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A Multidisciplinary Approach to Human-Machine Systems Development

Cognitive Engineering in the Aviation Domain

Edited by Nadine B. Sarter and Ren Amalberti

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An Introduction to Cognitive Systems Engineering

The way that humans interact with machines has long been a subject of study. The advent of computers has made machines more complex, and the task of operating machines has moved from a manual to a supervisory control one. The term *Cognitive Systems Engineering* (CSE) -- the systems is sometimes dropped -- was coined by Hollnagel and Woods (1983) to reflect this change in the way that machines are operated from one based around perceptual-motor skills to one that based around cognitive activities such as problem solving and decision making. The term was also intended to reflect the increased sophistication of machines which can, in some sense, be regarded as cognitive systems.

The editors in their introduction note that CSE has identified new cognitive demands, introduced new concepts, and developed new methods for designing and evaluating systems. The new cognitive demands have largely arisen as a result of the increased complexity of the technology. The new concepts have been introduced by the multidisciplinary nature of CSE, drawing together behavioural sciences and engineering. The new methods place greater emphasis on the context in which work is performed, and hence rely on observing how human-machine systems are used in naturalistic settings (e.g., Zsambok & Klein, 1997).

The roots of CSE lie in the nuclear power domain. The ideas have spread to other domains, however, and *Cognitive engineering in the aviation domain* provides a snapshot of recent CSE research. The editors identify two particular problems that CSE needs to address. First, the already low accident rate needs to be further reduced to compensate for the projected doubling of traffic over the next decade. Second, the sceptical attitude towards CSE held by some, based on the big changes needed to embrace it, needs to be overcome.

The Phases of CSE

At an abstract level the development of cognitive systems can be considered in four phases: analysis, design, evaluation and training. Although these phases will not always occur in a fixed linear sequence, they will be considered sequentially in assessing the book s contribution to each, although some of the contributions will cover more than one phase.

Analysis

The preferred method of analysis within CSE is Cognitive Task Analysis (CTA, e.g., Seamster, Redding, & Kaempf, 1997). Apart from Flach and Rasmussen, however, the book has little to say about it. They note the need for CTA, pointing out that it is naturally an iterative ongoing process, and hence will normally only be completed for small systems. CTA takes account of contextual factors on performance, but there is also a need to consider the cultural and historical factors which can also affect performance.

Systems analysis techniques typically focus on the current or proposed work situation. There is much to be learned from reflecting on similar work situations to identify patterns of problems, however, as noted by Woods and Sarter. They re-analysed previous research in the same area, along with findings from incident reports and accident investigations. The results are used to find new ways of dealing with the perceived problem of human error, making automation more of a team player, and maintaining and improving safety.

Another area that is sometimes overlooked during analysis is the role of system maintenance. Reason points out that the issues underlying maintenance errors, which form a large proportion of all errors in aviation, relate to analysis and design. Many of the problems stem from temporary mismatches between system designers and the capabilities of the people who have to service the systems after deployment. In other words, all of the different contexts in which people have to interact with the system need to be analysed.

Design

One of the goals of CSE is the design of systems that allow for adequate situation awareness -- how well the pilot is adapted to the current work environment. Flach and Rasmussen suggest that situation and awareness are on opposite sides of the equation that has to be balanced to meet predefined system goals of safety, economics and so on. Situations are described in terms of the sorts of constraints that shape human-machine system performance, using Rasmussen s (1986) abstraction hierarchy. In contrast, awareness is considered in terms of the constraints that occur due to the resources and limitations of the distributed cognitive process. The qualitatively different types of processing that can occur within distributed cognitive systems -- Rasmussen s (1986) skill-, rule-, and knowledge-based framework -- need to be considered during design.

The task oriented display design method developed by Abbott encompasses analysis and design. Task analysis is halted when relevant information is identified, and the information is provided in a form appropriate to the user s task. The method was used to generate the Engine Monitoring and Control System (E-MACS) which was compared with the commercial Engine Indication and Crew Alerting System in a simulator. Pilots were better at detecting failures using the E-MACS display, and also expressed a subjective preference for it.

Evaluation

Postponing evaluation until the system has been developed is not a feasible option in aviation due to the potential costs involved if the delivered system fails to meet its requirements. For this reason, modelling and simulation are often used in the aviation domain, so that conceptual designs can be evaluated. This is the approach embodied in the MIDAS (Man-machine Integrated Design and Analysis System), described by Corker. It incorporates facilities for defining domain models and multiple interacting agents, and has been used to evaluate the envisaged interaction and co-ordination activities in a future free flight system in the USA.

Another model of human performance that can be used in evaluation is Hollnagel s Contextual Control Model (COCOM). In the COCOM performance results from the interaction between three components: the person s capabilities for action in a particular context (competence); how actions are performed (control); and mental representations of the situation (constructs). Control of performance is determined by the number of simultaneous goals that have to be achieved, the subjectively available time and the current control mode -- scrambled, opportunistic, tactical or strategic -- and by functions that select which action to perform next and evaluate that action s outcome.

The Netherlands Aerospace Laboratory Avionics Display and Design Evaluation System, described by Jorna, is used for rapid prototyping. Evaluation of the prototypes is performed by conducting controlled experiments on human performance in simulated situations. The air traffic management (ATM) human factors testbed was developed to investigate effectiveness and safety issues surrounding interactions in the envisaged future ATM environment. The testbed is used to gather various forms of behavioural data, which is supplemented by tailored questionnaires and standard workload measures. The results are used to inform the understanding of human behaviour in advanced systems and of the strategies used to redesign human-machine interfaces.

De Keyser and Javaux carried out comparative evaluations of the cognitive complexity of autopilot mode transitions on the Airbus A-320. The conditions for the mode activations were modelled using production rules. These rules were combined with contextual preconditions to generate a tree structure representing the logic of the production rule. The complexity was calculated using the average number of conditions that needed to be evaluated to determine the truth value of the whole expression. The approach is limited in that it only considers complexity at the syntactic or structural level.

The French en route air traffic organizer project described by Leroux provides a comprehensive example of the development of a system through to evaluation, and including training aspects, using CSE ideas. The project s aim is to specify and design decision support aids for en route controllers, leading to the development of an electronic assistant for the controllers. Each of the design phases is described together with the results of the first phase of the evaluation.

Training

Paries and Amalberti note that training is used to compensate for weaknesses in system design, together with standard operating procedures. The main reason for this is that the window of opportunity for making changes to the design is a narrow one in the long lead times associated with new aircraft development (Graeber & Mumaw, 1999).

Nowadays training focuses on management skills more than handling skills to take account of the changed nature of the flight crew s task. Management skills are subject to cultural variations, however, which can cause problems because aircraft designs are based on the constraints and objectives of the overall social, technical, economic and cultural system, which noticeably differs between East and West.

Error management also has to be included in training. Plat and Amalberti report that flight crews took longer to detect software bugs than other problems. The difference was explained by the lack of alerts to bring the bugs to the crew s attention. The crews often cycled the automation off in an attempt to clear the bug or confirm the problem. System safety is potentially compromised because the crews incorrectly estimate their knowledge limitations and do not have a generic fall-back strategy to deal with novel situations.

Pilot training is costly, especially where high-fidelity simulators are involved. Mitchell describes desktop based simulators that are a more cost effective way of delivering some parts of pilot training. The vertical path navigation (VNAV) tutor has been shown to increase the ability to explain VNAV operations in pilots who were transitioning to glass cockpit aircraft. An intelligent assistant that monitors human-machine system behaviour and offers advice where appropriate, the Georgia Tech Crew Activity Tracking System, has also been developed, and in trials it correctly interpreted 92% of pilot actions.

Summary

Cognitive engineering in the aviation domain offers an insight into the depth and breadth of CSE. It is not a gentle introduction to CSE, however, although it does include pointers to more general texts (Rasmussen, 1986; Rasmussen, Petjersen, & Goodstein, 1994; Woods, Johannesen, Cook, & Sarter, 1994). Newcomers to CSE would be advised to peruse these first, before dipping into this book to see what can be done with CSE in aviation. Those unfamiliar with aviation may find the examples rather opaque, however, and a glossary would have helped.

There are a few other omissions too. The introduction does not describe the structure of the book, which is somewhat unusual for an edited book. It is therefore not entirely clear why the book is divided into just two parts, neither of which has an introductory overview, or where to dip into the book to find out more about a particular issue. It would also have been beneficial to have a summary chapter to pull all the threads together and point to future directions.

Although it is useful to have a collection of papers on CSE based research work in aviation, many people working in the domain will already be familiar with much of the book s contents. The main areas where the book fails, however, are that it does not present any methods or tools that can be directly used by those working in industry, and that it does not clearly explain how different disciplines can contribute to CSE, and hence what it takes to become a cognitive system engineer. In these respects, *Cognitive engineering in the aviation domain* represents something of a missed opportunity to make CSE more accessible to a wider audience.

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