Out-of-the-Loop Performance Problems and the Use of Intermediate Levels of Automation for Improved Control System Functioning and Safety

David B. Kaber

Department of Industrial Engineering, Mississippi State University, 125 McCain Engineering Bldg., Miss. State, MS 39762

and

Mica R. Endsley

Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Ave., 33-115, Cambridge, MA 02139

Human supervisory control and monitoring of automated systems, as well as, passive system(s) information processing can all be classified as forms of out-of-the-loop (OOTL) performance. Whether the operator's task is to decide if process control intervention is necessary, detect a critical system event, or accept or reject the actions of a computer controller, he or she is removed from direct, real-time control of the system. OOTL performance is a critical issue in overall automated systems functioning because it is associated with numerous negative consequences including: (a) operator failure to observe system parameter changes and intervene when necessary (vigilance decrements); (b) human over-trust in computer controllers (complacency); (c) operator loss of system or situation awareness; and (d) operator direct/manual control skill decay. These consequences have been found to impact human performance under both normal operating conditions and system failure modes, with a greater effect on the latter [15] leading to serious problems in operator ability to perform their assigned tasks when working with automated systems.

Level of automation (LOA) has been put forth as an approach to ameliorating OOTL performance problems. It is intended to determine the optimal assignment of control between a human operator and computer in order to keep both involved in system operations. LOA considers the capabilities and capacities of both the human and computer controller in determining their optimal coupling. It constitutes a systems approach to resolving OOTL performance problems by minimizing the negative consequences associated with the removal of the operator from active system control, and allows for the strengths of both human decision making and computer processing to be realized. When compared to a technological approach that assesses only the capabilities of the computer in allocating as much responsibility to the machine as possible, and assigning the remaining tasks to the human operator, the advantages can be considerable.

A LOA taxonomy will be presented along with research examining its utility in a dynamic control task. Using LOA to identify optimal combinations of human and computer control was found to produce improvements in system performance under intermediate levels. These levels involve joint human and computer control of various system functions, such as monitoring, planning, and option selection and implementation. Results indicated decreases in the number of system processes/tasks overlooked by operators. These improvements may translate into cost reductions due to improved operational safety and are anticipated to be applicable to process control operations.

INTRODUCTION

Within the last 20 years, safety in process control and automated systems has become an increasingly important issue due to severe accidents resulting in environmental damage and loss of human life. Incidents motivating safety research in control systems have ranged from nuclear power plant melt-downs, such as that at the Unit 2 Plant of Three Mile Island in 1979 [*1*], to commercial airliner mishaps, including the crash of US Air B-737 on take-off at New York's LaGuardia Airport in 1989 killing two people [*2*]. These incidents have been attributed to human information processing errors, specifically a lack of operator awareness and understanding of process or automated system states. Such errors are contributed to by problems with: (a) control system interfaces presenting process or task relevant information to operators, and (b) allocation of system functions to human and automated controllers. Failure of interface designs to consider human cognitive and physical capabilities has produced performance pitfalls in process control including poor instrumentation readability and reachability; operator inability to mentally transform information from useless to useful forms; and operator inability to active controls, interpret codes, locate individual displays and respond to alarms [3]. Problems in control system function allocation include assigning tasks to human and automated controllers on the basis of computer capabilities and capacities along and not considering those of the human, as well. This has resulted in, for example, as many tasks as possible being assigned to automated control with a fragmented task set left for operator control [4]. It is often difficult to train operators in this set of tasks. Further the operator, during actual process or system functioning, is usually albeit completely removed from the control loop. Consequently, he or she may be posed with an inappropriate taskload, and is susceptible to boredom, vigilance and complacency.

Both poor system interface design and inappropriate function allocation among human and computer controllers can increase the probability of human information processing errors including misperception of displays, lack of comprehension of the meaning of displayed information and poor decision making in process and systems control. These errors can occur during both normal and abnormal operations, and can lead to degraded performance and accidents.

There exists a need to: (a) develop interfaces that accommodate process control system operator capabilities, and (b) facilitate appropriate system function allocations between human and computer controllers keeping both involved in the control loop. The objective of this paper is to address the latter by: (a) identifying process or automated system roles limiting operator task involvement and promoting the potential for poor human performance and safety; and (b) offering an approach to optimizing human and automation collaboration in process or automated system functioning. The approach was tested in a simulated dynamic control task and results are presented demonstrating improvements in performance and safety under normal operating conditions and failure modes.

OUT-OF-THE-LOOP PERFORMANCE

When an operator is removed from a control loop due to allocation of system functions to an automated/computer controller, the level of human system interaction is limited and, consequently, operator awareness of system states may be reduced. This poses a serious problem during normal operations preceding system errors, malfunctions or breakdowns because operators are often slower to respond to such events when removed from a control loop versus actively controlling a system [5]. Further, during failure modes, operators who have been removed from system control may not know what corrective actions need to be taken to stabilize the system and bring it into control. As well, these same operators may have forgotten critical manual control skills for error recovery due to their required absence from the loop. Examples of automated system (e.g., aircraft) mishaps, attributed to human OOTL performance, include the near crash of Air China's Boeing 747 into the Pacific Ocean in 1989. The aircraft experienced a gradual engine failure that the human pilot was not aware of because of autopilot compensation (through rudder control) up until the point of failure of the autopilot, itself. Subsequently, the jet stalled and plummeted thousands of feet, being recovered within a few seconds of the ocean surface [5]. Another example is that of the catastrophic crash of Northwest Airlines MD-80 at Detroit Airport in 1987 due to improper configuration of the flaps and slats of the aircraft. All persons were killed but 1 because an automated take-off configuration warning system, which the crew relied on, failed to function [6]. They did not realize the aircraft was improperly configured for take-off and failed to check manually [7]. In both of these cases of automation error, when computer control facilities failed, operators, out of the direct control loop, were unaware of the state of the system, and in at least the one case, were unable to compensate for the failure mode before an accident occurred.

Lack of operator awareness leading to accidents may also arise in process control environments including, for example, petrochemical refining in which a delicate balance of pressure, volume and temperature must be maintained for efficient and safe system functioning. Operators may fail to be vigilant of potential errors (e.g., imbalances) or exhibit overtrust in automated/computer control due to inappropriate process function allocations among themselves and the computer. Inappropriate allocations may constitute assignment of all tasks for which problems have been identified and technological solutions exist to automation, and relegate the human operator from controller to the roles of supervisor, monitor and passive information processor. Unfortunately, these are roles to which humans are ill-suited [8].

SUPERVISORS

As supervisors of automated control, humans do not directly act on the process being controlled, but rather they supervise the behavior of computer controllers between them and the process [9]. They observe the actions of a computer and agree or disagree with it. During normal operating conditions, a human supervisory controller monitors displays and looks for signals that intervention may be required to prevent process errors from occurring due to, for example, poor automated decision making. In the event of an error, he or she is required to directly control the process for failure recovery and return to supervisory mode. Human performance under supervisory control (SC) is often poor because of the limited taskload placed on operators under normal conditions reduced control involvement and producing the consequences of loss of process/system awareness and decay of direct control skills, which are critical for error recovery.

MONITORS

Systems monitor is a role, which is as difficult for humans to fulfill as supervisory controller. It involves waiting to detect a critical process events, such as fluctuation of a pointer on a temperature gauge beyond a certain degree. It requires operators to scan displays without taking any action to change the state of the process unless needed [9]. Its sole purpose is to determine whether a process is functioning normally or if human intervention is required. During normal operating conditions, a monitor is required to sample many indicators of process status and evaluate the need for intervention while automated control handles functions that were once carried out by humans [5]. Consequently, the operator has less to do, in terms of direct control, but is often overloaded with process components to monitor. This has the potential of increasing the probability of failing to observe critical events leading to errors. During failure modes, the monitor is often expected to function in a manner identical to a supervisory controller; that is, exercise direct control on the process for recovery.

The requirements and purpose of monitoring are so similar to those of SC that the two are often regarding as being synonymous. Even the OOTL performance problems that monitoring and SC suffer from are similar, yet they do constitute two very different acts. (Supervisory control, unlike monitoring, can involve: (1) choosing appropriate plans for dealing with system errors and failures, (2) executing plans for directing the system to a new goal, and (3) allocating manual control from moment-to-moment between the operator and computer [9]). With respect to OOTL performance problems, humans are poor at monitoring because of complacency and vigilance issues resulting from removal from a control loop and required functioning at a high level of control, like SC. Complacent operators tend to exhibit overtrust in computer controllers to perform process functions flawlessly. This usually occurs in tasks involving highly reliable automation in which it is easy for the operator to instill a great deal of confidence [10]. Complacency results in reduced process control accuracy or delay in detecting failures [10]. Human vigilance problems involve failure, on an operator's behalf, to attend to critical process events, such as equipment breakdowns. This usually occurs as a result of prolonged monitoring. There is much evidence that operator ability (speed and reliability) to detect process state changes is dependent upon whether humans are actively involved in direct task control versus simply monitoring or supervising the process [11, 12].

PASSIVE INFORMATION PROCESSORS

The role of passive information processor, much like that of supervisory controller, involves observing the actions of other operators or computer controllers and agreeing or disagreeing with them. The operator's task is to understand the actions of another system controller and thereby accept or reject its actions. The key difference between passive information processing and direct action on the process is that the former involves functions similar to those maintained during process monitoring (e.g., scanning information sources); whereas, the latter involves manual control functions including process planning, decision making, selecting responses and implementing strategies.

During normal operating conditions passive information processors detect the need for manual process intervention and attempt to maintain understanding of the state of the process. In the case that intervention is required, operators must exercise direct control skills for recovery and return to passive functioning. Human performance is often poor during intervention because operators have been relegated to passive information processor under normal conditions. This is due to the lack of control loop involvement inhibiting dynamic process awareness and, consequently, understanding for facilitating process recovery [13].

SUMMARY

The lack of operator involvement in process or automated systems control in supervisory modes and passive information processing, as well as complacency and vigilance in process or automated systems monitoring, all contribute to critical human cognitive errors, specifically the loss of operator situation awareness (SA), to which the safety incidents discussed above have been attributed. Further, this lack of control involvement contributes to the loss of human manual control skills for process or automated system error recovery. These pitfalls of OOTL performance have motivated the development of a systems approach to allocating functions, as part of active control, to human and computer controllers intended to maintain involvement of both in ongoing operations. This approach is level of automation (LOA).

LEVEL OF AUTOMATION

In an attempt to prevent operators from being reduced to automated control system supervisors, monitors and passive information processors, possibly leading to OOTL performance problems, LOA allocates system functions to human and computer controllers based on consideration of the capabilities and capacities of each under normal operating conditions and failure modes. It requires identification of the functions to be allocated (e.g., systems monitoring, planning, decision making and acting) and the specific tasks within each function that must be performed. (For example, systems monitoring may involve scanning displays for specific information sources, reading instrumentation, transforming system variable samples into useful forms, etc.) These tasks can then be matched to controller sensing and processing abilities. The LOA method has the potential benefits of: (a) maintaining appropriate operator control involvement and taskload to reduce susceptibility to complacency, vigilance and lack of system awareness by taking into account human and computer performance abilities during failures, (b) reducing system errors due to poor automated decision making by relying on human decision making capabilities, and (c) enhancing system performance through computer data processing.

Level of automation differs from alternate approaches to system function allocation such as a technological based method focusing only on computer capabilities and capacities (under normal operating conditions) for assignment formulation. Process and automated system control design using a technological approach has been driven by a desire to reduce costs through reduction of operator workload and, consequently, human staffing requirements (Endsley and Kaber, in review). This usually results in assignment of a majority of tasks to the computer and relegation of the human to one of the identified OOTL performance roles. Unfortunately, the approach also produces the discussed operator performance problems and poor system functioning during failures.

Many different combinations of human and computer for system function performance may result from the LOA approach if controllers are capable of performing multiple functions. Some combinations or levels of automation have been presented in human performance and automated systems literature including those formulated by Sheridan and Verplanck [14] in the context of a teleoperation system.

TABLE 1. Endsley and Kaber's (*15*) LOA Taxonomy

LEVEL OF AUTOMATION	FUNCTIONS			
	MONITORING	GENERATING	SELECTING	IMPLEMENTING
1. Manual Control	Human	Human	Human	Human
2. Action Support	Human/Computer	Human	Human	Human/Computer
3. Batch Processing	Human/Computer	Human	Human	Computer
4. Shared Control	Human/Computer	Human/Computer	Human	Human/Computer
5. Decision Support	Human/Computer	Human/Computer	Human	Computer
6. Blended Decision Making	Human/Computer	Human/Computer	Human/Computer	Computer
7. Rigid System	Human/Computer	Computer	Human	Computer
8. Automated Decision Making	Human/Computer	Human/Computer	Computer	Computer
9. Supervisory Control	Human/Computer	Computer	Computer	Computer
10. Full Automation	Computer	Computer	Computer	Computer

They developed 10 levels of automation by assigning the functions of "gets," "selects," "starts," "approves," and "tells" to either a human operator or computer controller. The levels were presented in a taxonomy. Endsley and Kaber [*15*] developed a 10-level taxonomy of LOA intended to be applicable to a wide array of dynamic process and automated system control domains, specifically advanced manufacturing, teleoperations, air traffic control and aircraft piloting. These domains have many features in common including: (a) multiple system goals, (b) multiple tasks competing for an operator's attention (each having different relevance to system goals), and (c) high task demands under limited time resources. Further, the domains share common functions for allocation to the human and computer controller comprising: (a) monitoring—scanning displays to perceive system status, (b) generating—formulating options or strategies to achieve system goals, (c) selecting—deciding on a particular option or strategy, and (d) implementing—carrying out the chosen option. Endsley and Kaber [*15*] formulated their levels of automation by assigning these functions to human or computer, or a combination of the two, depending on the sensing and processing capabilities of each in the various domains. The resulting levels are presented in Table 1.

EXPERIMENT AND RESULTS

We conducted an experiment to examine the influence of the 10 levels of automation presented in Table 1 on human operator performance and SA in a simulated dynamic control task. The simulation was developed based on a similar task employed by Tulga and Sheridan [*16*]. It incorporated the common features of the dynamic system control domains studied by Endsley and Kaber [*15*] in developing their taxonomy. The simulation required subjects to carry out task processing; select and eliminate targets (boxes of different colors and sizes) moving across a display towards a deadline at its center. All targets moved to the center of the scope with different velocities. Rewards were offered for target eliminations, and penalties were assessed for allowing them to reach the deadline (expire). The operating parameters of the task included: (1) no partial credit was given for incomplete target eliminations, and (2) all targets present on the display, at any given time, could not be eliminated; therefore, operators were required to generate strategies for reducing expirations and collisions.

Thirty university students performed the simulation in four 10-min trials, two of which were used to examine the LOA effect on manual performance during simulated automation failures (dynamic shifts to manual control), and two of which isolated the influence of LOA on operator SA. During the automation failure runs, manual control of the system was allocated to subjects three times (at random intervals) for a fixed period of 1 min. The SA trials involved three simulation freezes occurring at random points in time to administer (Situation Awareness Global Assessment Technique [*17*]) queries aimed at assessing operator perception, comprehension and projection of states of the system.

We found that subject performance, measured in terms of the number of tasks addressed, was significantly improved by levels of automation involving computer aiding in the implementation aspect of task functioning. Specifically, under low-intermediate levels ('Action Support' [level 2] and 'Batch Processing' [level 3]) performance was considerably greater than with 'Manual Control' (level 1), and better than with levels of automation that added computer assistance to other task roles, such as strategy generation and selection. Decreases in the number of tasks addressed were observed at levels of automation involving joint human-computer strategy generation ('Shared Control' [level 4], 'Decision Support' [level 5], and Blended [level 6] and 'Automated Decision Making' [level 8]), as compared to levels requiring purely human strategizing (Action Support [level 2] and Batch Processing [level 3]). This finding was attributed to allocation of the generation role to operators possibly causing task overload. Joint human-computer selection of processing plans ('Blended Decision Making' [level 6]) had no significant impact on performance as compared to purely human (Decision Support [level 5]) or computer (Automated Decision Making [level 8]) selection. Also, performance under human selection (e.g., 'Rigid System' [level 7]) did not significantly differ from that under computer selection (e.g., 'Supervisory Control' [level 9]).

Performance measured in terms of the number of target expirations (tasks overlooked) decreased as a function of LOA with the highest number of expirations occurring under Manual Control (level 1). Levels of automation involving purely computer generation of options or joint human-computer generation (Rigid System [level 7] and Automated Decision Making [level 8]), produced the lowest number of target expirations. Although the way in which generation of options was conducted varied considerably between these two levels (in terms of the respective roles of the human and computer in the sharing of the generation option), this did not appear to have a substantial impact on performance.

Operator ability to recover from, and perform during, automation failures was significantly improved with levels of automation requiring human interaction in task implementation (e.g., subject selection of targets one-at-a-time versus queuing them for computer processing or using computer generated strategies). Specifically, the time-to-recovery of task control and the number of tasks addressed under subsequent manual control was worse when operators had been functioning at levels of automation requiring advanced queuing of targets (Batch Processing [level 3] and Automated Decision Making [level 8]). This result was attributed to the ability of operators to focus on future tasks; thus, ignoring the present system state (e.g., computer failure).

Significant differences in operator SA were only observed for system state comprehension queries. It was found that levels of automation not requiring the human to perform strategy selection (Blended [level 6] and Automated Decision Making [level 8], Supervisory Control [level 9], and 'Full Automation' [level 10]) allowed for improved subject task understanding, as compared to all other aided levels and Manual Control (level 1) mode. Other modes of automation corresponded to poorest levels of operator comprehension of task priorities and completion status. This finding was attributed to the added burdens of the selection and monitoring roles being allocated to the human at these levels along with the responsibility of strategy generation, which may have limited time resources available for perceiving targets.

Based on the above results, we concluded the following: (a) the distribution of human versus computer control made a significant performance difference in the implementation and option generation roles of the dynamic control task, but not in the decision making portion (option selection); (b) improvements in system processing were facilitated by computer aiding in the implementation aspect of functioning at low-intermediate levels of automation; (c) reductions in overlooked processes were driven by joint human-computer planning at upper-intermediate levels of automation; (d) levels of automation allowing for advance process planning in the selection role distracted operators from current task events (automation failures) and produced decrements in control response times and task processing ability; and (e) improvements in operator SA, specifically the understanding of task priorities and completion status, were facilitated by reductions in taskload under levels of automation involving human-computer or purely computer strategy selection.

These conclusions demonstrate the named potential benefits of the LOA approach to process and automated system design. Specifically, enhancements in performance due to computer data processing and human cognitive abilities were realized. These occurred at intermediate levels of automation in the form of increased operating efficiency and effectiveness, assessed in terms of completion, and attentiveness to, system processes.

CONCLUSIONS

Improvements in process and automated system performance due to the use of intermediate levels of automation, maintaining human and computer involvement in a control loop, may translate into cost reductions as a result of improved operational safety. By limiting operator susceptibility to vigilance, complacency, loss of system or situation awareness and direct/manual control skill decay, due to OOTL performance roles, improved human information processing under normal conditions, and expedient failure mode recovery, may result. This can increase the probability of safety system functioning and reduce safety incident rates. Similarly, such safety enhancements may yield, for example, reductions in machine wear, waste material, labor overtime and environment clean-up, as well as first aid costs, worker compensation claims and law suits for death due to operator negligence.

The named performance and safety benefits of LOA are anticipated to be realizable in process control operations including foundries and smelters, nuclear power plants, and petrochemical refining facilities. Specifically, using LOA to allocate system functions to human and computer controllers on the basis of process control task capabilities (e.g., remote control of robotic arms for carrying crucibles, monitoring and maintaining coolant water levels in reactors or chemical balances between feeder tanks in defractionators, etc.) may increase system error detection and remediation, and, consequently, safe process functioning.

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