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Cockpit Task Management: Preliminary Definitions, Normative Theory, Error Taxonomy, and Design Recommendations

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A preliminary formalization of the process that flight crews use to initiate, monitor, prioritize, execute, and terminate multiple, concurrent tasks is presented. I define key terminology and present a preliminary, normative theory of cockpit task management (CTM). An error taxonomy that is applied to three National Transportation Safety Board (NTSB) aircraft accident reports is introduced. Recommendations for pilot–vehicle interfaces (PVIs) intended to facilitate CTM and an example, prototype PVI that was effective in improving CTM performance are provided. In conclusion, I describe the complementary relationship between CTM and cockpit resource management (CRM).

Air travel is one of the safest forms of transportation, yet each year hundreds of lives and millions of dollars are lost due to air crashes. Accident investigations reveal that well over half of these accidents can be attributed to errors by the flight crew (Nagel, 1988).

This problem may be partly due to what Wiener (1987) called a "one box at a time" approach to cockpit automation. Conventional approaches to understanding flight-crew behavior and to developing cockpit automation have concentrated on isolated tasks. But the flight crew operates in a multiple task environment. A systematic approach to and an integrative theory of flight-crew multiple task behavior are needed.

A systems engineering approach (Sheridan, 1988) to the study of flight-crew

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behavior and cockpit automation led us to a concept we call *cockpit task management* (CTM), the initiation, monitoring, prioritization, execution, and termination of multiple, concurrent tasks by flight crews. Although this process is intuitively well understood by pilots, it is not always well executed. This article represents a preliminary attempt to name and formalize the process and to demonstrate the potential usefulness of the formalization in cockpit analysis and design. I present some background definitions for CTM, a preliminary version of a normative theory of CTM, recommendations for the design of pilot–vehicle interfaces (PVIs) to facilitate CTM, a description of a prototype PVI that successfully enhanced CTM performance, and a comparison of CTM and cockpit resource management (CRM).

DEFINITIONS

Formally speaking, a theory is a collection of statements about some domain. These statements contain terms that are used to denote things and relationships that are considered to be important elements of the domain. For the theory to be sound and, of equal or greater importance, for it to be useful in analysis and design, these terms must be clearly defined. Terms essential to a theory of CTM are defined next.

A dynamic *system* is an entity that may be described in terms of input, output, and state. *Input* is matter, energy, or information flowing into the system. *Output* is the flow of matter, energy, or information out of the system. *State* is the set of system attributes at a given time. In addition, state is a compact representation of the history of the system that, with input given, makes possible the prediction of future outputs and states (Padulo & Arbib, 1974).

Two systems that are connected by inputs and outputs form a more complex system called a *supersystem*. If a system is formed from simpler systems through input–output connections, the simpler systems are called *subsystems*. For example, an aircraft system can be partly defined as a collection of pilot, autopilot, airframe, and engine subsystems (see Figure 1).

Note that this is "relative" terminology because whether something is called a system, a subsystem, or a supersystem depends on the analyst's perspective. For example, if the aircraft is considered a system, then the autopilot is a subsystem. On the other hand, if the analyst is primarily concerned with the autopilot, then the autopilot is a system, the aircraft is a supersystem, and the altitude hold circuitry in the autopilot is a subsystem. When using this terminology, the analyst must be careful to identify his or her purpose and frame of reference.

A system *behavior* is a discrete sequence or a continuous series of system input, state, and output values over a time interval. For example, given a system composed of airframe and engine subsystems, a behavior could be defined as time series of throttle setting (input), altitude (state), and sound pressure level (output) values, as shown in Figure 2. A system exhibits a behavior if observed values of input, state, and output values match those of the behavior.

An *event* is a set of system behaviors in which some state component changes in a significant way at the end of the time interval. For example, the event—reach

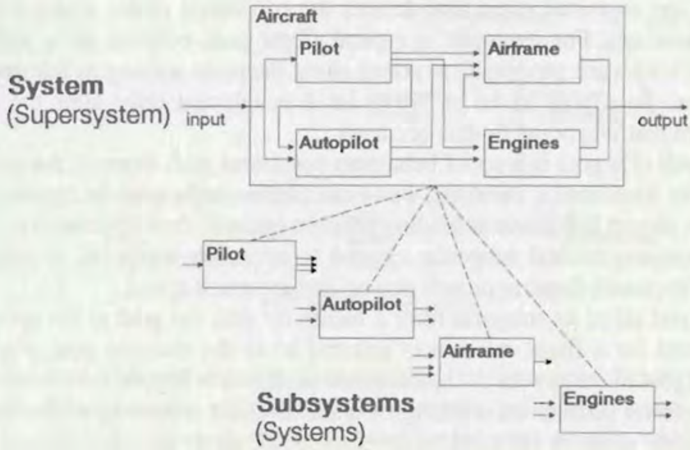

FIGURE 1 Systems, subsystems, and supersystems.

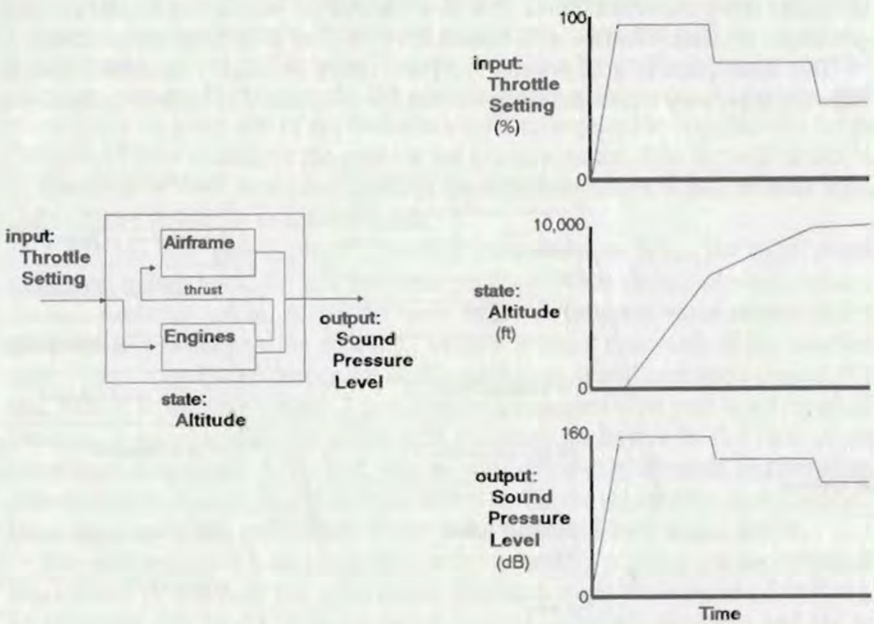

FIGURE 2 A behavior of an airframe/engines system.

10,000 ft—consists of a set of aircraft behaviors, each ending with an altitude value of 10,000 ft.

A *goal* for a system is defined by a set of desired behaviors. If one of the behaviors is exhibited by the system, the goal is achieved, otherwise the goal is not achieved.

A goal has an *initial event* that defines the conditions under which the goal becomes relevant. For example, a typical flight path consists of a series of waypoints, which are geographical points along the route serving as intermediate destinations. So a goal to be at Waypoint 8 is relevant only after the initial event—arrive at Waypoint 7—has occurred.

A *subgoal* of a goal is a set of behaviors consistent with those of the goal but restricted in time and/or in scope. For example, a single goal to approach the destination airport and arrive at landing position (prior to final approach) could be decomposed into several subgoals: cleared to approach waypoint, at approach waypoint, approach flaps, approach power, and approach speed.

A goal and all of its subgoals form a hierarchy with the goal at the apex. The topmost goal for a flight mission is referred to as the mission goal. Part of a simplified goal hierarchy for a flight mission is shown in Figure 3.

Goal *priority* reflects an ordering of a set of goals according to the relative importance or urgency assigned to them by the flight crew. More important or urgent goals have higher priorities. For example, a goal to remain clear of terrain and other aircraft established to maintain the safety of the aircraft and its passengers is clearly more important than a goal to avoid sudden maneuvers established for passenger comfort. The first goal should have a higher priority than the second.

This description of goal priority is a preliminary and highly simplified one. It does not accurately reflect the complex and dynamic nature of priority assignment

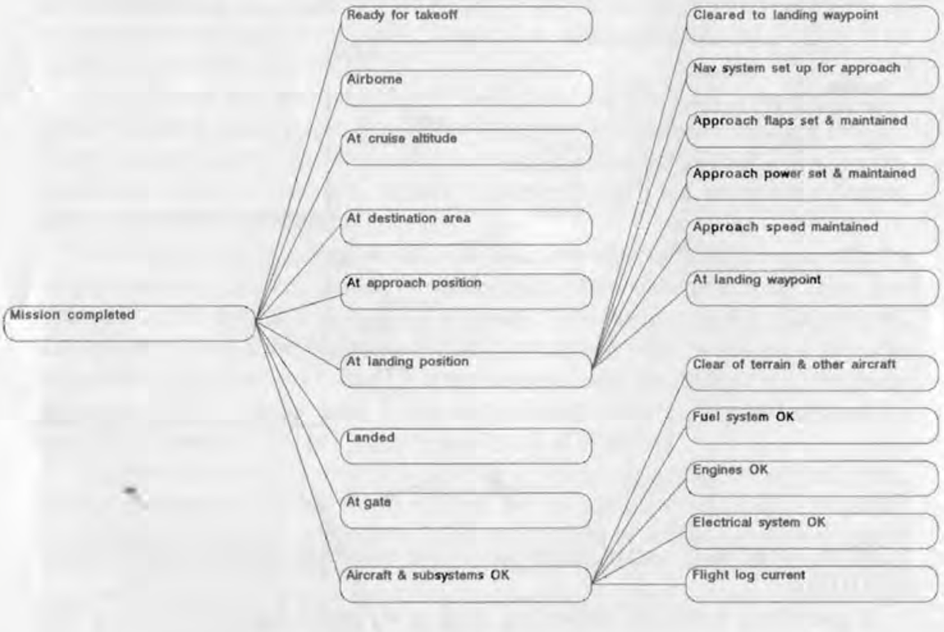

FIGURE 3 A partial goal hierarchy.

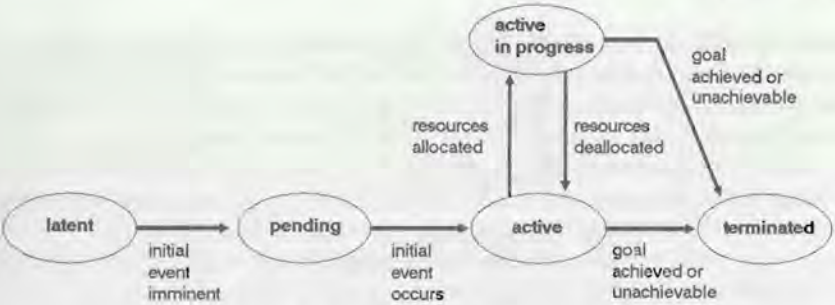

FIGURE 4 Task states.

which must take into account compliance with air traffic control directives, Federal Aviation Administration regulations, and company policies, to name just a few considerations. It reflects a minimal definition of goal priority which must be expanded as the theory is developed.

A *task* is a process that is completed to cause a system to achieve a goal. A task involves the behaviors of one or more secondary systems or subsystems necessary in order to produce inputs to the primary system to achieve the goal. For example, for the goal to arrive at Waypoint 7, there must be a fly to Waypoint 7 task. The pilot, the primary flight controls, the cockpit displays, the hydraulic system, and the engines are just a few of the secondary systems required to complete the fly to Waypoint 7 task to achieve the goal for the primary system (the aircraft) to arrive at Waypoint 7. These secondary systems are called *resources*. Stated another way, tasks require resources to achieve goals.

A task has state (see Figure 4). Initially, a task is latent. When the initial event of its goal is imminent, the task becomes pending. When the initial event occurs, the task becomes active. A task becomes active in progress when resources are allocated to it to achieve the goal (i.e., while it is being executed). If the task has been in this state but resources are deallocated from it and execution ceases, the task returns to the active state. A task may be terminated if its goal is achieved, if the goal is unachievable, or if the goal becomes irrelevant. In the case of an unsuccessful termination, the task may be considered to be aborted. Further state decomposition is possible and perhaps desirable, but the set of states just described is satisfactory for the preliminary theory to be presented later in this article.

The goal to approach the airport and arrive at landing position was decomposed into cleared to approach waypoint and at approach waypoint subgoals. Similarly, an approach task could be decomposed into get approach clearance and fly to approach waypoint subtasks.

An *agenda* is a hierarchy of tasks to be completed during a mission. Each task is defined to achieve a specific goal and should become active when the goal's initial event occurs. Figure 5 shows the partial agenda for the partial goal hierarchy shown in Figure 3.

When an initial event occurs, the corresponding task becomes active. Two tasks that are simultaneously active are called *concurrent tasks*.

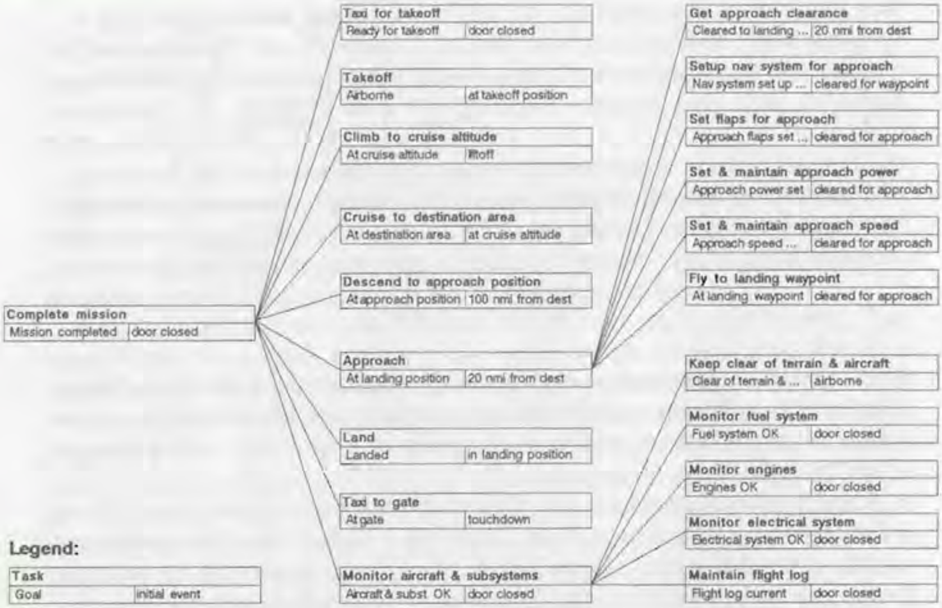

FIGURE 5 A partial agenda.

RESOURCE-LIMITED PERFORMANCE

Executing a task involves the coordinated behaviors of one or more systems or subsystems called *resources*. Certain resources are required to complete each task, and if the resources are not available, the task cannot be completed satisfactorily and the goal cannot be achieved.

A variety of resources are required for cockpit tasks. Equipment resources include autopilots, radios, displays, and controls. Human resources include the captain, first officer, and flight engineer. Because resources are systems, they can be decomposed into simpler subsystems. Human resources can be decomposed into personal sensory, motor, and cognitive resources. Cognitive resources can be further decomposed into the verbal and spatial resources identified and studied by Wickens and his colleagues at the University of Illinois (Wickens, 1984; Wickens & Liu, 1988).

Because two concurrent tasks may require the same resources, this poses a potential problem. Behaviors of necessary resources that are compatible with achieving one goal may be incompatible with achieving another goal, and the performance of one or more of the tasks may suffer. That is, task performance is limited by resource availability. With resources like displays or hands and feet, this is obvious. But it is also true for cognitive resources (Navon & Gopher, 1979; Wickens, 1984). A situation in which task resource requirements exceed resource availability is called a *task conflict*.

For example, given the agenda in Figure 5, if air traffic control clearance to an approach waypoint is obtained the set and maintain approach power task would become active. Assume that this task requires a multifunction display resource on which an engine display format must be shown. Suppose that now a primary electrical system failure event occurs and a subtask to diagnose/correct the electrical system becomes active. Assume that this subtask requires an electrical system display format on the same display resource. If the two formats cannot be displayed simultaneously, a resource shortage resulting in a task conflict exists.

Even if two displays are available to complete both of these tasks simultaneously, there still might be a task conflict due to cognitive resource limitations. Assuming for the purpose of this illustration that no other crew member is available to assist the pilot in completing these two tasks, he or she may lack sufficient cognitive resources to attend to both of them simultaneously. This might result in errors in completing one or both of the tasks.

A PRELIMINARY, NORMATIVE THEORY OF CTM

The process by which the flight crew manages an agenda of cockpit tasks is called CTM. CTM is described as a procedure that is executed by the flight crew as follows:

1. Create initial agenda.
2. Until mission goal is achieved or determined to be unachievable:
    a. Assess current situation.
    b. Activate tasks whose initial events have occurred.
    c. Assess status of active tasks.
    d. Terminate tasks with achieved or unachievable goals.
    e. Assess task resource requirements.
    f. Prioritize active tasks.
    g. Allocate resources to tasks in order of priority:
        1. Initiate newly activated high-priority tasks.
        2. Interrupt low-priority tasks (if necessary).
        3. Resume interrupted tasks (when possible).
    h. Update agenda.

This procedure and the following explanation comprise a preliminary normative theory of CTM that seeks to identify the task management functions which should be performed by the flight crew. Together they represent an initial formalization of the functions the flight crew should use to manage their activities successfully.

Given a hierarchy of goals to accomplish in a mission, the first CTM step for the flight crew is to create the initial agenda. This agenda consists of a task to achieve each goal. An initial event must be defined for each goal/task pair.

Once the agenda has been created, a process of agenda management begins and continues until the mission goal is achieved or unachievable. In the latter case, the process should end only after the aircraft and its subsystems reach some safe state.

The flight crew must assess the current situation. The states of all relevant aircraft systems and subsystems must be considered to determine if significant events have occurred.

When initial events occur, the flight crew must activate tasks that are contingent upon those events. This means that these tasks enter the active state (see Figure 4) and should become active in progress as soon as resources are available.

The flight crew must assess the status of active tasks to determine if satisfactory progress is being made toward achieving the tasks' goals. Not only must the current status of each task be assessed, but if the task's goal is not yet achieved, the status of the task must be projected into the future to determine the likelihood that the goal will be achieved. A task's status may be declared satisfactory if its goal is achieved or is likely to be achieved, marginal if achievement of its goal is uncertain, or unsatisfactory if the goal is violated or is unlikely to be achieved without corrective action.

Based on this assessment, the flight crew should terminate tasks with achieved or unachievable goals. Tasks whose goals become irrelevant due to changing circumstances should also be terminated. Termination removes tasks from competition for resources.

For the remaining active tasks, the flight crew should assess task resource requirements to determine what resources are required to complete them. A newly activated task might be started with minimal resources, but a task of marginal or unsatisfactory status might require additional resources to achieve its goal.

The flight crew should prioritize the active tasks. Factors that can influence task priority include the following:

1. The importance and urgency of the task's goal.
2. The importance and urgency of other active tasks' goals.
3. The current and projected status of the task.
4. The current and projected statuses of other active tasks.

Prioritization can be defined as a pairwise comparison of tasks based on these factors and others that results in an ordering of active tasks.

As a result of the previous steps, the flight crew must then allocate resources to tasks in order of priority. This is an assignment of resources to tasks, with preference given to high-priority tasks, so that the tasks may be executed. The flight crew should initiate newly activated high-priority tasks to make them active in progress (Figure 4). They should interrupt low-priority tasks that are active in progress when high-priority tasks requiring the same resources become active. When the high-priority tasks finish and resources become available again, the flight crew should resume interrupted tasks, returning them to the active in progress state. These steps result in a set of tasks in the process of execution.

This process causes changes in the set of pending and active tasks and changes in task status and priority. The flight crew should update the agenda to reflect these changes and repeat the process.

Figure 6 shows a diagram of CTM in the approach phase of a flight mission.

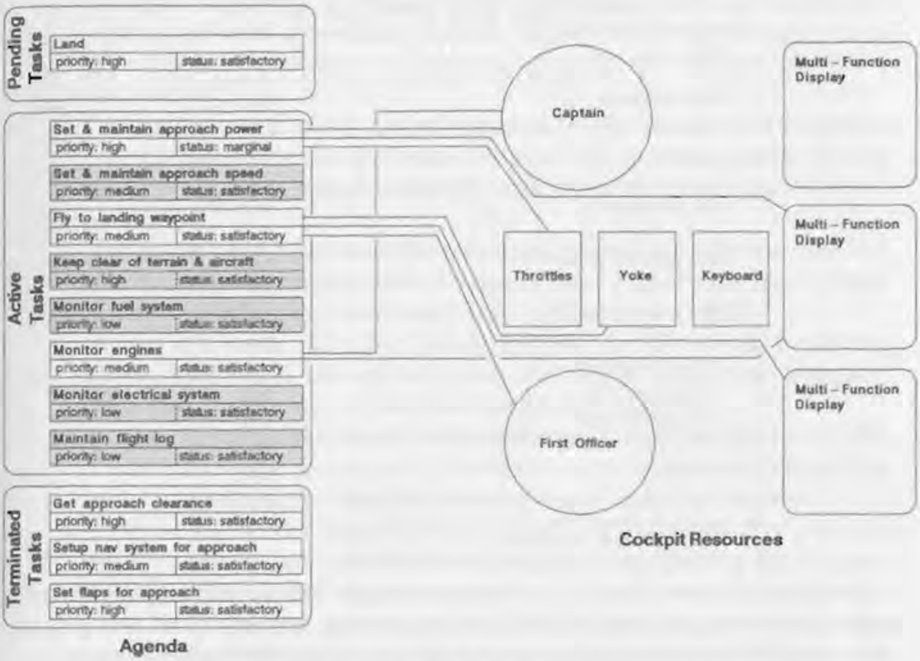

FIGURE 6 CTM during approach.

Three approach-related tasks—get approach clearance, set up navigation system for approach, and set flaps for approach—have already been completed and are therefore in the terminated state. Eight tasks are active, three of which are actually in progress. The first officer is flying the aircraft (executing the fly to landing waypoint task). The captain is executing two tasks (set and maintain approach power and monitor engines). The other active tasks are interrupted due to resource limitations. Because the approach is well along, the landing process is imminent, so the land task is pending.

CTM ERRORS

The theory of CTM presented here provides a framework for understanding flight-crew multiple task behavior. In particular, by considering the accuracy and timing of the functions in the CTM procedure, a preliminary error taxonomy has been developed by Chou (1991) and is presented in Table 1. Chou is currently applying a derivative of this taxonomy to a collection of National Transportation Safety Board (NTSB) aircraft accident reports to arrive at a better understanding of the significance of CTM.

To illustrate, when an engine of a commuter aircraft failed on takeoff from Houston William P. Hobby airport in Houston in 1980, the captain failed to initiate

TABLE 1
A Preliminary CTM Error Taxonomy

CTM Function	*Error*
Task initiation	early
	late
	incorrect
	lack
Task assessment	excessive
	lack
Task prioritization	high
	low
Resource allocation	high
	low
Task interruption	incorrect
Task resumption	lack
Task termination	early
	late
	lack
	incorrect

Note. From Chou (1991).

an engine-out recovery task (task initiation—lack). The aircraft crashed, killing seven passengers and crew (NTSB, 1981). In the now famous L–1011 Everglades crash in 1972, which killed 99 (NTSB, 1973), the flight crew failed to assess the status of the primary flight task, possibly because they incorrectly prioritized tasks relating to diagnosis and repair of a landing gear status lamp (task assessment—lack; task prioritization—high). This crew also misallocated resources to cockpit tasks; all three crew members plus a jumpseat occupant became totally absorbed in the diagnosis task (resource allocation—high). In 1984 a DC9–31 captain failed to terminate a landing task in the presence of turbulence, hail, and heavy rain at Detroit (task termination—late). The aircraft crashed and, though no one was killed, damage to the aircraft was substantial (NTSB, 1985).

It is reasonable to project an increase in the number of CTM error-induced accidents as traffic density and cockpit complexity grow, unless appropriate countermeasures are introduced.

RECOMMENDATIONS FOR PVIs TO FACILITATE CTM

Such countermeasures could and should come partly in the form of improved flight-crew training and cockpit procedures, countermeasures that are advocated by proponents of CRM (Orlady & Foushee, 1986). But these methods should be complemented by improved cockpit design. I believe that CTM should be a primary consideration in the design and development of future PVIs. Based on the preliminary, normative theory of CTM and the CTM-based analysis of a variety of accidents and incidents, I believe a PVI should perform the following functions to facilitate CTM:

1. Maintain and display a current agenda. The PVI should maintain an internal representation of the mission task agenda and provide an external, visual representation in the form of a dynamic agenda display for the flight crew's information.
2. Maintain a model of the current situation. A representation of important aircraft and environment systems and subsystems, which accurately reflects the states of these systems, especially with regard to active tasks, should be maintained.
3. Recognize when tasks should be started and inform the flight crew. The PVI should use the situation model to recognize when initial events occur so that appropriate tasks may be activated and the flight crew notified.
4. Assess task status and inform the flight crew. The PVI should be able to assess the status of tasks and advise the flight crew via the agenda display, especially concerning marginal and unsatisfactory tasks.
5. Recognize when tasks should be terminated and inform the flight crew. The PVI should be able to note and advise when events occur which indicate that tasks are completed or that their goals are unachievable or irrelevant.
6. Help the flight crew determine task resource requirements. The resource requirements of each task should be dynamically assessed by the PVI, and the flight crew should be informed.
7. Help the flight crew prioritize tasks. The PVI should contain factual and procedural information to allow it to prioritize tasks dynamically as events occur and advise the flight crew.
8. Help the flight crew initiate tasks. Machine resources required by tasks should be automatically configured by the PVI for those tasks. Appropriate procedural information should be presented to the flight crew.
9. Help the flight crew interrupt tasks. The PVI should be able to recognize and advise which low-priority tasks should be interrupted so that high-priority tasks can be initiated.
10. Help the flight crew resume interrupted tasks. When resources become available again for interrupted tasks, the PVI should advise and assist the flight crew in resuming them.

My colleagues and I showed that these recommendations are both reasonable and effective through the successful development and evaluation of a prototype PVI.

A PROTOTYPE PVI TO FACILITATE CTM

The task support subsystem (TSS) is a prototype PVI developed at Oregon State University whose function, in part, is to facilitate CTM (Funk & Lind, 1991). It is a subsystem of an experimental avionics system that runs in a simulated aircraft. Prior to a mission, the pilot defines the tasks to be accomplished in the mission and provides parameter values for those tasks, including priorities and levels of automation. During the simulated flight, software modules called task agents (TAs) perform the CTM function to see that all predefined tasks are completed satisfactorily and on time.

Each task in the mission is represented by a TA that determines when the task should be started and configures the cockpit for the task. The TA monitors the pilot and aircraft subsystems to see that the task is completed correctly and on time. If the pilot fails to act on the task, the TA reminds him or her via a display; the TA alerts the pilot to actual or anticipated deviations from the task's goal. Most TAs also facilitate task execution by providing procedural prompts and recommendations. Some TAs are capable of completing their tasks automatically, at the pilot's discretion.

Multiple TAs are coordinated by a high-level TA that allocates resources, such as multifunction displays, based on priority. A mission display format serves to remind the pilot of tasks to be completed and shows the status of each active task.

The TSS, as part of the experimental avionics system, was evaluated in a simulator experiment. The simulator consisted of a single-pilot cockpit with a 19-in. monitor showing an out-the-windscreen view and three multifunction displays. One of the three displays was used exclusively for a horizontal situation indicator display format. The other displays were used for aircraft system display formats. A touch-panel overlay on the monitor provided simulated push-buttons for the multifunction displays. The simulation program included a 6 *df* model of a generic, single-seat military aircraft controlled by a stick and throttle. No autopilot was provided. The simulation also included on-board sensor and environment models.

Sixteen professional pilots with experience ranging from 1,000 to 4,700 flight hours participated in the evaluation. Each flew two equivalent missions which required the pilot to navigate to a specific location under time constraints, locate and designate a surface object, and respond to emergency events. In one of the two missions, the cockpit was equipped with the experimental avionics system, including the TSS. In the other mission, the cockpit was configured as for a conventional aircraft, lacking the experimental avionics system. Task execution performance (accuracy and speed), task management performance (accuracy and timing), and workload (subjective ratings) were measured for each simulated mission.

Analysis of simulation results showed a 38% improvement in composite task execution and management performance and a 13% reduction in workload. These results were statistically significant. In addition, the majority of the pilots in the study considered the TSS-equipped cockpit to be superior to the baseline cockpit and preferred it over the baseline.

PRACTICAL CONSIDERATIONS

In spite of the apparent effectiveness of the TSS in facilitating CTM performance, two major impediments exist to implementing it or its derivatives in operational aircraft. First, it would be almost impossible, from a technical standpoint, to retrofit existing aircraft with the full functionality of the TSS. The TSS requires state information from virtually all cockpit equipment, including navigation systems, radio equipment, displays, and controls. Even in an advanced aircraft with an avionics bus, this information is simply not available in its entirety. There are also space and weight costs associated with the hardware necessary for TSS implementation that could be prohibitive.

The second impediment to successful implementation is certification. The prototype TSS, which does not have all of the functionality necessary for full implementation, is already a complex software system that would require considerable time, effort, and cost for thorough verification and validation. The process of certifying a complete, fully functional TSS would be a truly formidable task.

Nevertheless, the concept of facilitating CTM through technological means should be pursued. A partial implementation of a TSS for a commercial transport aircraft could take the form of a "smart" electronic checklist using a hand-held or laptop personal computer as a computational platform. Instead of drawing state information directly from cockpit equipment, key information could be provided by the flight crew. As the flight crew finished steps in a task, they could "check off" the item on the TSS, which would provide information to the TSS on what tasks were progressing and would help keep the crew cognitively engaged in the tasks and in task management.

This partial implementation could be successful only if the electronic checklist form of the TSS replaced, rather than added to, the use of paper checklists, manuals, and logbooks. There should be no net increase in workload imposed on the flight crew or this new device would be (justifiably) subject to the same criticisms aimed at many recent developments in cockpit automation.

In addition to making the TSS technically more feasible, a partial implementation of the TSS would also make the process of certification simpler. Reduced functionality could lessen the effort required to verify, validate, and certify the equipment. A modular design would facilitate phased certification following phased implementation of TSS functions.

CTM AND CRM

Several references have been made to CRM. Several important aspects of the relationship between CRM and CTM are noted next.

CRM had its genesis in a simulator study conducted by Ruffell Smith (1979), which confirmed that significant relationships exist between pilot workload and errors, vigilance, and decisions. The study also showed was that there is a significant relationship between management of human and machine resources and flight-crew performance. Lauber (1986) subsequently defined CRM as " ... the effective utilization of all available resources—hardware, software, and liveware—to achieve safe, efficient flight operations" (p. 9). This rather broad definition certainly encompasses CTM. There are, however, some important distinctions between CRM and CTM.

First, CRM and CTM differ in scope. CRM is broad in scope and general, addressing the larger issues of social interaction, flight-crew coordination, and cockpit management. CTM is narrower and more detailed, focusing on situation assessment, task assessment, task prioritization, task execution, and task interruption.

The origins of CRM and CTM differ. CRM had its origins in the principles of organizational psychology and business management. CTM emerged from concepts of systems theory and cognitive psychology, specifically timesharing and workload.

CRM and CTM possess distinct approaches. CRM uses a management science approach in which the crew is seen as a team of individuals interacting in a social as well as a technical environment. CTM uses a cognitive science approach in which a flight crew is viewed as a resource-limited processor of tasks.

The applicability of CRM and CTM differ, at least in practice. CRM appears to be applied exclusively to multimember flight crews. On the other hand, CTM applies to single-pilot operations as well as to the behavior of individual crew members in multimember flight crews.

Measures to facilitate CTM and CRM are different. CRM accepts the cockpit as a given and seeks to achieve more effective utilization of human and machine resources through specialized training and improved procedures (Orlady & Foushee, 1986). CTM provides insights and recommendations on how to change the cockpit to facilitate better task management performance.

In summary, although CTM and CRM overlap in definition, in practice they are complementary. Although CRM clearly provides means for enhancing performance through better flight-crew coordination, it lacks a precise characterization of the tasks the flight crew must perform, which makes the establishment of measures and standards somewhat problematic. The normative theory of CTM presented here not only provides a precise definition of tasks and offers standards by which task management can be assessed, but it also leads to recommendations for the design of cockpit systems to help achieve those standards.

CONCLUSIONS

The preliminary, normative theory of CTM presented here addresses the management of multiple, concurrent tasks by flight crews. It represents an initial attempt to formalize a process that is intuitively well understood, but not always well executed, by the flight crew. This initial formalization provides a framework for understanding flight-crew multiple task behavior, suggests some basic standards for task management performance, and leads to a taxonomy of task management errors that can be used to analyze aviation accident, incident, and simulator data. More important, it leads to recommendations for improving task management performance through the design of cockpit systems. These recommendations have been at least partly validated by a prototype PVI.

But the theory and its results are preliminary. The theory itself requires refinement, and detailed examples must be developed. The normative theory must be supplemented with a descriptive theory that explains not just what should happen, but what can go wrong and why. A more complete CTM error taxonomy should be developed and applied to aircraft accident and incident reports as well as data from simulator studies. More extensive and detailed design recommendations should be developed. Prototype PVIs conforming to the recommendations must be created and evaluated to determine the value of the theories and the effectiveness of the recommendations.

Nevertheless, this theory is a starting point. It provides an initial formalization of a process that flight crews endeavor to perform well, and the example applications of the formalization demonstrate its potential usefulness in cockpit analysis and design.

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