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TEMPORAL COORDINATION CONTROL TASK ANALYSIS FOR ANALYSING HUMAN-SYSTEM INTEGRATION

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Evaluating whether prospective air defense systems will effectively integrate the activities of humans and computers is a pressing issue for developers and purchasers of such systems. We need effective ways of modeling human-system integration while such systems are under development and while the possibilities for action are underspecified. We present a Cognitive Work Analysis-based analytic framework under development for characterising air defense control tasks and also for characterising the larger framework in which such control tasks must be coordinated. The challenge is to produce a formative rather than descriptive or normative model, within which broad logical and temporal constraints can be represented, so revealing possibilities for action as events unfold.

INTRODUCTION

A key concern in the acquisition of today's complex systems is whether there is appropriate integration between humans and computer-based support systems. We were asked to provide advice about a broad range of human-system integration (HSI) issues in Australia's forthcoming Airborne Early Warning and Control (AEW&C) platform (Sanderson, Naikar, Lintern, & Goss, 1999; Naikar & Sanderson, 1999; 2000). For example, in surveillance tasks, what level of multi-sensor integration would be most effective and how much intervention and inspection of process should human controllers be allowed? How should the human be kept aware of system decisions and the assumptions behind those decisions? Moreover, should it be possible to configure individual consoles for any human controller role (multi-functionality) or should consoles have dedicated functionality?

Because there is no equivalent to Australia's AEW&C platform that yet exists, we could not deduce answers to HSI issues from operational or simulator experience. Moreover, since in their early documents the AEW&C tenderers did not provide enough detail about the physical functioning of equipment for us to infer how operators could interact with equipment, we could not fully evaluate the technical proposals from the HSI angle. We therefore decided to perform a cognitive work analysis (CWA) of the airborne mission segment (AMS) of AEW&C in which we would capture what is *intended* in the system. Our goal was to build an analytic framework into which details about physical design and HSI implications could be placed and evaluated as they became available during system development. The CWA of AEW&C would therefore be built as far in advance of the development of AEW&C as is practicable, and would thereby help Australia's Defence Science and Technology Organisation (DSTO) provide advice on human engineering and HSI issues as needed. As we have argued elsewhere (Sanderson, Naikar, Lintern, & Goss, 1999) the analytic products of CWA can be updated and used throughout the system life cycle, from requirements definition right through to system decommissioning.

We chose CWA as an analytic framework for several reasons. First, CWA is *formative* (Sanderson, 1998; Vicente, 1999) in the sense that the analysis simply describes the requirements that must be satisfied—when human and computer agents cooperate—if the system is to achieve its functional purpose, rather than describing the system itself or describing specific action sequences it gives rise to. Second, because of its formative nature, CWA is uniquely suited to aiding revolutionary rather than evolutionary design (Vicente, 1999). The AEW&C platform, and the HSI issues it poses, are sufficiently different from what has gone before to be considered a revolutionary step in the development of such systems. Third, CWA uses five analytic phases that successively constrain what constitutes effective action in the work domain in question. Information may become available about the different phases quite opportunistically, so being able to represent such information independently is a boon.

CWA FRAMEWORK FOR AEW&C

Table 1 shows the five phases of CWA and lists the sources we used for an initial set of CWA-based analytic tools for AEW&C. Our work domain analysis (WDA) was developed from the AEW&C Concept of Operations, from discussions with subject matter experts, and from requirements statements about the platform. The result of this analysis plus a description of how it was used in tender evaluation is given in Naikar and Sanderson (2000). The WDA, however, simply provides an event-independent account of how the work domain is structured purposively and physically—it does not indicate how the elements of the work domain are used over time to support control tasks in response to events. For this we needed to conduct a control task analysis (CTA), where the system responds to the current state of the work domain with activity or "control tasks" that produce outputs or changes on the work domain. The CTA was based on subject matter expert projections of probable AEW&C control tasks, given AEW&C requirements and knowledge of similar operations in existing AWACS, air defense, and surveillance systems. As will become clear, to meet the needs of a CWA a system as complex as AEW&C, we had to extend CTA beyond descriptions in Rasmussen et al (1994) and Vicente (1999).

There was insufficient information for a reliable and valid strategies analysis (SA) since the functioning of equipment was unknown. Therefore the family of optional strategies that the equipment might afford for carrying out control tasks was unknown. Interestingly, however, there were strong initial expectations about the number of crewmembers and the roles they might play. One important aspect, then, of the social-organizational analysis (SOA) was quite highly constrained from the outset. However the issue of how crewmembers would share control tasks with intelligent onboard systems remained an HSI issue for expert human factors input. Finally, worker competencies such as levels of expertise, degree of training, kind of information system support needed, etc. were also issues to be resolved in light of the rest of the analysis.

Phase of CWA	Sources of information for AEW&C
Work Domain Analysis	In Concept of Operations, from SMEs, from requirements (Naikar & Sanderson, 2000)
Control Task Analysis	From existing AWACS, air defense and surveillance systems, from SMEs
Strategies Analysis	Determinants undefined or unavailable
Social-Organizational Analysis	Some expectations from Concept of Operations, requirements, and SMEs.(also a basic HSI *question*)
Worker Competencies Analysis	Determinants undefined or to be inferred from previous phases (also a basic crew complement *question*)

Table 1: Phases of CWA with sources of information for each phase in the AEW&C HSI project.

TEMPORAL COORDINATION ACTIVITY ANALYSIS

Control task modules

If judgments about the effectiveness of HSI are to be made for AEW&C, we need to examine how control tasks are achieved by humans and system working together. Rasmussen et al (1994) suggest that event-dependent descriptions of system functioning (activity analyses) can be done in terms of the work domain itself, or in terms of decisions. We decided to combine these. First, we wanted to show how AEW&C Airborne Mission Segment (AMS) activity exploits specific physical resources of the work domain to satisfy specific priorities or values of the work domain. Second, we wanted to show how each control task might be shared between humans and computers. Therefore, each control task was presented as a node (see shaded box in Figure 1). Above the node were listed priorities and values from the WDA that had to be respected as the control task was executed. Below the node were listed the generalized function that the control task supported or promoted, the physical functionality being exploited to perform the control task, and the physical devices being used. To the right of the control task node we were usually able to identify the actor or set of possible actors for the control task.

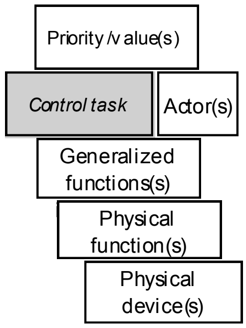

Figure 1: Generic identification of a single control task (shaded) showing placeholders for its connections back to physical and purposive elements in the WDA.

We tried to represent control tasks at the level of granularity that would best allow us to characterize the human-system integration solution provided in a proposed design solution, when that information became available. We then used Rasmussen's decision ladder formalism to characterize and distinguish different levels of HSI. Figure 2 presents two linked decision ladders that show how the information gathering and action planning steps in a control task might be allocated across human and computer. Information input from specific physical devices is indicated.

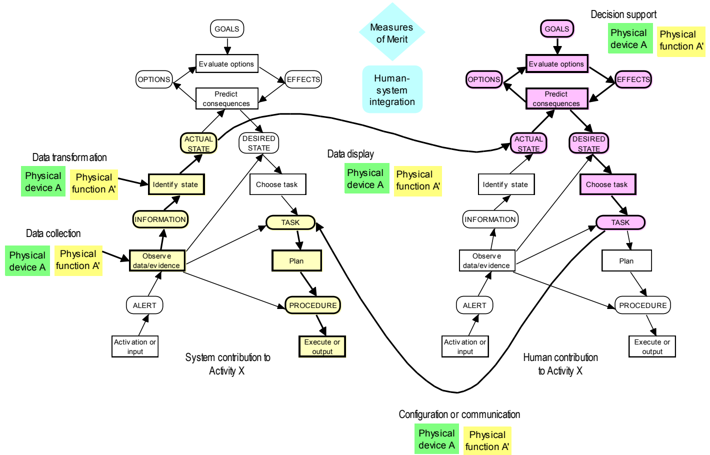

Figure 2: Linked decision ladders show decision steps carried out by system (left) and by human (right) for a specific control task, plus the physical functions and devices used.

The level of HSI then becomes a characterization of the relation between the two decision ladders, based on work by Sheridan and Verplanck (1978) and more recently by Moray, Inagaki, and Itoh (in press). The following six HSI levels are an example of the kinds of distinctions made:

- **HSI level 1**: human performs the whole interpretation or decision action
- **HSI level 2**: system generates the options for interpretation or action
- **HSI level 3**: system generates options for interpretation or action and suggests best option for human to implement
- **HSI level 4**: system generates options for interpretation or action and implements best option if human authorises
- **HSI level 5**: system generates options for interpretation or action, implements best option, and informs human
- **HSI level 6**: system generates options for interpretation or action, implements best option and informs humans only if requested

The HSI characterization may be at one level only, or may range adaptively across a range of levels. In our CTA, each control task is associated with a set of linked decision ladders showing the HSI mechanics of the control task in question.

Flow of control tasks

In a collaborative work environment such as the AMS of AEW&C, control tasks usually do not exist in isolation from each other. Instead they are done in coordination with other tasks done by other actors to produce an outcome that is more than the sum of the parts (Hutchins, 1995). Our goal in the CTA was to capture the necessary conditions for control tasks to be initiated and to capture constraints on their coordination with other control tasks, while revealing all possibilities for action in a work domain.

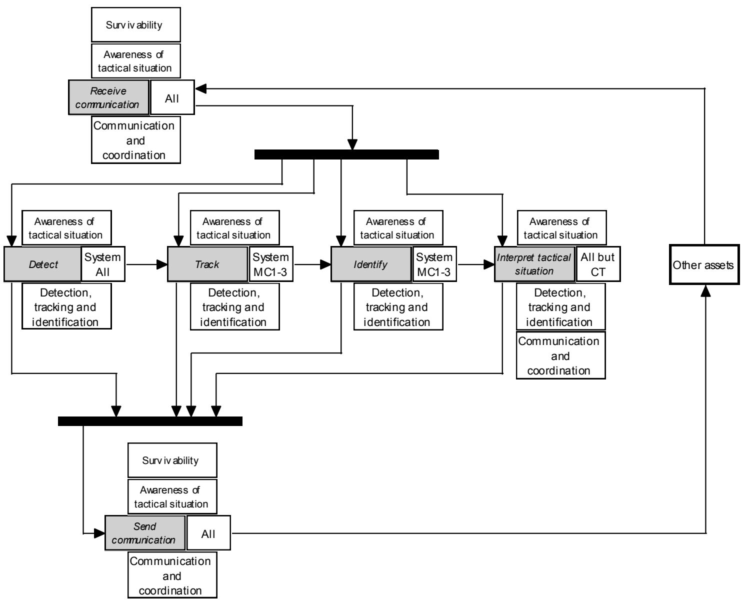

Figure 3: Surveillance activity module showing necessary and sufficient relations between control tasks for the significance of contact information to be assessed, with the possible help of other platforms. [To save space, control tasks have not been linked to physical devices and functions as in Figure 1]

Figure 3 shows a cluster of control tasks associated with detection, tracking, and identification of contacts in AEW&C. The diagramming is roughly adapted from activity diagramming in the Unified Modeling Language (UML) (Fowler & Scott, 1997). Each control task may have a separate HSI level, so is separately represented. Some control tasks must at least be initiated before others can be initiated—thus the connecting arrows. Because AEW&C came with an initial crewing concept (see Table 1) we were also able to annotate control tasks with the crew member or members who might be expected to carry it out. Finally, each control task can be separately affected by communication with assets outside AEW&C. Clearly, the number of possible control task sequences is vast, but it is also bounded by the constraints in this diagram. Each control task is also associated with a pair of decision ladders, as shown in Figure 2, that characterize HSI for that control task.

Our experiences indicate that a great deal more work needs to be done to find a notation for CTA that will deliver a truly *formative* analysis of control task activity. The notation should simply describe constraints or requirements, rather than describing a typical activity sequence (*descriptive*) or an idealized one (*normative).* Many forms of task analysis do not have the property of showing logical and temporal constraints that *shape* adaptive activity, and instead show the activity itself.

Temporal coordination

Quite independently of the issue of finding a notation for formative activity modeling, it was clear that a full evaluation of HSI in AEW&C could not rest on the analysis of single control tasks or even clusters of control tasks. Air defense is a collaborative activity in which controllers interact with each other and with the results of each others' work as the system responds to external events. Moreover, in evolving scenarios, controllers might be required to change roles to help colleagues handle mounting workload in a critical area of operation, such as controlling a strike package. Any analysis of HSI in AEW&C control tasks should, therefore, take into account not only the work domain that the control tasks are supporting, but also the entire activity context in which control tasks take place. Control tasks may demand different kinds of HSI at different phases of mission because of the nature of incoming events and the continually shifting background context of other control tasks, being performed either by oneself or by crew colleagues.

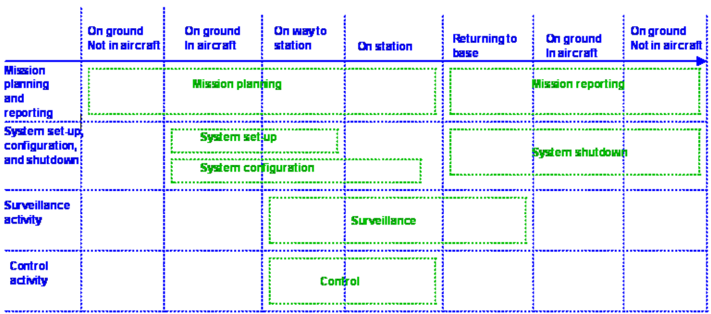

Figure 4: Temporal coordination control task analysis framework for AEW&C.

To enframe the shifting background context of any control task, in order to judge HSI effectiveness, we drew up a grid that identifies the major classes of control tasks (rows) and mission contexts (columns) for AEW&C. The result is a framework for representing, formatively, the requirements for the temporal coodination of AEW&C control tasks (see Figure 4)—a temporal coordination control task analysis or TC-CTA. The major classes of control tasks are mission planning and reporting; system set-up, configuration, and shutdown; surveillance activity; and asset control activity. The precise nature of these major classes of control tasks changes depending on the mission context. Therefore mission planning is a preoccupation of mission contexts as the platform is on its way to station and on station, whereas mission reporting is a preoccupation once the platform is no longer on station. Figure 4 allows us to express the fact that mission planning, for example, is an activity that stretches over multiple mission contexts. However in each mission context it is performed against a different background of other tasks. For example, if the mission context is "on ground in aircraft" then mission planning is performed against a background of system set up and system configuration control tasks. If the mission context is "on station", then mission planning is performed against a background of system configuration tasks, surveillance tasks, and asset control activity.

The full TC-CTA contains networks of control tasks showing the constraints between them, as partly seen in Figure 2. Each control task is associated with linked decision ladders, as seen in Figure 3, which show the HSI level for the control task at that point. To date we have worked through some key control tasks in this fashion, including the tasks of preparing for mission and allocating assets to controllers.

The TC-CTA is an analytic product that starts to describe the constraints and degrees of freedom in how humans and systems together might instantiate a work domain to achieve goals. The grid guides the analyst to constellations of control tasks that form around certain events or phases of mission, such as those for surveillance activity shown in Figure 3. The connections from control tasks to work domain elements show the physical and purposive constraints operating on control tasks. Connections to decision ladders show how human and system collaborate to achieve a control task, as in Figure 2.

INFERENCES FROM TC-CTA REPRESENTATIONS

The TC-CTA provides a framework for characterizing and evaluating the effectiveness of HSI solutions for AEW&C. For example, it has allowed us to perform an analysis of which control tasks must pass information between themselves during each phase of mission. Where control tasks in question are not performed entirely automatically, we can infer that certain human controllers (where prespecified) should be communicating with each other. We can then look at technical solutions intended to support such information flow to see if it will do so in a timely and effective manner.

Interestingly, the TC-CTA also supports the design of representative experiments and representative training regimens relating to HSI on AEW&C (see Naikar & Sanderson, 1999; Lintern & Naikar, 2000 for a discussion of training issues and the contribution of WDA). The TC-CTA identifies not only the control tasks that controllers must perform, but also provides information on the following "situational" factors:

- What else is likely to be happening at the same time?
- How fellow crewmembers are occupied and how tasks interconnect?
- What priorities and values are likely to be uppermost in crewmembers' minds?
- What physical resources are being used by crewmembers?
- What constraints and degrees of freedom exist in the scheduling and coordination of control task activity?

Such information could be invaluable when designing scenarios for low- or high-fidelity simulator environments.

In summary, the TC-CTA framework we have described appears to provide a useful way of pulling together what is known about a work domain, and the activity to be performed in it, to start to answer questions even before there is detailed information about the engineering and information technology that will support activity. However there are crucial notational issues that need to be resolved before a fully formative representation of activity possibilities can be achieved.

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