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T. B. Sheridan

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Automation, Supervisory Control and Workload In Flight Management

Thomas B. Sheridan
Massachusetts Institute of Technology
Cambridge, MA

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NASA
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Ames Research Center
Moffett Field, California 94035

INTRODUCTION

This communication is the final report for NASA Ames Research Center Grant NSG-2118 to Massachusetts Institute of Technology, the period covered by the grant extending from November,1975 to November, 1980. The research was all carried out by graduate students in the MIT Man-Machine Systems Laboratory. It resulted in two Ph.D. theses and four master's theses. All the research was in collaboration with and supervised by the principal investigator. Indirectly the various research projects also contributed as laboratory demonstrations in a graduate course on man-machine system modeling.

The generic theme of the research was how automation in the cockpit is changing the task of the pilot and affecting his performance. In general we may say that the pilot's task is changing from that of a continuous in-the-loop controller to that of a "flight manager" or supervisor of automatic systems. The natural evolution of technology has provided him more and different systems, mostly electronic, to program, to monitor, to interpret the results from and to be concerned about the failure of. Further, within any one system, the pilot may have more alternative modes or ways to control certain variables - in some cases, e.g. flight control, whole hierarcies of commands and displays ranging from pure and direct manual control to inertial navigation and autoland. Presumably all these new avionic aids are to make the flight more reliable and more efficient, though the charge has been made sometimes that they are "killing the pilot with kindness."

Along with new automation there has been an effort to devise experimental paradigms and conceptual and mathematical models which may help generalize research results and predict performance under various hypothetical system designs. That is where this research claims to have made its greatest contributions. There are various aspects of these models which may be mentioned here and which reappear in the several studies to be cited specifically. One aspect is the "multi-task" quality of modern flight management, i.e., that pilots are faced with numerous semi-independent tasks some of which must be done in parallel and some in sequence, and the attentional demands of which are partly predictable (can be planned in part) and partly unpredictable. The successful pilot "keeps ahead of the airplane" by anticipating what tasks can be planned and attended to ahead of time, leaving sufficient margin for those tasks demanding attention at unpredictable times or at a pace which is forced by circumstance and which the pilot cannot set.

Another recurrent theme is that of "mental workload", an ill defined, difficult-to-measure, inferred or hypothetical or "intervening" property of pilot behavior which nevertheless is of increasing interest. The apparent reason is that as we automate the pilot out of routine skill tasks we seem to keep adding more cognitive and monitoring tasks which may at times be dull and undemanding but at other times can be demanding and stressful to the breakpoint.

Six separate studies are summarized below. Each was published earlier as an individual technical report.

1. IS THERE AN OPTIMAL WORK-LOAD IN MANUAL CONTROL? (Verplank, 1977)

Most people would agree that somewhere, between boring and fatiguing, there is an optimum mental work-load for manual control tasks such as driving a car, flying an airplane or regulating a processing plant. In particular, automation raises this question for the designer of man-machine systems: Is it possible for tasks to be too simple? Currently used concepts and measures of work-load are inappropriate to predicting, for example, the effects of underload.

It was proposed at the outset of this study that there is an aspect of work-load that sustains performance and facilitiates transitions to new tasks or emergencies. Information transmission rate was proposed as the appropriate measure for this kind of "facilitating work-load". It was shown how the information transmitted can come not only from the external disturbances but also from the human operator's uncertainty in his own output. Measures were developed for both external and internal sources.

Two experiments with simulated driving tasks and varying amounts of external disturbance were used to study long-term performance and transitions. Results showed that average performance over the run was always best when there was no input disturbance. The rate of deterioration in performance over the run could not be distinguished on the basis of the disturbance conditions. In fact, the results suggested that tasks of intermediate difficulty may produce worse decrements than either easier or more difficult tasks (just the opposite to what the above-stated hypothesis of an optimum would predict). The relative variability of performance was one performance measure where the no-input condition produced worse performance, yet the difficult condition was best, so no intermediate optimum disturbance was found. Performance upon transition was confused by many factors which made it difficult to say that the differences were due to work-load. For example, with no warning the intermediate pre-conditons may be best, with warning worst. Also, it may be that work-load is simply without meaning in explaining the details of transition performance.

The application of the information measures developed did not help much in sorting out or explaining the results. the only correlation found was between the slope of performance for the no-input case, and the amount of internal information transmitted. Greater information transmission correlated with greater performance decrement, just opposite to what the faciliation hypothesis would predict.

Several new directions for human factors research were suggested. Better models are needed for what is meant by work-load, for how to measure it and for what aspects of performance can be predicted. Information transmission may not be of value in explaining the temporal details of performance, but may help in quantifying activation or facilitation aspects of operator loading. Internal sources of uncertainty help to explain "self-loading" and important limitations in other areas of human operator performance such as monitoring, learning and adaptive behavior.

2. DYNAMIC DECISION MAKING IN MULTI-TASK SUPERVISORY CONTROL: COMPARISON OF AN OPTIMAL ALGORITHM TO HUMAN BEHAVIOR (Tulga, 1978; Tulga and Sheridan, 1980)

In this research a multi-task dynamic decision paradigm was developed to represent the systems within which pilot and other decision makers would seem to operate. This paradigm was described in graph-theoretical context. It was shown that, like some other combinatiorial optimization problems including Job-Shop Scheduling, Traveling Salesman, etc., it too is representable as a multi-path decision process. We called the algorithm "T-Path".

Since one of the properties of the T-Paths is the dynamic nature of the graph describing them, was shown that estimation of future tasks and discount rate on returns from planned sequences of actions are necessary. A dynamic programming optimization algorithm was developed which takes into consideration both the currently available and estimated tasks and gives an optimal path to follow, under the given model parameters β and γ, the latter being the urgency factor for tasks closer to the deadline.

Using a computer-graphic display for the experimental system, experiments were done with human subjects under different task-loads to identify the parameters β and γ at which model task choices best matched the human data. In addition to control theoretical identification criteria, two new criteria were introduced to account for the multi-task nature of the problem: (i) percentage of time operator attended the same tasks at the same instants and (ii) percentage of tasks that are attended eventually by both the model and the human operator. Experimental results were found to be fit easily by the "T-Path" model.

To differentiate several cases studied, an objective 'loading factor' was developed, which reduced to the utilization factor of Queueing Theory as a special case. Also, a new Work-Load Hypothesis was introduced to describe and predict subjective human opinion of mental work load as a function of this loading factor. One remarable result from these experiments was that, while subjective work load increased with objective loading factors so long as the operator could "keep up", as loading factor increased further the subjective rating of work load declined, as though the operator progressively concerned himself less and less as his relative performance deteriorated.

3. MAN-MACHINE PERFORMANCE FOR A SIMULATED AIRCRAFT WITH MULTI-LEVEL AUTOMATIC CONTROL SYSTEM (Yoerger, 1979)

This work examined the supervisory control hierarchy of flight control, i.e., the ever more prevalent situation where a large number of control configurations are simultaneously available to the pilot. Which mode should he use, when?

A digital simulation of a YC-15 transport aircraft with control wheel steering was implemented, with flight instruments and map displays shown on a vector graphics terminal. Additionally, three more automatic control configurations were also simulated. This allowed for a systematic increase in automatic control of the same dynamic system.

An experiment was conducted to determine the effects of automatic control mode, wind disturbance level, and inter-subject differences on both performance and subjective assessment of task demand. Subjects were required to follow a three-dimensional path. Performance was found to improve and task demand was found to decrease when the subjects were given direct set-point control over state variables which also corresponded to the task such as heading and vertical speed, as opposed to control inputs which related less directly to the task, such as vehicle attitude.

Transitions from higher to lower levels of automation were experimentally examined. It was theorized that differences in accuracy of the human's internal representation of the system state for different levels of automation would be revealed by observing transitions to the least automatic mode after failures had occurred in several more automated modes. No differences were found, however. By observing transitions from the most automated mode to different, less automated modes, the suitability of these less automated modes for failure recovery could be tested.

Two control configurations were found to be unsuitable for failure recovery. Pitch angle setpoint control resulted in poor performance, primarily due to display/task incompatibility. Heading setpoint control was unsuitable due to the inability of the subjects to quickly choose a new heading from the information displayed and enter it with the available control device.

4. SUBJECTIVE SCALING OF MENTAL WORKLOAD IN A MULTI-TASK ENVIRONMENT (Daryanian, 1980)

In this research we sought to determine the differential weightings of subjective mental workload factors which entered into the "objective workload" index used by Tulga in his abstract multi-task experiments. These were: (1) average interarrival time between appearance of new blocks (tasks); (2) speed with which blocks moved toward the deadline; and (3) productivity, or rate at which blocks diminished to zero when attended to (cursor was set on them). All 27 combinations of three levels of each factor were used, each combination being paired with each other combination for all possible pairs. Three subjects, after 100 seconds at each of two such tasks, used a five-level scale to rate which had the highest workload, and to rate the relative certainty, 1 being certainly of one stimulus, 5 being certainly for the other, 3 being indifference between stimuli.

A classical Thurstonian ("law of compartive judgement") scaling procedure was used. The reader is referred to the referenced report for a primer on this scaling technique. Essentially a Thurstone scale orders the judged stimuli while using consistency in ordering any two vaules to weight the psychological distance between those two values along the judgement scale. The sum of such weightings determines the location of any stimulus on the judgement scale.

Experimental results revealed rather strikingly that one factor, the interarrival time, correlated quite highly with mental workload as derived by the Thurstonian scaling transformations. Speed and productivity did not so correlate. This was evidently due to the fact that strategies changed radically with interarrival time, but did not change so radically for the other factors, at least with the ranges of each employed in the experiments. Response transitivity was least (subjects had most difficulty in deciding which stimulus of a pair had greatest mental workload) when interarrival time was short (and speed and productivity varied).

5. CONTROL MODELS OF AIRCRAFT IN-TRAIL FOLLOWING (Buharali, 1980)

This report applied the theory of optimal control to modelling a string of airplanes following one another in-trail.

The work was motivated by interest in providing to commercial pilots computer-based displays of nearby traffic, plus maps and time-lines, by means of which he presumably can perform better longitudinal control relative to separations and schedules. Unfortunately, while there was communication with personnel at several NASA aviation planning groups, no empirical in-trail following data were available, either from actual or simulated flight, to fit the models. It is hoped that some to-be-conducted simulations incorporating the cockpit display of traffic information (CDTI) will provide such data, and that the models will find direct usefulness thereby.

Current models of in-trail following are based only on the longitudional separation from a single leading aircraft. The work here described is novel in that it considers control criteria (objective functions) which include for each aircraft in a string: (1) distance and velocity relative to the immediately leading aircraft; (2) distance and velocity relative to the aircraft in front of that one; (3) deviation from reference position and velocity; and (4) control effort.

Three different versions of the model made different assumptions about what the "lead pilot" in a string will do relative to responding to disturbances, and whether he will return to steady-state reference position and velocity.

Further variations in the modelling effort include: (1) use of a threshold on position and velocity error signals below which a pilot does not control, and (2) use of a dual control law (a different criterion for separation closure than for separation opening).

Factors determining practical parameter values are discussed in the full report and some parameters are derived. Based on these parameters a number of computer simulation runs are presented graphically for the various models described above.

6. USE OF A DISAGGREGATED MODEL AS AN AID TO THE HUMAN OPERATOR IN FAILURE DIAGNOSIS IN COMPLEX AUTOMATED SYSTEMS (Hasan, 1981)

Supervisory control requires sufficient attention to the detection and diagnosis at faulty system components before they can cause irreparable damage.

This work studied a 'disaggregated-model' - based diagnostic technique to help the human operator in detection and isolation of faulty system components in aircraft and other large scale systems. A disaggregated model, in contrast to a complete model, corresponds to separation of a physical system model into disparate process. Such models can be simulated continuously in parallel or at the discretion of the human operator. Inputs to these models are the measured variables at corresponding locations throughout the system. Output from these models are then dynamically compared against corresponding variables from the physical system. The human operator plays the dual role of system monitor and failure monitor in the implementation of the proposed technique.

An experimental demonstration was conducted using a simulated aircraft to investigate the feasibility and usefulness of the proposed technique. Specifically, the effect, of aids based on different levels of disaggregation, on the operator performance in failure diagnosis was determined, along with three other factors of interest, namely the level of external disturbance and sensor noise, the failure size, and whether the operator served as monitor or in-the-loop controller.

The dynamics of a YC-15 transport aircraft were simulated with control-wheel steering as well as a setpoint autopilot control. The flight instruments, course map and other variables of interest were displayed dynamically on a color-raster graphics terminal. Diagnostic aids based on three different levels of disaggregation were implemented. Parameters, controlled by potentiometer settings, were made to fail in random appearing fashion as trained subjects flew the simulated aircraft along predefined paths.

Operator performance was evaluated in terms of the response times for failure detection and isolation and the number of correct failed-parameter isolations. Aid based on disaggregated models was found to provide significantly improved performance when compared to aid based on a complete model. The isolation time was found to be more sensitive to the level of disaggregation than the detection time. Effect of failure size (magnitude of discrepancy) was found to be insignificant. Noise level was moderately significant in failure detection but was insignificant in failure isoltion.

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