Figure 1).

Means–Ends Links Between Adjacent Levels of Abstraction

So far, each level of the AH has been described independently. However, an important feature of the AH is that it also provides a mechanism for identifying means–ends links between levels of abstraction (i.e., between adjacent rows in Figure 1). Figure 7 shows a subset of the linkages between generalized function and physical function. For example, a propeller is a structural means to achieve the end

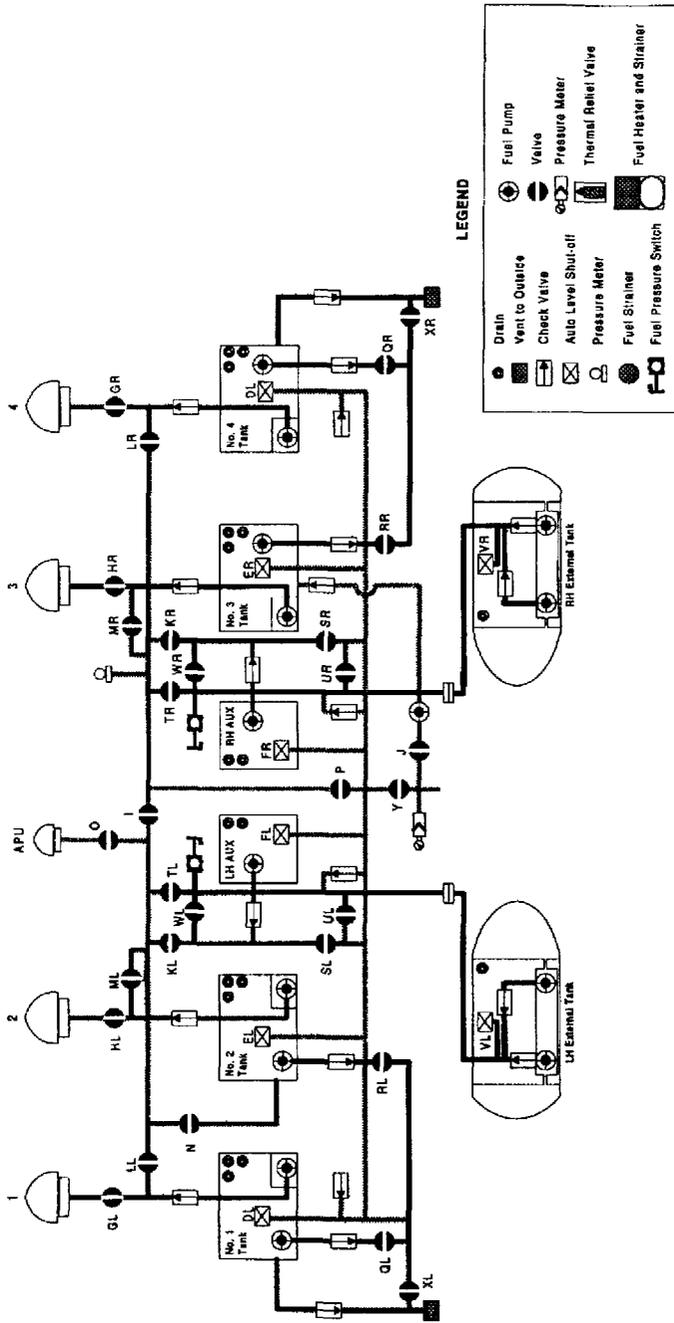


FIGURE 6 Physical function-level representation for fuel system.

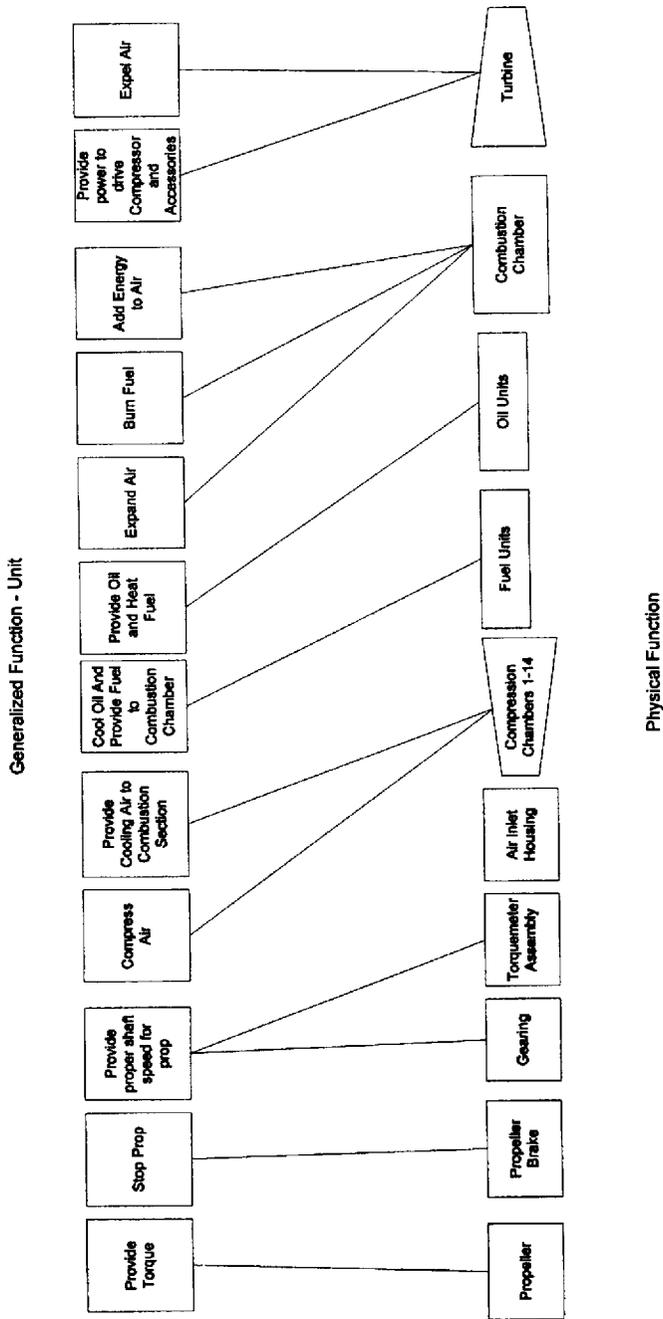


FIGURE 7 Examples of the means-ends mappings between adjacent levels of the abstraction hierarchy illustrated in Figure 1.

of providing torque. These means–ends relations are crucial in goal-directed problem solving because they represent system relations that users need to take into account. Identifying these links and then building them into the interface (see next section) provides explicit support for adaptive problem-solving behavior.

Conclusions

As shown in Figure 1, this AH-based systems analysis has identified eight different representations for each of the engineering systems that should be included in our prototype EID interface, as well as the linkages between them (e.g., Figure 7). To determine if these information needs are being satisfied, we conducted an analysis of the information currently displayed in the C-130 aircraft (Dinadis & Vicente, 1996). Interestingly, we found that the information requirements are satisfied at the upper and lower levels of the AH but are only moderately covered at the levels in between. The lack of information at these intermediate levels represents a set of “blind spots” for the crew. To compensate for these deficiencies, the crew members we observed in the simulator and on missions use a flight log to help them remember and derive the information that is not directly provided on the display. This requires that crew members manually calculate actual rates of change and compare them to ideal rates, which they must also compute. This process can become quite inefficient, time consuming, and cognitively taxing when crew members are faced with diagnosing an abnormality. The prototype interface described in the next section tries to reduce these cognitive demands by directly providing a functional visualization of the engine and fuel systems for the C-130.

EID PROTOTYPE DESCRIPTION

In the previous section, we described the systems analysis that was conducted to identify the information content and structure of the EID interface. In this section, we describe how those multiple representations were mapped onto visual forms that facilitate information extraction.

General Description

Figure 8 shows the layout of our prototype EID interface. The screen is divided into six distinct display regions, five of which serve a unique role in communicating information. These five display regions, labeled as *Viewports 1–4b*, are linked to the AH analysis by the information that they contain. They were designed to include all eight engine and fuel system representations identified in the previous section (see

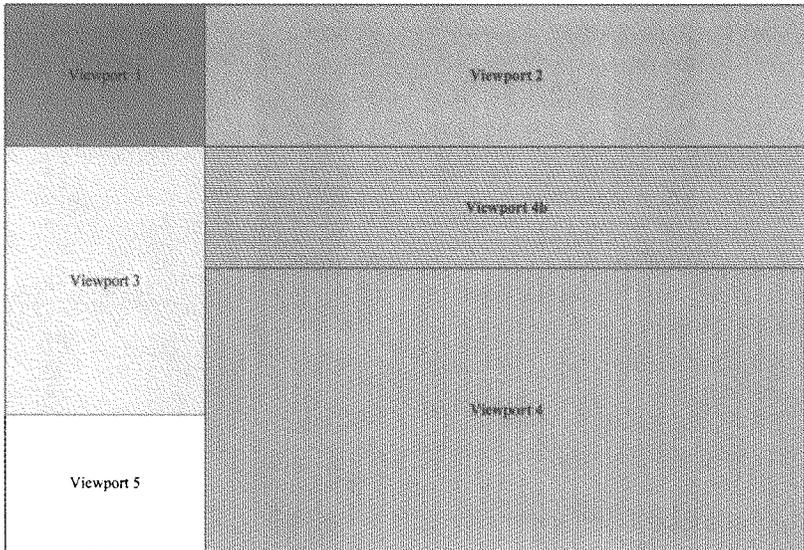


FIGURE 8 Viewport layout in prototype EID aviation display.

Figure 1). The fact that there are less displays than system representations results from the ability to integrate two or more different views of a system into a single visual form (Vicente, 1992). Figure 9 shows the relation between the viewports in Figure 8 and the space in Figure 1 for the fuel system. The shading of each view in Figure 9 corresponds to the viewport shading displayed in Figure 8. For example, parts of views F1–F6 in the part-whole/AH have been integrated to create the fuel system overview display in Viewport 3, as indicated by the shading corresponding to Viewport 3 overlaid on Cells 1–6 in Figure 9. In cells in which there are two or more types of shading, the information identified in the AH is located in more than one display region. For example, in Cell F7, the horizontal and vertical shading indicate that the generalized function–component information (i.e., component flows) can be found in both Viewports 4 and 4b. Figure 10 shows an analogous mapping between AH cells in Figure 1 and display regions in Figure 8 for the engine systems.

The six display regions indicated in Figure 8 are dedicated to specific types of information:

Viewport 1: Performance. This viewport describes the overall purpose of the two systems. Figures 9 and 10 illustrate the connection between this information and the AH analysis.

Viewport 2: Engine System Overview. This viewport contains information relevant to each engine's purpose, represented at the highest levels of the AH.

Viewport 3: Fuel System Overview. The fuel system overview contains information at the higher levels of the AH, relevant to the fuel system's purposes and functions (see Figure 9).

Viewport 4: Systems Display. This display contains information located in views E4 to E8 of the AH, which describe the system flows and settings.

Viewport 4b: Systems Information. This display provides information required in views E2 to E7 and F7 in Figure 1. As described in the following, it facilitates movement between the overview displays (Viewports 1 to 3) and the more detailed systems display (Viewport 4) of Figure 8.

Viewport 5: Thrust Display. This display would not exist in a real interface and was added for demonstration purposes only. Four "thrust levers" set the thrust for each respective engine to either reverse (REV), idle (IDLE), cruise (CRUISE), or takeoff (FULL).

Figure 11 shows the resulting prototype interface designed for the Hercules C-130 aircraft systems, using VAPS prototyping software on a Silicon Graphics Inc. Indigo workstation.

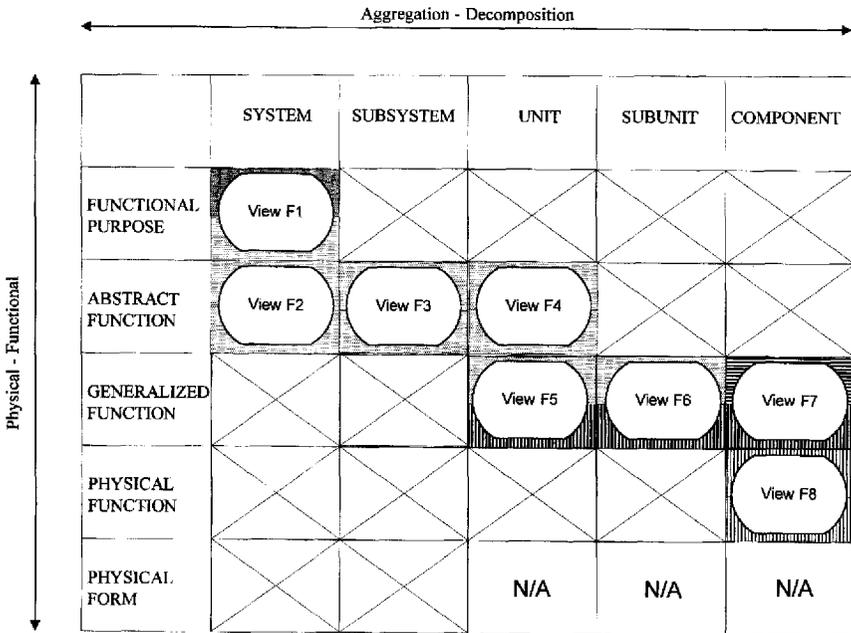


FIGURE 9 Relation between viewports in Figure 7 and space in Figure 1 for the fuel system.

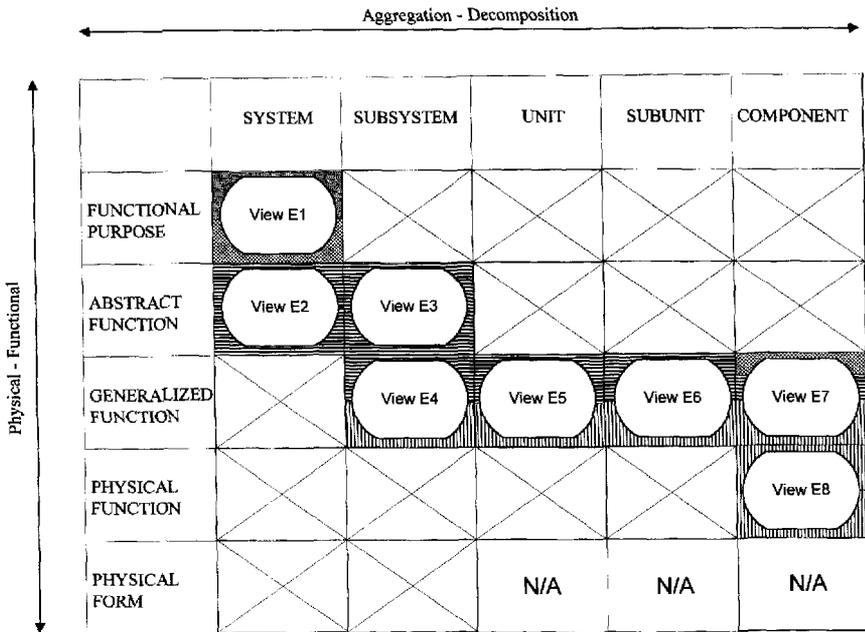


FIGURE 10 Relation between viewpoints in Figure 7 and space in Figure 1 for the engine system.

Performance Display

The performance display in the upper left corner of Figure 11 indicates how well the two systems are cooperating to propel the aircraft to its destination. A map with gray concentric circles, combined with a “zoom” rotor, provides a goal-relevant frame of reference for location distances. The red circles shrink proportionally to the distance that the aircraft is able to fly, incorporating factors such as fuel levels, engine efficiencies, airspeeds, outside air temperatures, and altitudes, and so forth. A solid red circle alerts the crew as to how far they can safely attempt to fly, whereas a dashed red circle indicates the absolute maximum distance that can be flown before running out of fuel. This display precludes the necessity to perform detailed calculations and guesswork regarding the available distance that can be flown.

Engine Overview

The engine overview, located in the upper right row of Figure 11, is the primary display for the engines. It contains the 12 most important parameters for each engine

organized within an emergent-feature display containing 12 spokes (1 for each parameter) that are scaled according to engine power level (Coekin, 1969). Any deviations from a normally operating engine (represented by the green dashed dodecahedron) should be easily perceived. Actual engine performance is presented by a solid dodecahedron superimposed on the diagram. The way in which the polygon deviates from the normal goal state provides an indication of the fault source. To aid in identifying performance boundaries, alarm levels have been incorporated into the display in the form of tick marks along each spoke axis, yellow for cautions and red for warnings. The color of the entire polygon indicates actual engine performance and also changes to the alarm level corresponding to the worst engine parameter. Finally, if a particular engine is selected by clicking on the center of a polygon, then more detailed information on that engine is obtained in the systems information display (see the following). Similarly, any of the spokes of a particular engine display can be selected, automatically bringing up a more detailed representation of the physical components that are directly pertinent to that engine parameter in the systems display (see the following). Because these means-ends links have been identified in the AH analysis and built into the display, users do not have to store and retrieve this knowledge on their own.

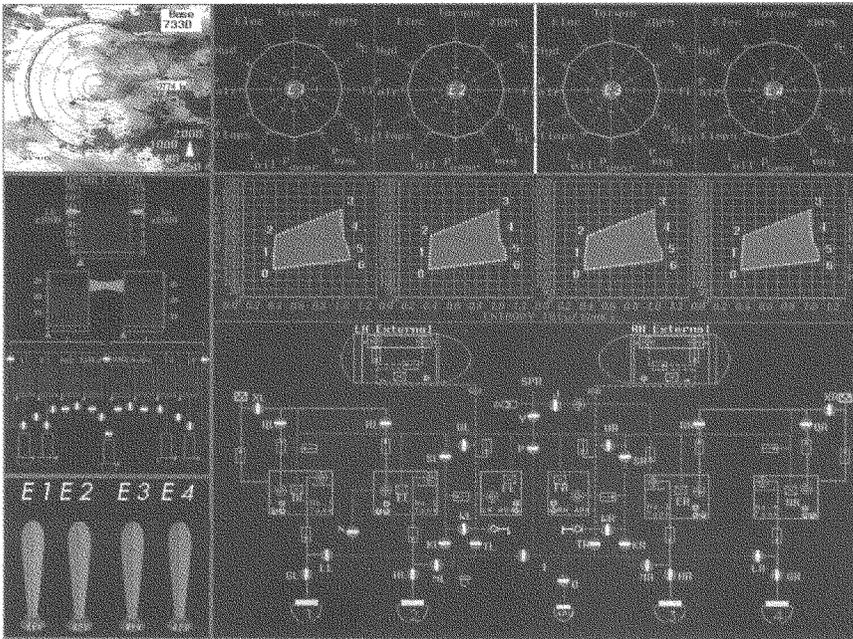


FIGURE 11 Prototype ecological interface design for the C-130.

Fuel System Overview

The fuel system overview, Viewport 3 located in the middle left of Figure 11, contains functional information relevant to the higher order fuel system requirements in the AH. It has been organized to logically progress from the state of the aircraft's entire fuel supply (top graphic), to the two wing-side supplies (middle graphics), and to the eight individual tanks (lower graphics).

The four levels of information provided in this display are the following: (a) fuel flow (FF) to each engine, located at the bottom of Viewport 3; (b) tank fuel levels and indications of flow to and from tanks (located above the FF indicators in Viewport 3); (c) wing-side fuel amounts and fuel flows, including dumped or lost fuel (located above the tanks in Viewport 3); (d) overall fuel system amounts, flows, losses (intentionally or otherwise), and predicted amounts (this graphic is located at the top of Viewport 3). Interactions between tanks are illustrated via piping and controllable valves that connect the tanks. Furthermore, by selecting a particular tank in the fuel system overview, a zoomed-in physical representation of the components relevant to that tank will automatically be displayed in the systems display (see the following), thereby linking functional and physical information. This feature is another example of how the links between levels in the AH can be built into an EID interface to offload the cognitive demands on users.

Systems Display

The systems display (Viewport 4), located in the lower right portion of Figure 11, contains physical information relevant to the lowest levels of the AH for both aircraft systems. The information displayed here is context sensitive because it is dependent on the user's interaction with the other screens, as described previously. Panning capabilities are provided through the use of sliders, located along the left and top perimeter of the viewport (not shown).

System Information Display

The system information display is an extension of the systems display. Information provided within Viewport 4b of Figure 11 is directly dependent on the context of the systems displays. There are two types of views that are associated with the system information Viewport: engine state diagrams and trend data presentation.

Engine state diagrams. As shown in the middle row on the right of Figure 11, the system information viewport is set, by default, to display state diagrams for

each engine. State diagrams are a standard tool used in engineering design to describe the performance characteristics of a thermodynamic system (Wood, 1991). The vertical axis represents energy, and the horizontal represents entropy. Units of horsepower were used for the energy axis to maintain the user's familiarity with power production calculations as much as possible. The numbers surrounding the state diagrams represent the different engine stages and have been extracted from standard engineering engine stage numbering methods. Zero (0) represents air that has been imported from the environment; 1, the inlet to the compressor; 2, the combustion inlet; Stage 2-3 represents the heat acquired through the combustion of fuel; Stage 3-4, the work being done by the propeller; Stage 4-5, the work of the turbine; and Stage 5-6, the work provided by the exhaust gasses in the form of thrust. Stage 6-0 is an imaginary connection in aircraft engine cycles, representing the ambient air (modeled as a constant pressure heat sink), recycled from the exhaust to the engine inlet. The state diagrams provided in the interface are based on a normative Allison T56-A15 engine. The expected behavior of each engine is represented in Figure 11 by a dotted white polygon. The shaded area represents how the actual engine is operating compared to normal operation. In Figure 11, the area matches the dotted outline, indicating that the engines are operating normally. With this display, users should be able to notice quickly how the engine is straying from its normal performance and, more important, to identify the stage(s) responsible for the problem. The state diagrams also allow users to select any segment of the diagram (e.g., 2-3) and then automatically view, in the systems display underneath, a physical representation of the engine components that are related to that segment. This feature is made possible by the means-ends relations identified in the AH analysis, thereby relieving the cognitive burden on users.

Trend information. Trend data can also be presented in the system information display. When a specific engine is selected, the state diagram for that engine remains, but the other diagrams are replaced by trends for parameters of the selected engine (see Figure 12 for an example). The incorporation of trend data allows users to focus their attention on a particular engine, obtaining detailed information that can help diagnosis of slowly evolving events, such as slow fuel leaks from a tank. Deviations can be monitored over time, instead of only instantaneously as in the existing Hercules C-130 systems status displays.

Example of Low Fuel Flow to Engine 2

A hypothetical fault will be used to demonstrate how the information provided in the various viewpoints could be used together to guide users to an accurate diagnosis of a fault. The example consists of a lower than expected rate of fuel being received by the nozzles of Engine 2. A partial screen shot of this scenario is shown in Figure

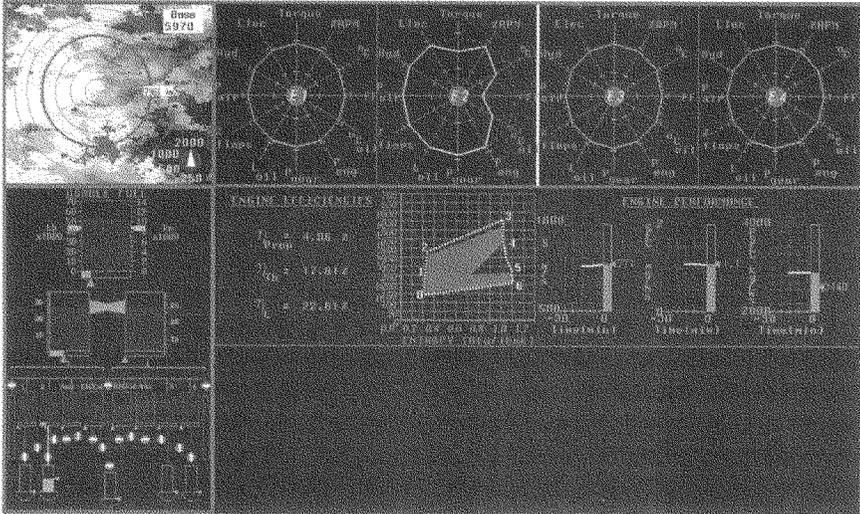


FIGURE 12 Prototype ecological interface design showing an abnormal state (low fuel flow to Engine 2).

12. The abnormal shape of the state diagram and the deviation of Engine 2's star diagram are evident. Both shapes are indicative of a low fuel flow rate to the engine nozzles (on the star diagram: low fuel flow, lower power output, low torque, and a low engine oil pressure; on the state diagram: shape of diagram, particularly between Stages 4–5) and, when combined, could help guide the users toward searching for the root of the problem. The engine icon in the fuel system overview display (extreme lower left) indicates that the flow sent to Engine 2 from the fuel system is sufficient (triangle equal to the bar height). These three pieces of information allow users to infer that there is a low fuel flow problem and narrow the search domain to within the engine. Users could then zoom in on the appropriate engine components (e.g., nozzles) to pinpoint the root cause and select compensatory actions. This example shows how the system models represented by the AH and built into the prototype EID interface can help users cope with potential interactions between systems, something that existing status displays cannot do very well.

This chain of reasoning is quite different from that currently being followed by users. Active problem solving replaces regimented procedure following. In a similar scenario within a current Hercules aircraft, one crew member stated that he would either shut the engine off, or live with the reduced power production, without delving any further into the fault, unless another engine was lost (Dinadis & Vicente, 1996). Crew members currently follow this practice because the information provided to them is insufficient to efficiently search and rectify such a fault.

Conclusions

To summarize, the three principles of EID will be restated, along with examples of how they were implemented in this interface:

1. *SBB*: To support interaction via time–space signals, the user should be able to act directly on the display. Direct manipulation is facilitated through the use of panning features and selectable components.
2. *RBB*: To provide a consistent one-to-one mapping between the work domain constraints and the cues or signs provided by the interface. The circular distance indications in the performance display (top left of Figure 11) are salient perceptual cues that map onto goal-relevant domain constraints.
3. *KBB*: To represent the work domain in the form of an AH to serve as an externalized mental model that will support problem solving. The AH was used to create the interface, and the cells and links identified there have been mapped onto the various viewports.

There are numerous benefits that could potentially be obtained from this approach. First, users should be able to determine the state of the system at a glance and rapidly and effectively extract information from the display. This factor also has implications for training, as the interface should help inexperienced users learn how different systems are related to each other. Second, the context-sensitive approach to the aircraft systems, combined with the AH's normative system models, should reduce the requirement for memorization of physical and functional relations. At the same time, it should provide a better conceptual understanding of the codependencies within and between systems, as well as the dynamics involved. Third, the design is intended to support planning and compensatory activities by allowing users to directly act on the display surface.

A POTENTIAL OBSTACLE: THE ROLE OF PEOPLE IN THE SYSTEM

We have argued, at a theoretical level, that EID has something to offer aviation. We have also shown, at an implementation level, that EID can be applied to aviation by describing a concrete design example. Nevertheless, there is an important obstacle standing in the way of transferring this technology to industry—the operating philosophy inherent in EID is quite different from that dominating the aviation industry, especially with respect to the role that people are expected to play in system operation. Although this issue may seem ethereal, it has critical practical implications. The role that people are expected to play affects the cognitive activities in which they will be engaged which, in turn, affects the type of interface support that they need. More information is available about the operating philosophy in commercial

than in military aviation, so our discussion will focus on the former sector. However, it is important to acknowledge that there seem to be differences in the operating philosophies in these two contexts (cf. Nordwall, 1995, p. 21).

Current Aviation Industry Operating Philosophy

The current attitude in the aviation industry is that the pilot's role is not so much to understand in a deep sense what is going on in the system but rather to diligently execute the steps in a given procedure to satisfy mission goals. This is somewhat of an oversimplification, as the two activities are not mutually exclusive and can be combined to varying degrees. However, there are several pieces of evidence that indicate that this is indeed the current trend in the industry. First, in our discussions with domain experts, the emphasis that is placed in operations to "execute the bold face" became clear. The argument for this seems to be that, if something goes wrong, pilots will not have the time or the psychological resources required to diagnose the root cause of the event and then develop an appropriate compensatory plan. Instead, pilots are supposed to rely on the designers' analyses and forethought that have been incorporated into the procedures made available to them. As a result, the focus is more on "doing" rather than on "understanding."

Second, the training programs that pilots undergo are putting less emphasis on knowledge of aircraft systems functioning. Whereas in the past, pilots were exposed to a great deal of theoretical training and instruction about the functional structure of the aircraft's systems, today these aspects receive much less attention. Scott (1995a) quoted one source as saying, "maybe pilots don't really need to know the details of how a system operates anymore" (p. 14). Scott (1995b) also quoted United Airlines' manager of fleet operations for the Airbus A-320 and Boeing 737 as saying, "we've moved away from teaching as much about how the aircraft works" (p. 15).

There seem to be several reasons for this "procedures culture." First, in many cases, a detailed understanding of what is occurring within commercial aircraft may not be required to compensate effectively because there are few degrees of freedom available for action. For example, if the only choice is between an emergency landing and stabilizing the aircraft to continue flying, then detailed fault diagnosis may not be necessary. Second, systems management is secondary to the primary task of flying the aircraft, so spending too much time problem solving on the former can detract from the latter. Third, following procedures requires less time and deep processing than adaptive action, which can be very important in a time-pressured environment. Fourth, aircraft systems are becoming more complex, so the job of learning how they function is more difficult than before. Fifth, aircraft systems are being built to be more reliable than in the past. Thus, faults should occur very infrequently. Moreover, when they do occur, automation will

frequently be able to detect and diagnose the problem and inform the pilot as to what actions need to be taken. In the case of the MD-11, for example, the automation even compensates for failures by automatically reconfiguring the aircraft systems. As a result, the argument is that there is less of a need for understanding on the part of the pilot. Sixth, airlines want to train their pilots as economically as possible, and the result, according to one pilot, is that they emphasize “button-pushing rather than knowledge of systems” (Scott, 1995a, p. 14). Finally, there seems to be a general attitude that rare events that fall outside of the scope of procedures and the capability of automated systems simply will not occur in practice. For example, “United’s pilots are taught to handle both *routine* and unusual situations they will *most likely* encounter in *typical* line service, such as adverse weather and wind shear” (Scott, 1995b, pp. 15–18, italics added).

EID Operating Philosophy

The operating philosophy behind EID is vastly different from that found in commercial aviation. EID was originally developed in the context of process control systems in which the greatest threats to system safety are events that are both unfamiliar to users and unanticipated by designers. In these novel situations, users are required to play the role of an adaptive problem solver if they are to be able to effectively cope with the rare event. Procedures are not applicable by definition, because this class of events has not been anticipated by designers. As a result, in addition to supporting people in more routine situations requiring SBB and RBB, EID also tries to support users to be adaptive, reflective agents. This is accomplished by providing users with an interface that contains detailed information about the status of system components, functions, and purposes, as well as the relations between these. Users are not told what sequence of actions to take but instead are given the support that is required to develop a safe path of action that is appropriate for the unique contingencies of that event. This approach is very different from designing displays solely to support procedural activity (Rasmussen, 1999/*this issue*).

The implications of the EID operating philosophy have not been definitively established, but the following differences with current aviation design practices seem likely. First, an EID interface would have more information than a traditional cockpit display. Second, users would have to have an understanding of the system if they are to be able to effectively interpret and use the information provided by an EID interface. Third, users should be selected according to their capability to be adaptive problem solvers, rather than just compliant procedure followers. Fourth, procedures would play a less prominent role during abnormalities. These changes amount to a qualitative change in systems design. The question that remains is whether such a change is necessary or can be justified. It is certainly possible that the EID philosophy may make sense for process control but not for aviation.

Reasons Why EID May Be Relevant to Aviation

We hypothesize that there are a number of reasons why EID can make a valuable contribution to the commercial aviation industry and is thus worth considering.

Increase in absolute number of unanticipated events. The amount of air traffic is increasing worldwide and will continue to do so in the future (Perry, 1997). In China alone, air traffic is expected to double in volume over the next 8 years (Boone, 1995). Therefore, events like Sioux City (National Traffic Safety Board, 1990)—which have previously been perceived to be very rare freak occurrences—will likely occur with greater frequency. If the probability of a rare accident per flight remains constant, by the year 2015 there may be one major aviation accident every 7 to 10 days (Perry, 1997). Such an increase in the absolute number of unanticipated events would likely make the public more wary of aviation safety, as the string of accidents in 1996 have begun to show. Providing the additional support to help crews deal with unanticipated events may be perceived to be a worthwhile investment, given the number of human lives at stake.

Procedures do not capture all events. Despite the fact that the commercial aviation industry is highly focused on procedural operation, there are several sources of evidence showing that procedures simply do not capture all events. First, several authors in the industry have acknowledged this fact, including some who work on improving the design of procedures (e.g., Degani & Wiener, 1994). Second, if one examines the current list of emergency operating procedures available in many aircraft, it is clear that certain events for which there is now a procedure (e.g., flying through volcanic ash) were simply not on the list originally. Third, there are several well-known examples of accidents that were caused by events that were unanticipated and for which there were no procedures (e.g., National Traffic Safety Board, 1990). There will always be events for which procedures do not exist.

Increase in system complexity. The new generation of high speed civil transport (HSCT) aircraft will be more complex and have more redundant backup systems than the current generation. As a result, pilots may have more action alternatives that they can choose from in the face of abnormal events, especially if the automation is ineffectual. To choose an effective alternative, pilots may need to make a more detailed diagnosis, much like operators in process control systems, and thus their interfaces must support effective fault diagnosis performance.

Feedback for proactive control. Identifying problems before they lead to grave consequences requires that users have detailed feedback about the operation of aircraft systems. Only with such rich feedback can users proactively deal with problems. Otherwise, compensation can only begin once an alarm is activated. By this time, negative consequences or inefficiencies may have already occurred (Trujillo, 1994). The need for proactive monitoring is particularly great for extended transport operations aircraft that may not have an airport nearby to land at when a problem arises.

Feedback for monitoring automation. Even if the operation of aircraft systems is automated, this does not mean that pilots do not need to be aware of what is occurring in those systems. Because the automation is not perfect, pilots should monitor what the automation is doing. Similarly, if the automation reconfigures a system to deal with a fault, pilots need displays with rich feedback to determine what the current configuration of the system is and how that impacts on the operation of other related systems. If anything, increases in automation make the problem of interface design more, rather than less, critical (Oliver, 1990).

Revealing interactions between systems. System status displays that are currently used in operation, or that are being proposed by researchers, are designed to show the state of a single aircraft system at a time. With the exception of the prototype presented here, we do not know of any displays that show interactions between aircraft systems, despite the fact that the systems are in fact interconnected, either physically or functionally. With current designs, it is up to the pilots to retain these interactions in their mental model and to reason appropriately in case of a fault. This can be a demanding cognitive task, especially under time pressure. It should not be surprising to find, therefore, that "failure to understand all the implications of certain system failures on the capability of other aircraft systems has been cited as a contributing factor in several accident and incident cases" (Palmer & Abbott, 1994, p. 2). To deal with this problem, an interface should clearly reveal the interactions between subsystems, as EID does.

Supporting multiple fault management strategies. There need not be a conflict between the traditional practice of only providing information to help pilots stabilize an abnormality and the practice advocated by EID of supporting deeper diagnosis activities. Pilots' initial goal in the event of an abnormality is to stabilize the aircraft, and current displays are geared toward supporting this task. However, pilots would also like to have access to more detailed status information

so that they can perform a more detailed diagnosis, after they have stabilized the aircraft (Rogers & Abbott, 1996). Current status displays are not designed to support this activity.

Implications

Although there may be some very good reasons for the existing procedures culture in commercial aviation, a strong case can be made that there is a gap when it comes to helping crews deal with situations requiring KBB (Rogers, Schutte, & Latorella, 1996). Displays that provide rich feedback about aircraft systems structure and state are required to evaluate system status, to verify actions performed by the automation, and to track interactions caused by the evolution of fault events. This is precisely the approach taken by EID. Thus, we predict that the principles of EID will become increasingly important in glass cockpit aircraft. One possibility is to use EID to help pilots on those rare occasions when there are no relevant procedures. Another possibility is to use EID to help ground-based maintenance and dispatch workers to perform fault diagnoses in real time. A final possibility is to use EID to create embedded training displays that could be used by pilots during flight to enhance and maintain their understanding of aircraft systems.

Although it may be unrealistic to expect that the changes that would be required to implement EID in aviation would be readily adopted by industry, the HSCT program mentioned earlier provides an opportunity for long-term change. This research program is a rare opportunity for innovation, because some of the constraints that characterize current designs can be relaxed. Therefore, the HSCT program may provide an important window of opportunity for EID to have an impact on the design of status displays in the aviation industry.

CONCLUSIONS

This research has shown that the EID framework can be meaningfully applied to aviation and that it is not just restricted to process control systems. Furthermore, a prototype design was implemented in an attempt to illustrate what a transparent, functional, visualization of system structure might look like. Although this represents a step beyond merely stating that existing interfaces should be more transparent, it is important to point out that EID concepts in aviation are untested. Extensive empirical testing is required to determine if more accurate mental models and more efficient and reliable performance are achieved and if there are unanticipated risks too.

One could argue that, because the prototype described here is so different from current designs, it has little chance of being accepted by the aviation industry and by users. Indeed, differences in operating philosophy were identified as a potentially

large obstacle to adopting this approach to interface design in commercial aviation. To determine if potential users had an analogous set of concerns, we conducted an informal walkthrough to get feedback on the prototype EID interface from C-130 flight engineers (FEs) that currently work with a SSSI set of displays (Dinadis & Vicente, 1996). The interface we designed is radically different from the one that these FEs are accustomed to working with, so we did not expect a great deal of acceptance. Surprisingly, the seven FEs we interviewed were quite positive in their evaluation. For example, one representative comment was "this [interface] looks like it would be extremely easy to do trouble shooting ... As a project where you are presenting it and you are saying, hey will this work, I'd say yeah, it would work." Perhaps, then, EID can help designers create qualitative design changes that improve performance and deep knowledge while still achieving user acceptance. This possibility should be pursued in the context of the HSCT program.

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