Cognitive Engineering Laboratory

Applying Ecological Interface Design and Perceptual Control Theory to the Design of the Control Display Unit

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Cognitive Engineering Laboratory

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ABSTRACT

A comparative evaluation of two alternative interface design approaches was performed. The two frameworks, Ecological Interface Design (EID) and Perceptual Control Theory (PCT), were both applied to the design of the Control Display Unit (CDU) interface of the CH-146 helicopter. The CDU function of radio communication was studied. A work domain analysis of the radio communication domain and a PCT-based analysis modelling pilot-CDU interactions were conducted. Both analyses resulted in the identification of interface design requirements. A qualitative comparison of the similarities and differences of these requirements was made. EID- and PCT-based interfaces were designed based on these requirements. The effectiveness of these interfaces was assessed by means of an analytical evaluation using task situations of radio communications performed under normal and abnormal circumstances. The evaluation demonstrated that both interfaces supported radio exchanges under normal operations. However, the EID interface permitted support for diagnostic activities during abnormal operations whereas the PCT interface failed to do so.

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INTRODUCTION

Interface designers have numerous human engineering techniques to study operators' behavioural and cognitive performance in order to develop more efficient human-machine interactions. Some newer techniques are also available where the main focus of study is the work domain agents act on. The motivating factor for choosing one technique over another depends on several parameters such as the nature of the complexity of the tasks and/or domain under study, the availability of resources, the designer competencies, etc. Nonetheless, the pertinence of these different approaches to the application in question cannot be easily assessed if no comparative measures are established a priori. Therefore, it is important for researchers to assess the effectiveness of one technique over another to demonstrate their robustness and ability to yield information requirements pertinent to interface design. Such an endeavour can be accomplished by means of a comparative evaluation. Such comparisons of design techniques are needed to assess any discrepancies and complementarities between approaches, and, hence, highlighting each approach's unique set of contributions.

As Rouse (1984) mentioned, a comparative evaluation "involves determining whether or not different systems or versions of systems differentially affect the measures of interest" (p. 3-3). Such an analysis therefore should not be aimed at assessing whether one technique is better than another, but rather at assessing how they are relatively distinct from each other. Unfortunately, comparison of alternative approaches for the design of interfaces applied to the same research vehicle are very rare (Miller & Vicente, 1998). Only a few examples can be found in the literature such as Xu (1996) and Miller and Vicente (in preparation).

Scope of the Research and Objectives

The main thrust of this thesis is to pursue such a line of thought explicitly delineating the strengths and weaknesses of two contrasting frameworks for the design of interfaces in an exploratory fashion rather than on a competitive basis. This comparative exercise also allows

one to have greater insights on the two research techniques. The two alternative approaches compared are Ecological Interface Design (EID) and Perceptual Control Theory (PCT). EID reveals on the interface the structure and functional relationships of the studied work domain and makes the states and constraints of the domain visible to the operator (Vicente & Rasmussen, 1990). PCT applied to the design of interfaces on the other hand assures that the interface contains the proper feedback messages necessary for effective communication between the human and its environment (Farrell & Chery, 1998).

These two particular frameworks, EID and PCT, were chosen in an attempt to satisfy one of the main research thrusts of the Defence and Civil Institute of Environmental Medicine (DCIEM) which is to develop and validate tools and techniques for effective design. PCT has been one of the main interface design methods used by the Systems Modelling Group at DCIEM for human-machine interactions. Moreover, the Systems Modelling Group has expressed an interest in EID as a framework for the design of interfaces for complex systems. Thus, an exploratory comparative evaluation seems appropriate for the assessment of each framework's ability to identify requirements necessary for the support of operators during normal and abnormal situations.

The vehicle used to instantiate the principles of each approach is the Control Display Unit (CDU) of the Griffon CH-146 helicopter used by the Canadian Forces. A CDU is a computerised device which is part of the flight avionics management systems of aircraft and was designed to aid pilots' communication, navigation, and mission planning activities. The functionality of the CDU used in this research is radio communication which is chosen due to the various concerns it has brought to the Griffon operational community (Captain Peter Schiedler, personal communication, 22 August 1995). The current interface possesses an alphanumeric keyboard and an electroluminescent rectangular screen with adjacent keys (as

shown in Figure 1) (Canadian Marconi Company, 1995a) and was designed using a task-based approach (Murray Gamble, personal communication, May 1999).

In this work, the principles of EID and PCT are both applied to identify information requirements needed to be implemented in the CDU interface. Then, two interface designs of a CDU incorporating the requirements from each approach are presented followed by an analytical evaluation of the EID- and PCT-based interfaces. Next, a discussion regarding the similarities, dissimilarities, and effectiveness of the frameworks for the support of normal and abnormal operations is given. Some design implications are then made. Conclusions follow regarding the effectiveness of these two frameworks for Griffon pilot-CDU interactions.

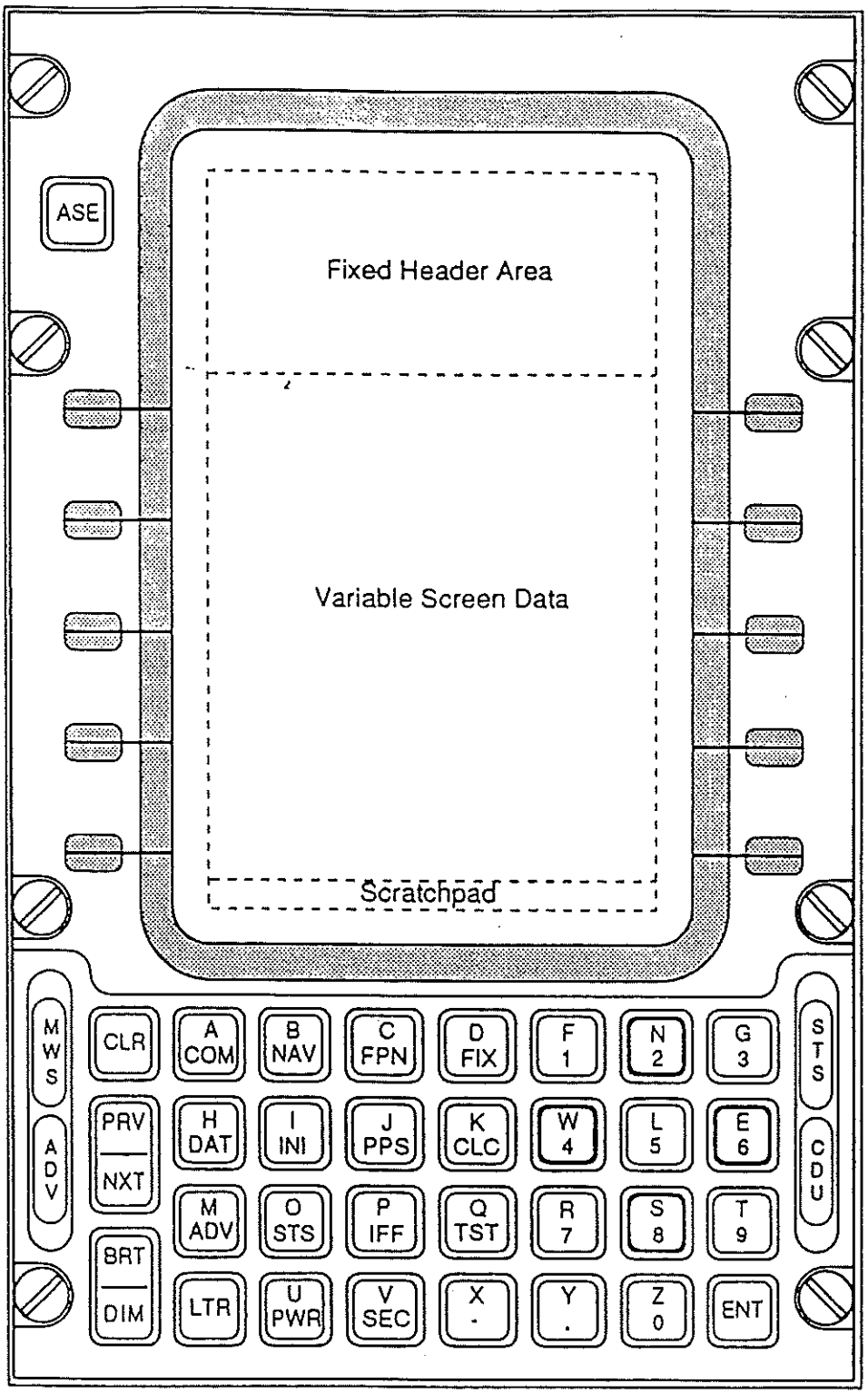


Figure 1. Current CDU interface used in the CH-146 Griffon Helicopter (Canadian Marconi Company, 1995a).

This research aims at accomplishing several novel objectives:

- Apply EID and PCT to a new application area, i.e., radio communications,
- Perform a comparative evaluation of EID and PCT in order to assess the similarities and differences between the informational basis of the two frameworks, and
- Perform an analytical evaluation between EID and PCT which aims to assess the ability/inability of the information requirements to support operators under normal and unfamiliar situations pertinent to radio communications using the CH-146 CDU interface as a vehicle.

Expectations

Some expectations can be derived for the comparative evaluation based on the theoretical framework described in Vicente (1999). For instance, Vicente (1999) states that task analysis techniques, modelling tools studying behaviours and/or cognitive processes necessary for operators to undergo their job, are limited in their ability to identify information requirements for complex systems. Also, they might be ill-suited for the identification of requirements supporting unanticipated events. These techniques primarily focus on "the one" effective way to perform a job, describing sequences of actions. Metaphorically, one can consider such a sequence of action as a specific trajectory within a workspace, thereby providing procedural guidance to operators.

On the other hand, work domain analysis techniques, "a form of work analysis that identifies the functional structure of the work domain" (Vicente, 1999, p. 10), can complement the downfalls of task based approaches since they describe the work domain capabilities. The analogy of directions vs. maps for navigation can assist in conceptualising the complementarity of task- and work domain analysis techniques, respectively. For instance, directions from point A to point B are quite effective since they prescribe where one needs to go by providing a detailed description of necessary actions to arrive at the destination

point. However, some unanticipated circumstances such as traffic jams or road construction can make these directions become insignificant. A map, on the other hand, which reveals all possible trajectories to point B from point A would be quite useful to overcome these cases. However, the map does not prescribe the user where to go or would not advise the user of where he/she is.

Consequently, it is expected that EID, being an example of a work domain analysis technique, leads to information requirements which provide necessary support for operators to adapt to situations unforeseen by designers (Vicente & Rasmussen, 1992; Vicente, 1999). Therefore, the EID-based interface is expected to accommodate scenarios incorporating unanticipated events. Also, given that the information disclosed by the framework includes functional relationships present in the work domain and the basic premises governing the domain, it is anticipated that little guidance would be provided to operators as to how tasks can be undertaken with the interface, as well as what these particular tasks are (Vicente, 1999). This then would unfortunately add to the demands of the operators.

Conversely, it is expected that PCT, being an example of a task analysis technique, leads to information requirements geared towards the accomplishment of particular tasks. This attribute is quite favourable since operators are given adequate procedural orientation for the performance of common tasks and has been documented as being efficient for the purpose of interface design (Vicente, 1999). However, the requirements might be unsuitable for the support of unanticipated circumstances. Given that PCT-based interfaces are inherently goal-sensitive, scenarios falling outside the boundaries delimited by the designers would be unsupported by the resulting interfaces, and operators would have to rely on experience and other resources to cope with these situations.

Table 1 summarises the complementarity between work domain and task analysis techniques by listing some of their advantages and disadvantages as identified by Miller and Vicente (1998). These claims are used as the expectant basis of this thesis for EID and PCT.

Table 1. Some advantages and disadvantages of work domain- and task analysis techniques as identified by Miller and Vicente (1998).

	Work domain analyses	Task analyses
Mental economy	Effortful	Efficient
Ability to adapt to unanticipated situations	Flexible	Brittle
Scope of applicability	Broad	Narrow

Research Contributions

First, this work allows both frameworks to explore new domains (radio communications) and allows them to be applied to a novel research vehicle (control display unit). Second, performing a comparative evaluation of these two paradigms to interface design is also a novelty and brings new insights to the current body of research. Third, the similarities and differences between frameworks are made explicit since both are applied to the same research vehicle. One can then better appreciate the weaknesses and strengths of one method vs. another and further their theoretical grounds. Also some important design implications are drawn from this research contributing to the field of human factors.

Summary

Very few comparative evaluations aiming at contrasting similarities and differences of alternative approaches have been conducted in the realm of interface design. Several benefits could be obtained if this type of evaluation were to be done more frequently, e.g., suitability of the applicability of a technique over another, assessment of their strengths and weaknesses, assessment of their robustness, etc. This thesis supports this objective by comparing two alternative approaches, Ecological Interface Design (EID) and Perceptual Control Theory (PCT) for the design of the interface of the control display unit of the CH-146 Griffon

helicopter for radio communications. An analytical evaluation is also performed for the assessment of the ability or inability of the information requirements from both frameworks to support various scenarios. It is anticipated that the EID interface will provide support for task completion under unanticipated situations but provide little ease to undergo operator's common tasks. On the other hand, the reverse is expected with the PCT interface. It is anticipated that procedural guidance will be provided with the PCT interface under normal operations while little support will be provided by the informational basis during unanticipated events.

In the next two sections, a review of EID and PCT is provided, starting with their theoretical foundations, a description of their modelling tool, the framework's limitations, and an enumeration of the domains in which they have been applied.

ECOLOGICAL INTERFACE DESIGN

Theoretical Basis

Ecological Interface Design (EID) is a framework that provides a structured approach for designing interfaces for complex systems (Vicente & Rasmussen, 1992). It prescribes a set of design principles which attempt to resolve the design concerns of knowing what the interface content is, the structural basis of the information, and its form (Vicente & Rasmussen, 1992). EID has three principles to accommodate the above design concerns: First, EID proposes as a modeling tool the Abstraction Hierarchy (AH) for the representation of complex work domains (thereby providing the information content of the interface as well as the structure by its means-end representation). The AH is a generic framework for the description of work domains in a multi-level representation conveying possibilities for action (Rasmussen, 1985). Second, there needs to be a one-to-one mapping of the work domain semantics onto the visual representation of the interface. Third, the human operator needs to be able to directly act on the display (direct manipulation). These last two principles accommodate the representational form of the interface requirements.

The Abstraction Hierarchy

The Abstraction Hierarchy (AH) is a modelling tool that allows one to depict complex work domains at different levels (Rasmussen, 1985). Each level can represent the domain using a different functional representation having its own nomenclature and principles. The levels are related via a structural means-end relationship (structural means-end in the sense that it represents *objects* that can be used as means to achieve ends as opposed to action means-end where sets of *behaviours* are used to link the levels) and depict the set of available means with respect to relevant ends to be achieved. Actions are not to be included when analysing the work domain since one is creating a representation of what is being acted on (Vicente, 1999).

As one goes up the hierarchy, one gets a refined comprehension about the domain significance, while going down the hierarchy, one gets a more detailed explanation of how the domain actually functions (Vicente & Rasmussen, 1992). In the case of process control, it has been useful to assign five levels of abstraction to the domain (Rasmussen, 1985):

- Functional purpose (purpose for which the device is designed),
- Abstract function (first principles or theoretical laws governing the domain),
- Generalised function (necessary functions that the domain is designed to achieve),
- Physical function (components of the domain), and
- Physical form (components' physical appearance, location, and spatial relationships).

The application of these labels has been seen as inappropriate for other domains (Sharp & Helmicki, 1998; Hajdukiewicz, Doyle, Milgram, Vicente, & Burns, 1998) and as suggested by Vicente (1999), the number of decomposition levels as well as their content is domain-specific and depends on the work domain's constraints.

The following sections present EID's limitations and the various domains to which it has been applied.

Limitations of EID

The extent of the Abstraction Hierarchy (AH) representation is limited by the analyst's knowledge of the work domain. Note, however, that such a limitation is not specific to the AH but to any modelling tool. By the same token, the analysis does not incorporate the modelling of other structural means-end levels beyond the boundaries of the work domain delimited by the analyst, which may therefore limit the analysis. Also, the availability of technology may impede the representation of the work domain: certain high level functions might be difficult to represent or impossible to sense due to sensor availability or due to the nature of the parameter to measure (Vicente & Rasmussen, 1992). Besides, the sensed data is susceptible to noise, leaving the possibility of gathering uncertain measurements, and thereby,

conveying inaccurate information on the interface. Another limitation includes the framework's disregard of the tasks pertinent to operators' job. This deficiency may lead to interfaces providing functional information seemingly unrelated to the tasks at hand and procedural guidance might be unsupported as well.

EID's Application Areas

To date, process control, medicine, information retrieval, software engineering, and aviation have benefited from EID and allowed the theory to be applied to a diversified set of applications (Chery & Vicente, submitted manuscript). Also, several research projects involving process control microworlds were conducted using EID interfaces as research vehicles. These projects demonstrated that higher-order functional information (i.e., representation of global work domain's states and underlying governing laws) facilitated operators' problem-solving activities and supported unanticipated events (Vicente, 1995 for a review). Other research projects have endeavoured to study the influence of individual differences on performance on EID based interfaces and expertise shaping (Howie, 1996), and means-end information integration (Burns, 1998).

Summary

EID is a framework for designing interfaces of complex systems and involves three principles. Several limitations have been attributed to the framework (e.g., restricted modelling of structural means-end levels within the domain's boundaries as delimited by the analyst, availability of the technology, possibility of having uncertain data, inability to model operator's tasks). Nonetheless, EID has been applied to many applications from different fields and has been seen as very effective for supplying information requirements facilitating problem-solving and providing support during unanticipated situations.

PERCEPTUAL CONTROL THEORY & INTERFACE DESIGN

Theoretical Basis

Perceptual Control Theory (PCT), developed by Powers (1973), is a psychological paradigm which models humans interacting with their world. It takes its premises from the principles of classical control theory, and is based on the tenet that all behaviour is the control of perception (Powers, 1973): "Behavior is the process by which organisms control their input sensory data. For human beings, behavior is the control of perception" (p. xi)[1].

The PCT framework models human-world relationships and considers the human as a negative feedback loop system, interacting with an environment prone to disturbances (Figure 2). Similar to classical control theory, such a negative feedback system is error-correcting in nature and attempts to maintain system stability.

As Figure 2 shows, PCT considers the human as an error-correcting agent, thereby exhibiting compensatory behaviours to achieve stability. As can also be seen from the figure, desired states of the controlled variables (or reference signals) are compared to current states (perceptual signals) and any discrepancy generates a perceptual error signal which becomes the impetus for behaviours. Behaviours, according to the theory, represent possible means to minimise the error: their effect on the environmental variable of interest leads to effects on the perceptual signal (Powers, 1973). On the other hand, perceptions are generated within the "perceptual input function" from sensory information coming from the "remote physical phenomenon". Sensory information represents a means to minimise the error: given that the goal is known, one could attend to sensory information which would yield a resulting

[1] By control, it is meant that consistent results can remain in the face of environmental changes (Marken, 1997) and that reliable and repeatable results can be yielded in an unpredictable environment (Powers, 1997). By perception, Powers means "a perceptual signal (inside a system) that is a continuous analogue of a state of affairs outside the system" (Powers, 1973, p. 286). Powers does not explicitly define what he considers as a "system". However, he does discriminate between a "behaving system" and its environment when elaborating on the control-system unit of organisation. He maintains that same line of thought when illustrating the framework delimitating the boundary between the "system" and the environment (Powers, 1973, pp. 60-61).

matching perception. Note, however, that Powers does not explicitly prescribe a way to model the "remote physical phenomenon" but refers to the entity as a "...controlled quantity which we observe objectively" (Powers, 1973, p. 60). Even if the environment is considered as part of the control system, it is not extensively elaborated or described within the PCT model.

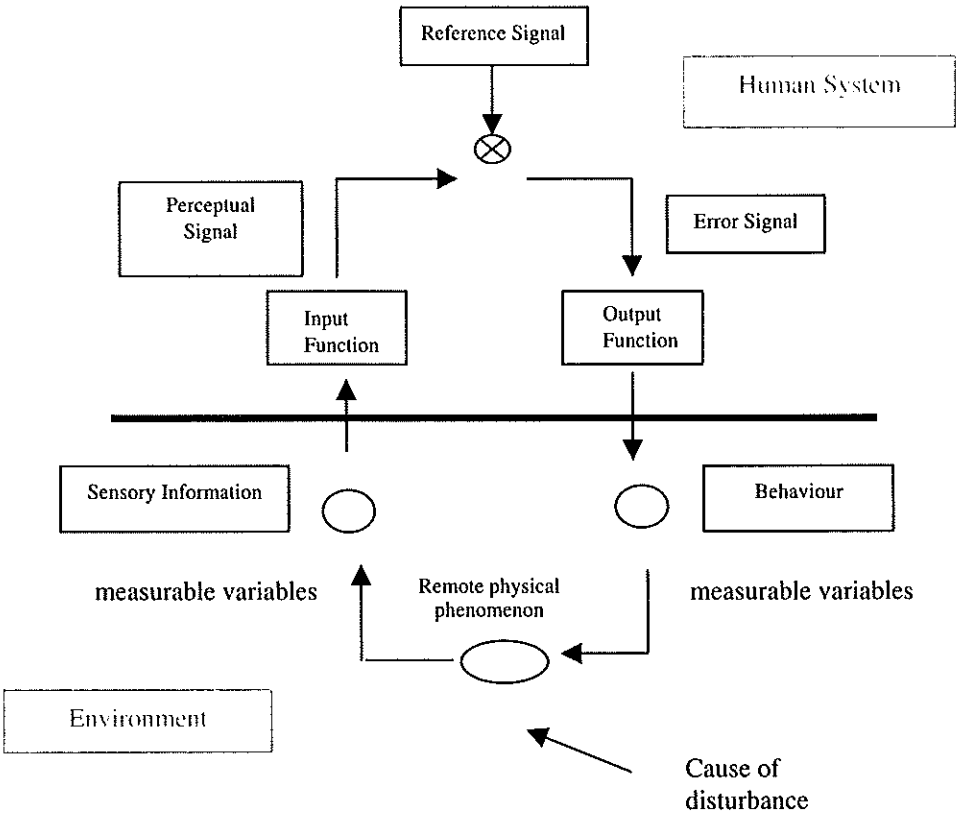


Figure 2. Perceptual Control Theory loop (Powers, 1973). The figure shows the human as a negative feedback loop system interacting with an environment prone to disturbances.

PCT can be seen as a hierarchical model of control systems where high level behaviours become lower level desired states and where low level perceptual signals become high level sensory information (Figure 3). The nature of the relationship between PCT levels is not made explicit (part-whole, classification, etc.). However, the relationship seems to be specified by an action means-end link since the means necessary to achieve the end in is the form of an act rather than an object.

PCT has been proposed as a conceptual framework for interface design in human-machine interactions (Marken, unpublished manuscript; Farrell & Chery, 1998). Farrell and Chery (1998) suggest that by designing for control loop stability between the operator and the machine, one can then implement necessary controls and displays on an interface in an attempt to minimise possible perceptual errors present in the human-machine interaction. The interaction between partners can be depicted by a PCT-based analysis which allows one to identify information requirements needed for the interface (Farrell & Chery, 1998). It also offers a structural basis for the organisation of the information due to PCT's hierarchical nature. This analysis attempts to ensure that proper feedback between the human and the machine is made explicit in a design for every level of the hierarchy in order to have effective communication flow between both agents. Feedback is explicit in the design since the interface accommodates actions and perceptions throughout all hierarchical levels. The information flow is then circular and forces the designer/analyst to consider the feedback instantiations in order to close the control loop.

PCT-based Analysis Technique

Task analyses are human engineering tools allowing analysts to depict the informational basis of an interface among other activities (e.g., prediction of system performance, design of training programs, design of workspaces, development of job description and user manuals, etc.) (Diaper, 1989). With regards to interface design, the outcome of task analyses often involves the breakdown of tasks, subtasks, and necessary skills operators need to possess in order to perform their jobs leading to proper controls and displays for the interface.

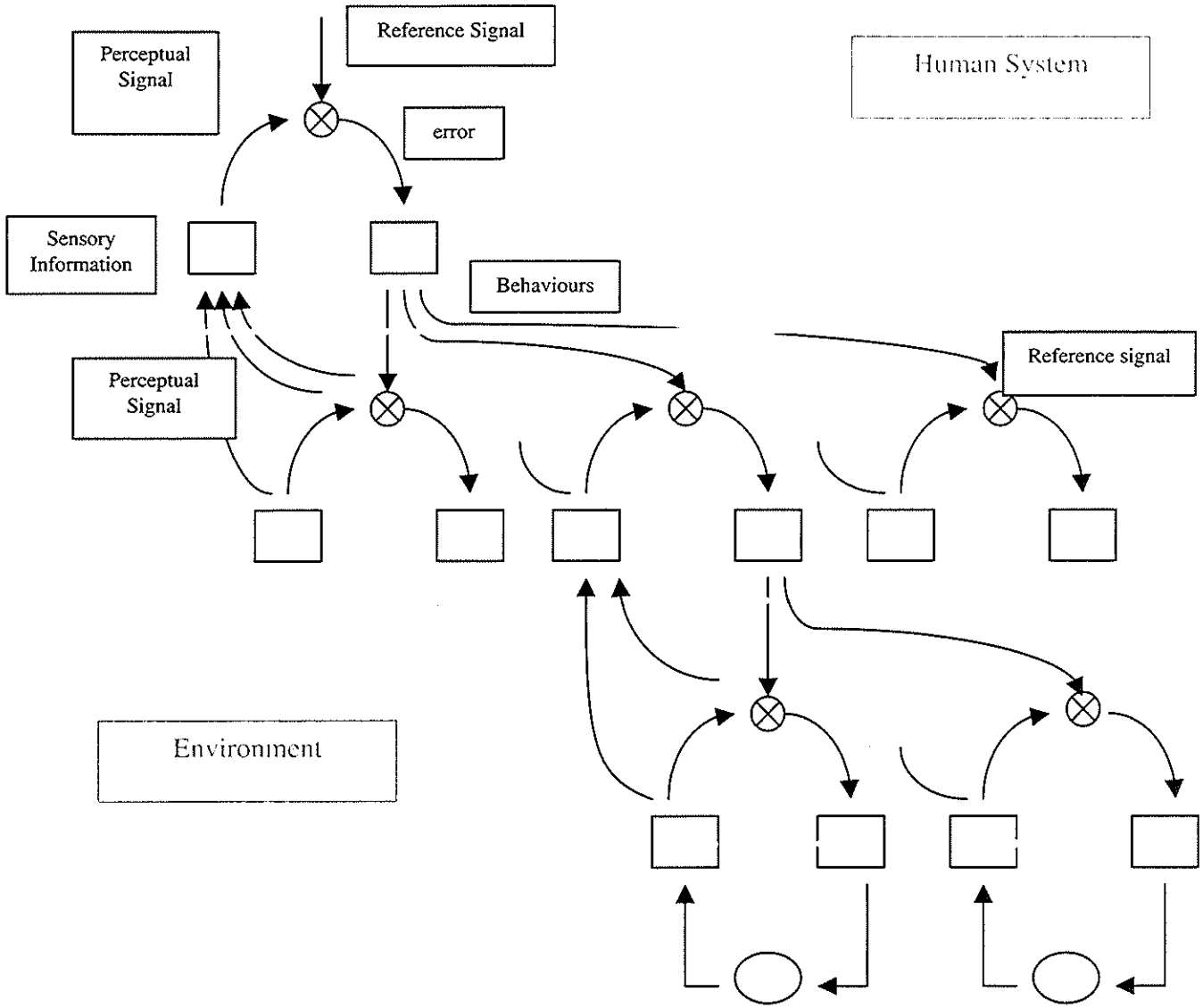


Figure 3. Hierarchical architecture of the PCT control units. Not all the presented control units are fully represented or fully annotated in order to avoid having a cluttered diagram.

A PCT-based analysis studies the identification of perceptions, behaviours, sensory information, and goals in the context of a PCT model (Farrell & Chery, 1998). A PCT analysis focuses on the stability of the perceptual control loops and attempts via proper displays and controls to bring closer to desired states (perceptual goals) the perceptions being controlled. To do this, an analyst can design displays which provide information for perceptions to be generated and for them to closely meet desired states. By the same token, controls can be designed to allow for the possibility of compensatory behaviours to occur given the operator's goals. Therefore, the design specifications are geared toward the minimisation of the perceptual error and are identified by this analytic exercise via the consideration of every task and subtask as closed-control loops. Also, the hierarchical representation generated from the analysis allows designers to yield an interface which attempts to support perceptual control for every loop. The interface then needs to provide necessary displays and controls so that loop stability is achieved at every hierarchical level by means of feedback.

A tabular representation was developed as a tool to perform the PCT-based analysis (Farrell & Chery, 1998). The tables are based on the PCT loop components and are comprised of ten columns corresponding to every PCT element (Figure 4).

	Perceptual Error	Decision-Making Processes	output/behavior	Interface Controls	
Goal					Environmental Variable(s)
	Perception	Integration Processes	input/sensation	Interface Displays	

Figure 4. The table used for the PCT-based analysis (Farrell & Chery, 1998).

For instance, the PCT-based analysis table has the following column labels (the PCT loop counterpart follows in brackets): Goal (reference signal), perceptual error (error signal), decision-making processes (output function), output/behaviour (behaviour), environmental variable (remote physical phenomenon), input/sensation (sensory information), integration processes (input function), and perception (perceptual signal). In addition, two columns are in the table but not in the PCT framework: interface controls and displays. These two items allow interface designers to suggest interface requirements accommodating the "input/sensation" and "output/behaviour" data into displays and controls respectively. Hence, the tables, given the PCT structure, permit the analyst to acquire information that can yield requirements necessary for stability for every control loop.

The PCT framework and other negative feedback control systems frameworks applied to human behaviour have been seen to be very accurate and quite successful in predicting closed-loop stability in manual control tasks (Bourbon, 1990, 1996; McRuer & Jex, 1967 for a review). Also, PCT applied to interface design can lead to explicit descriptions of possible tasks necessary for operators to bring their control units to stability. Given that the resulting requirements accommodate goals necessary to be satisfied, a PCT-based analysis would provide adequate assistance for the design of context-sensitive information. Feedback is also made explicit at all hierarchical levels of the PCT model in the interface for interaction between both agents to have effective flow. The design of necessary controls and displays allowing for the occurrence of effective interaction can then result.

Limitations of PCT & Interface Design

Some of the limitations of PCT applied to interface design are due to certain drawbacks inherent in the theory. Perceptions that are being controlled by an individual as well as their desired states cannot be known from an external observer but can only be inferred by observable measurements such as the cues presented and the behaviours which

follow. Thus, when doing a PCT-based analysis to model human-machine interactions, it is important to probe which perceptions and/or goals operators want to see controlled. The inability to know exactly the perceptions/goals being controlled can result in disclosing improper information requirements, therefore leading to ineffective interface design.

Also, the PCT model of the human-machine system can be seen as accurate (since it describes constrained behaviours) as long as disturbances and transfer functions are known a priori. As McRuer and Jex (1967) claim, one cannot predict all the outputs which can occur for a given error signal for closed-control systems. The variance which cannot be accounted for by the function, called the remnant, results from non-linear forms of behaviour and can be related to stress, fatigue, practice, etc.

Also, as previously mentioned, PCT does not systematically prescribe a way to model the remote physical phenomenon. Information, which might be pertinent for a PCT-based analysis, might therefore be omitted.

Moreover, PCT applied to interface design only allows one to acquire the informational basis of the interface and provides some guidance as to the structure of the information by its hierarchical nature. However, it does not prescribe a way to present that information in a visual form. Such an exercise is at the discretion of the designer who has to rely on documented design engineering principles and guidelines.

PCT & Interface Design's Application Areas

The PCT framework has not been extensively applied to interface design. However, some current research is being conducted in the domain of aerospace in the context of human engineering (William T. Powers, personal communication, 26 May, 1999). PCT has served as a paradigm for behavioural sciences (Powers, 1997; Marken, 1997) and some experiments based on PCT concepts can be found in the field of tracking behaviours (Bourbon, 1990, 1996).

Summary

PCT is a psychological paradigm allowing designers to model human's interactions with their environment. It uses the engineering concept of classical control theory as a framework to incorporate the human as a goal-directed, negative feedback system behaving in an environment prone to disturbances. PCT applied to interface design aims to depict human-machine interactions for the development of interfaces. A PCT-based analysis, using PCT-based tables, can be performed for the identification of requirements for the design of displays and controls necessary for operator's goal achievement. Several limitations can be found in the paradigm such as the difficulty in probing the appropriate operator's perceptions and goals, the difficulty in predicting non-linear forms of behaviours, the lack of a systematic way of describing the environment, as well as the lack of assistance for the translation of requirements into a representational form. Also, PCT has not been extensively applied in interface design but current work is being done furthering the theory.

The next two sections present the application of the principles of each framework, EID and PCT, for the development of the CDU interface for radio communications.

DEVELOPING AN ABSTRACTION HIERARCHY FOR RADIO COMMUNICATIONS

The first principle of EID requires the performance of a work domain analysis using the Abstraction Hierarchy (AH). A work domain analysis for radio communications has never been performed and required a vast amount of effort and time to gather the domain knowledge as well as to conceptualise the information in a structural means-end hierarchy. Such a representation of the domain was completed via an extensive study of the radio communication domain (Stone, 1926; Henny, 1938; King, Mimno &Wing, 1945; Terman, 1947; Menzel, 1948; Ratcliffe, 1959; Davies, 1965).

The five generic labels of the AH were not useful for the work domain studied in this thesis, similar to Sharp and Helmicki's (1998) and Hajdukiewicz et al.'s (1998) findings for medical applications. New labels were determined as outcomes of the radio communication study. The five identified constraint levels are presented with their corresponding generic AH labels (in brackets): *purpose* (functional purpose), *communication theory* (abstract function), *radiophony* (generalised function), *equipment* (physical function) and *physical form* (physical form). The levels are represented in their structural means-end relationship in Table 2.

The procedure under which these levels were obtained followed the guidelines proposed by Vicente and Rasmussen (1990). The transition between the levels of the hierarchy was performed through the Why-What-How sliding window. The level of the hierarchy at which one enters represents the "what" level. The level above specifies the reason or justification for the current level (e.g., represents the functions, or ends to accomplish), while the level below represents the possible structural ways or "means" with which the object/process can be accomplished. One can uncover those means-ends relationships by asking the questions "why" as one goes up and "how" as one descends the hierarchy (Vicente & Rasmussen, 1990).

Table 2. Structural means-end levels in the radio communication work domain.

	Work Domain
Purpose	Permit voice communication between different parties remotely located
Communication theory	Entropy at source, channel, equivocation, noise, encoder, decoder, entropy at destination
Principles of Radiophony	Signal transduction, frequency generation, interference generation, modulation, radiation, propagation, extraction, refraction, demodulation, absorption, attenuation, interference reduction, frequency conversion
Equipment	Microphone, electric sources, ionosphere, terrain, airspace, modulator, demodulator, antenna, filter, oscillator, correcting network, speaker
Physical Form	Location, appearance, and physical connections

means ↓ ↑ ends

For this work domain, one can start at the purpose level and ask "How does the domain permit voice communication between parties remotely located?". The level below represents the structural means to achieve this goal and the answer can be found in communication theory, as mathematically modeled by Shannon (1949). The means include the dynamics of the entropy of information source quantified in bits, encoder/decoder, the equivocation and noise present in the domain, channel necessary for transmission, and entropy at the destination. Secondly, "How can one instantiate communication theory?". This level involves the processes comprised in radiophony such as frequency generation, modulation, radio wave propagation, etc. "How do these processes take place?". The various physical means (equipment) are described such as oscillators, speakers, etc. The level below addresses the components' locations, appearance, and physical connections[2]. By the same token, one could ascend the hierarchy by asking the reason why a particular means is used starting at the "physical form" level and could uncover the labels as described.

[2] No lower levels were thought to be useful for CDU operators and therefore the analysis stopped at the physical form level.

Means-end Levels

The next section presents a more detailed examination of each level of the hierarchy.

Purpose. This first level involves the ability to allow voice exchanges between different parties in the work space.

Communication Theory. The first principles communication systems are governed by lie in communication theory, as mathematically modeled by Shannon (1949). Weaver denotes the general nature used by the word communication and believes that one can deal with communication at three levels (Shannon & Weaver, 1964):

- Technical: Deals with the accuracy of transfer of information from senders to receivers,
- Semantics: Deals with the interpretation of the meaning of the message, and
- Influential: Deals with the efficiency with which the meaning conveyed to the receiver leads to the desired outcome.

Shannon did not want to explore the semantics and influential aspects of communication and based his work on modeling the technical nature of communication processes (Shannon & Weaver, 1964).

With that in mind, Shannon's paradigm models communication as being a source-encoder-channel-decoder-destination system (Shannon & Weaver, 1964). These five parameters are necessary in any communication system (Shannon & Weaver, 1964) and are further described below (Figure 5).

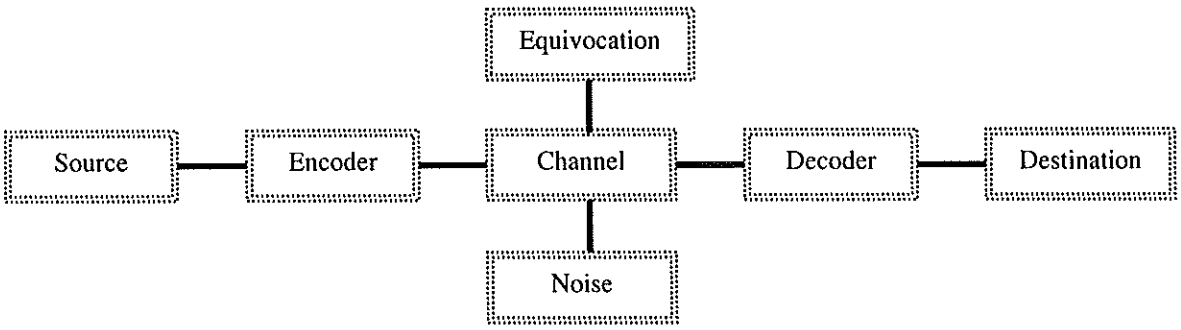


Figure 5. Shannon's subsystems involved in communication theory (Shannon & Weaver, 1964).

- *Information source.* This function of the system produces the message or sequences of messages to be communicated.
- *Encoder.* The encoder is responsible for the application of a suitable code to an original message in order to change its form in a way that is required or more suitable for transmission over the channel.
- *Channel.* The channel is the part of the system that allows the signals to be transmitted from the sender to the receiver and involves a physical medium separating senders and receivers. The channel's characteristics impose constraints on the capacity for communication and affect its ability to store and transmit information; the channel is limited by its sensitivity to distortions and noise.
- *Decoder.* This function is responsible for the reconstruction of the message where the original signal is being restored from the form in which it was transmitted.
- *Destination.* The function of the system for which the message is intended.

In Shannon's modelling, information can be treated like a measurable physical quantity, similar to density or mass, and quantified as entropy (Shannon, 1949). In this case, information is seen as a measure of freedom of choice when a message is selected; if, for instance, one chooses one possibility out of two alternatives, then the information associated with the situation is one unity or bit, given that the alternatives are equally probable. The concept of "information" does not apply to the individual message, as the concept of meaning would, but to the situation as a whole (Shannon & Weaver, 1964). This framework permits the mathematical quantification of the information transmitted (in bits) from the information source to the destination and permits the determination of the capacity of the channel as well as the rate of information transmission, the equivocation in the system (loss of bits of information), and the noise (added spurious bits of information). The entropy (or degree of

randomness) of information is measured by the log of the number of choices or messages available.

Also, noise represents unwanted additions in the channel and affects the channel by increasing the freedom of choice at the source. This leads to an increase in the uncertainty and therefore the information (the received signal becomes selected out of a more varied set of signals than was intended by the source) (Shannon & Weaver, 1964). Equivocation has the opposite effect by decreasing the uncertainty in the channel, thereby leading to a loss of information. Equivocation is the reduction of variety in a communication system where different signals are no longer differentiated by the destination.

Radiophony. This constraint level involves the various processes involved in radio communications and represents the means by which the principles of communication theory are functionally implemented. At this level, the various processes of radiophony are described: signal transduction, frequency generation, interference generation, modulation, radiation, signal propagation, refraction, attenuation, absorption, extraction, demodulation, frequency conversion, and interference reduction.

Signal transduction. This process involves the transformation of sound energy into electrical energy (Terman, 1947).

Frequency generation. This process involves the production of radio waves as a carrier of information (Terman, 1947).

Interference generation. This process involves the production of undesired electrical disturbance (Terman, 1947).

Modulation. Radio waves are mainly used to carry voice and/or sound. This information needs to be impressed on the wave in order for it to be propagated and received. The radio frequency wave generated by the domain is called the carrier wave and the process

by which it is being impressed by the audio signal to be transmitted is called modulation (Terman, 1947).

Radiation. Transmission involves the exposure to the channel of the radio waves for their propagation (Terman, 1947).

Propagation. Propagation involves the mechanisms by which the radio waves travel. Several other processes can affect propagation, such as attenuation and absorption. Two types of propagation have been documented: Ionospheric and tropospheric (Terman, 1947; Menzel, 1948; Davies, 1965). The frequency of the radio wave is one determining factor as to which type of propagation occurs (ionospheric or tropospheric).

- *Ionospheric propagation.* Refraction of the radio waves permits this type of propagation to occur and depends on the electrification state of the ionosphere (i.e., the electron density which is controlled by the solar ultra-violet rays) (Ratcliffe, 1959; Davies, 1965). The waves are refracted back to earth leading to the coverage of long-distance communications (Figure 6). The highest frequency capable of travelling by this means is called the critical frequency.
- *Tropospheric propagation.* The waves can also travel through tropospheric propagation and in this case, adopt a straight-line path. The waves have the potential of being fully absorbed by the ionosphere. The propagation is done within the earth's troposphere with no refracting medium as intermediary. The "line-of-sight" (the wave path from the transmitting antenna striking Earth tangentially) determines the critical limit for reception. Knowledge of the receiver's antenna's height becomes imperative, otherwise the wave might not be received by a receiver (Ratcliffe, 1959; Davies, 1965).

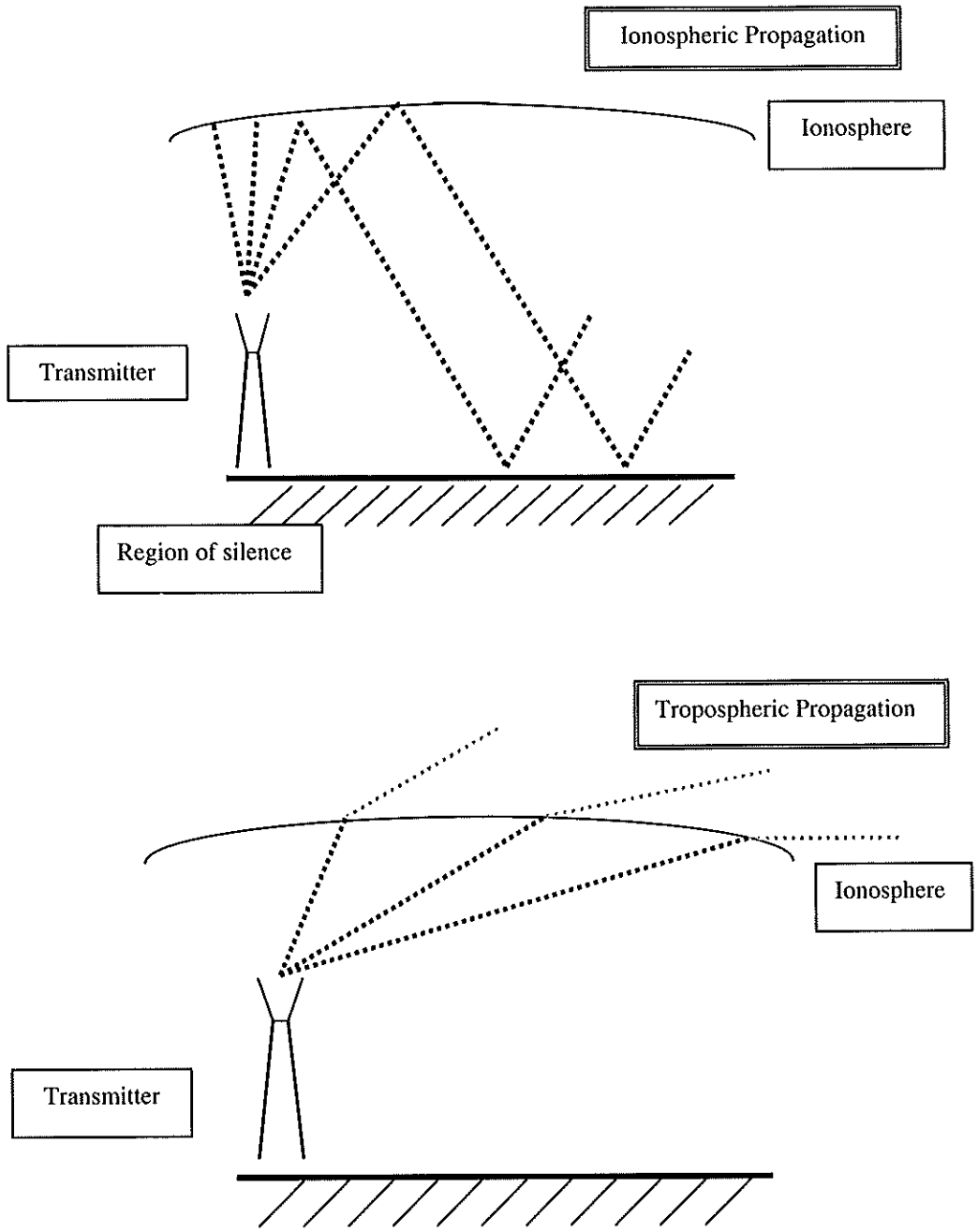


Figure 6. Diagram of ionospheric and tropospheric propagation of radio waves (Brown, 1975).

Refraction. Refraction is "the bending a wave undergoes in passing from one medium into another, as from air into water or from a denser to rarer layer of the atmosphere" (Menzel, 1948, p. 219). One can determine the maximum usable frequency (MUF) effective for this type of propagation given the density of the refracting medium. The MUF then represents the

critical frequency. The critical frequency can be thought of as the maximum frequency for which a wave will be returned to earth to allow transmission, given the angle of incidence and the ionosphere electron density characteristics. An approximation of the critical frequencies (f_o) can be calculated for the main ionospheric layers. So any frequency above f_o will escape the ionosphere while any below will be reflected back for that particular area of the ionosphere.

Absorption. Absorption is defined as "the loss of energy from a wave by dissipation in propagation" (Menzel, 1948, p. 219). For a frequency to be received, it needs to possess sufficient energy. Any energy loss can then affect the reception of a wave and this loss is caused by the presence of molecules with which the waves constantly collide through their path in the atmosphere (Terman, 1947). The collisions are more frequent when electrification in the ionosphere is greatest. The radio waves then have to cross a network of "absorbing layers" and the frequency at which the wave can accomplish that is termed the Lowest Useful High Frequency (LUHF) (Menzel, 1948). Higher frequencies can traverse the absorbing layers more readily than lower frequencies, given equal intensities (Menzel, 1948).

Attenuation. Menzel (1948) defines attenuation as the "decrease (of radio energy) in displacement with distance in the direction of propagation (...) and is defined for a sinusoidal wave of a certain frequency and of constant amplitude at any point" (Menzel, 1948, p. 219). Similar to the absorption effect, higher frequencies are not as susceptible to attenuation as are the lower frequencies.

Extraction. The extraction of radio waves includes capturing waves from different origins (man-made and natural sources) (Terman, 1947).

Demodulation. This process involves the reproduction of the original audio message signal as well as of the radio signal (Terman, 1947).

Frequency conversion. This process involves converting incoming signals to a predetermined fixed intermediate frequency (Terman, 1947).

Interference reduction. This process involves the minimisation of interference (Terman, 1947).

Equipment. This means-end level presents the various types of equipment which are involved in this work space: microphones, oscillators, modulators, demodulators, filters, correcting network, antennas, sources of electrical energy (e.g., industrial devices, atmospheric disturbances, etc.), the airspace, the ionosphere, the terrain features and obstacles, and speakers.

Physical Form. This layer presents how components are related to each other spatially and shows their appearance.

Means-ends Links

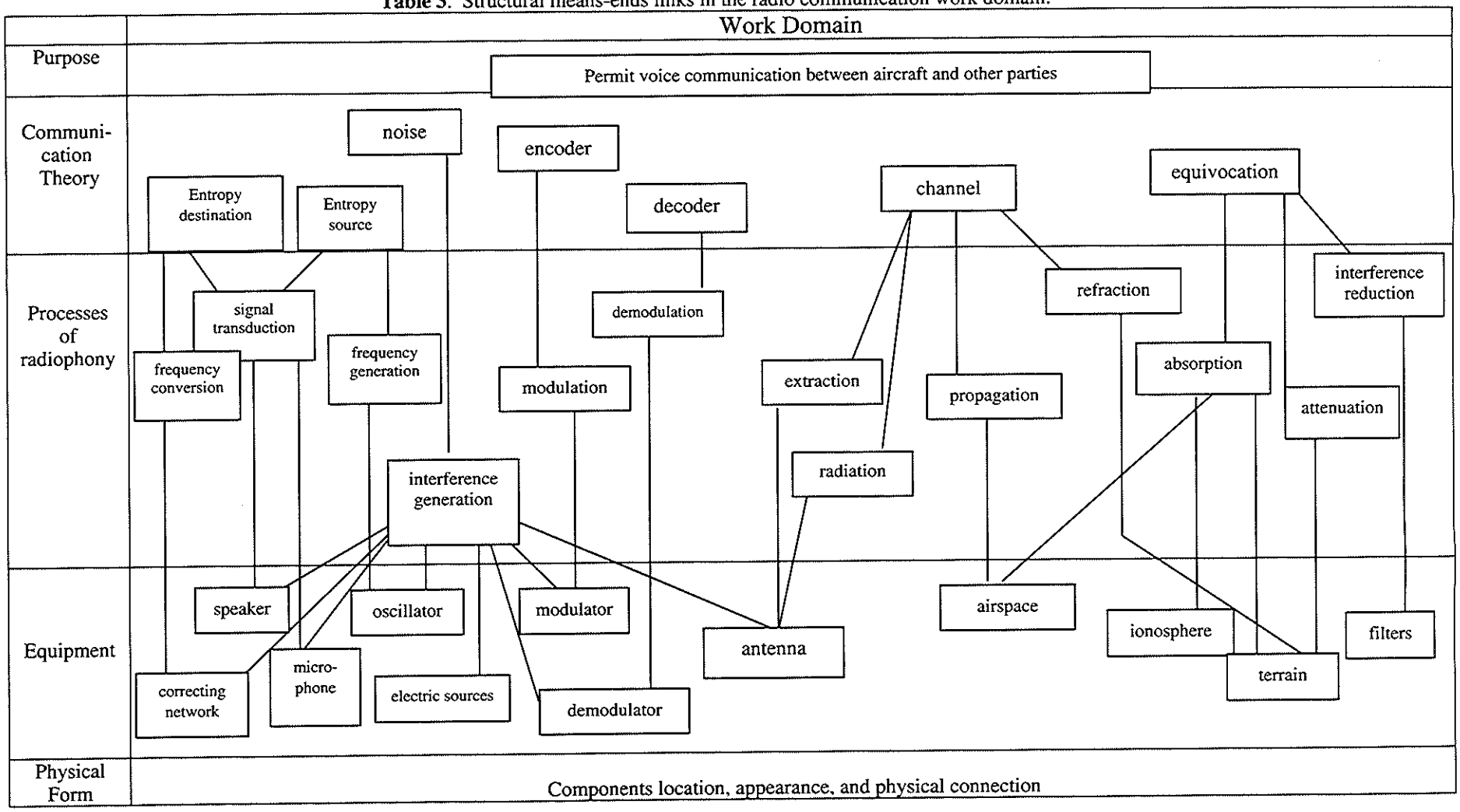
Table 3 shows the constraint levels for the radio communication domain and the means-end links between the nodes in the hierarchy.

Summary

A work domain analysis was performed for the radio communication work space using the Abstraction Hierarchy (AH). The generic labels of the AH were not useful for this domain; consequently, five new constraint labels were developed, all five being related in a structural means-end fashion. The five new labels are: Purpose, Communication theory, Radiophony, Equipment, and Physical form. The labels were disclosed through the "why-what-how" sliding window as suggested by Vicente (1999).

The following section involves the procedures followed for the implementation of the informational basis provided by the AH into a visual form for the EID interface.

Table 3. Structural means-ends links in the radio communication work domain.



DESIGN OF AN EID-BASED CONTROL DISPLAY UNIT

With respect to the second EID principle, it is necessary to provide a one-to-one mapping of the ecology of the work domain into a visual form. To do this, the variables affecting the domain need to be listed and their classification identified: variables that can be directly sensed, derived analytically from the sensed data, derived via heuristics from the sensed data, or not able to be sensed (Dinadis & Vicente, in press; Sharp & Helmicki, 1998). Such a classification is necessary in order to translate the requirements into an ecological form (i.e., the semantics of the parameter should be directly represented visually). The next section presents the variables involved in each level of the abstraction hierarchy and their classification.

Purpose Level

This level includes the global capabilities of the domain and whether the work domain can or cannot permit communications by means of radio, given the domain's current conditions. These variables, taken from the AH, are categorised as "analytical" since their states can be derived by the integration of several sensed data. The variables for this constraint level and their classification are listed in Table 4.

Table 4. Variables involved in the *purpose* level.

Abstraction Hierarchy level	Variable	Classification (mapping)
Purpose	Ability to transmit messages	Analytical
	Ability to receive messages	Analytical

Communication Theory Level

The first principles of the domain are represented by the dynamics of communication theory. All of the variables at this level also need to be classified as analytical since they can be found by integrating the sensed data. The variables and their classification are listed in Table 5.

Table 5. Variables involved in the *communication theory* level.

Abstraction Hierarchy level	Variable	Classification (mapping)
Communication theory	Entropy at source	Analytical
	Equivocation	Analytical
	Information transmitted	Analytical
	Noise	Analytical
	Entropy at destination	Analytical
	Encoder	Analytical
	Decoder	Analytical

Radiophony Level

This level represents the processes involved in accomplishing information transfer. The associated variables and classification are listed in Table 6.

Table 6. Variables involved in the *radiophony* level.

Abstraction Hierarchy level	Variable	Classification (mapping)
Radiophony	Audio signal	Directly sensed
	Frequency signal	Directly sensed
	Modulated wave	Directly sensed
	Transmitted signal	Directly sensed
	Lowest useful high frequency	Analytical
	Maximum useful frequency	Analytical
	Media refractive index	Direct or analytical
	Media dielectric constant	Direct or analytical
	Attenuation factor	Analytical
	Angle of incidence	Analytical
	Received Signal	Directly sensed
	Line of sight	Analytical
	Demodulated wave	Directly sensed

Equipment and Physical Form Levels

This level represents the components of the work domain, their settings, as well as their connections. The variables and classification are listed in Table 7.

In order to satisfy the third EID principle, it is necessary to allow for the perception/action loop to be closed by letting the operator directly act on the display (Vicente & Rasmussen, 1990, 1992). Vicente and Rasmussen (1990) suggests the use of either a trackball or a mouse as a suitable control for the fulfillment of EID's third principle. For the CDU, the use of a trackball is chosen over the mouse given the possible turbulence present in an aircraft.

Table 7. Variables involved in the *equipment and physical form* levels.

Abstraction Hierarchy level	Variable	Classification (mapping)
Equipment	Microphone	Directly sensed
	Oscillator	Directly sensed
	Correcting network	Directly sensed
	Modulator	Directly sensed
	Antenna	Directly sensed
	Airspace	Directly sensed
	Terrain features	Directly sensed
	Electric sources	Directly sensed
	Ionosphere	Direct or analytical
	Demodulator	Directly sensed
	Filter	Directly sensed
	Speaker	Directly sensed

EID Interface: General Description

The layout of the EID-based CDU interface is presented in Figure 7. The CDU interface has a rectangular screen displaying each individual means-end level in a different fixed viewport. The screen is divided into seven main display regions that are all displayed in parallel. Each viewport of the interface numbered 1 to 4-b represent particular levels and/or specific nodes of the abstraction hierarchy.

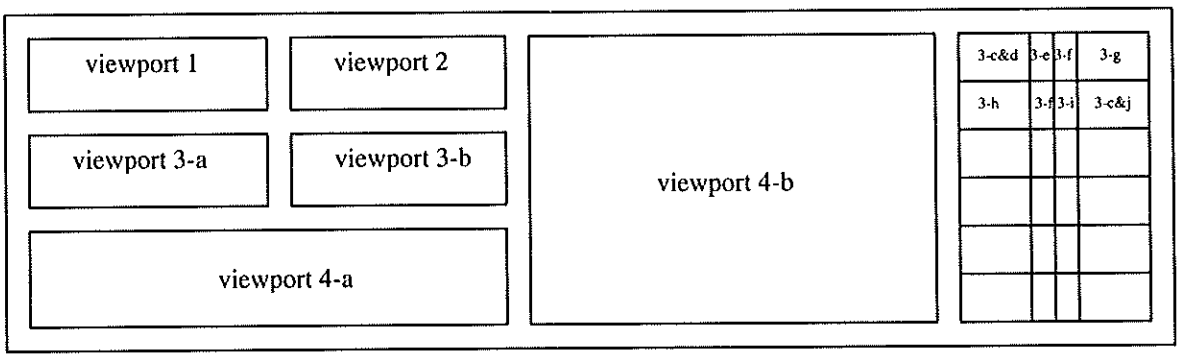
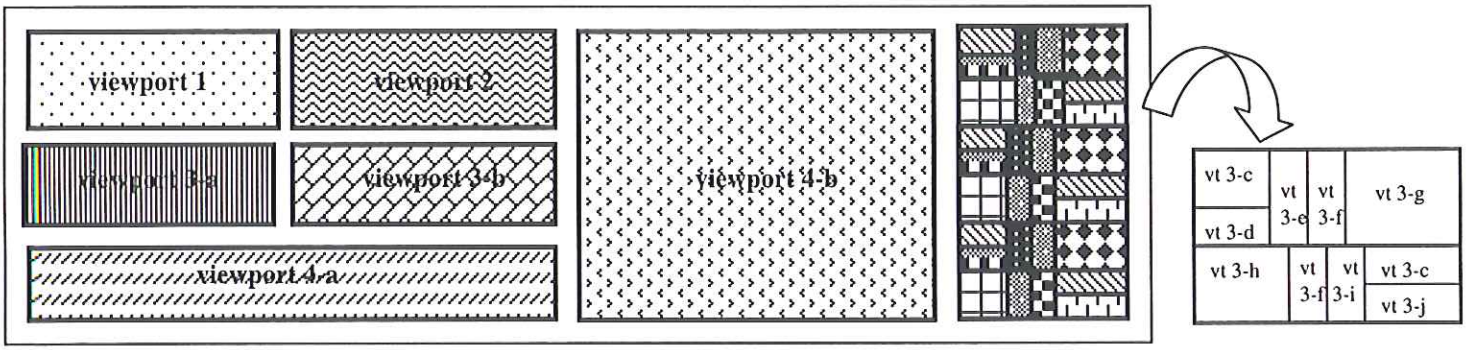


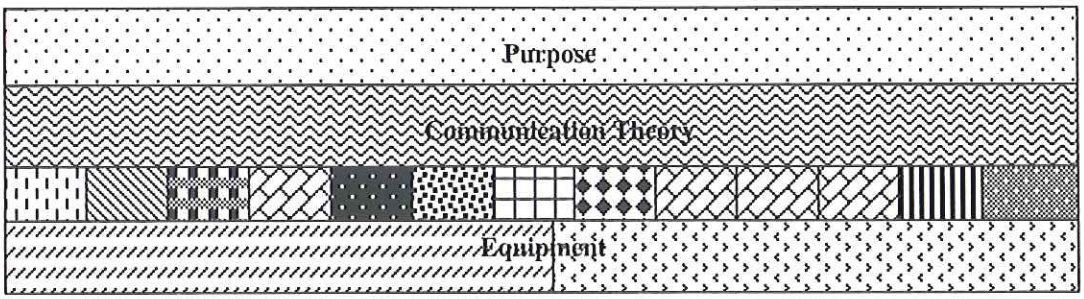
Figure 7. Layout of the EID-based CDU interface for communication management.

Figures 8a and 8b show the relationship between the display region on the interface and the AH representation. For instance, viewport 1 (in Figure 8a) illustrates the overall purpose of the radio communication domain relating to the corresponding shaded AH level of Figure 8b. Viewport 2 (in Figure 8a) shows the placement of the constraint level

"communication theory" (Figure 8b). Viewport 3-a illustrates the function "attenuation" which is a node included in the AH level radiophony. Viewport 3-b integrates four AH nodes at the radiophony level: refraction, absorption, propagation, and interference generation (shown in the corresponding shaded areas in Figure 8b of the AH representation). Viewports 3-c to 3-j show the location on the screen of eight functions involved in the radiophony level: signal transduction, frequency generation, modulation, radiation, extraction, demodulation, frequency conversion, and interference reduction respectively. Note that viewports 3-c to 3-j are displayed for each of the three radios on the interface. Viewports 4-a and 4-b represent the placement of the AH level "equipment". The requirements of the "physical form" level are superimposed on the other viewports throughout the display.



a) Placement of the viewports of the EID interface.



b) The corresponding shaded areas of the means-end levels and nodes of the radiophony level (frequency conversion, signal transduction, frequency generation, interference generation, modulation,demodulation, extraction, radiation, propagation, refraction, absorption, attenuation, and interference reduction respectively).

Figure 8. Relationship between the EID displays (a) and the means-end analysis (b).

EID Interface: Specifications

This section describes how each viewport of the CDU screen, corresponding to either an AH level or node, is illustrated on the interface.

Viewport 1 – "Purpose" Display. The purpose display, in the upper left corner of Figure 8a, shows how the work domain permits communication by means of a latitude/longitude map displaying spheric regions of allowable radio exchanges between parties given particular frequencies for a given range (as shown in Figure 9). The map shows the area's navigational coordinates with their latitude and longitude lines (the very fine dotted gray lines) as well as three spheres embedded in each other, each representing a radio frequency band (HF (thick solid black line), VHF (regular plain line), and UHF (dotted line)) under which communication can occur (Figure 9). The area of each sphere determines the distance within which communication can occur. Aircraft and radio beacons (designated by their call signs and displayed in the view, e.g., YYZ) within the vicinity of the "parent aircraft"[3], which is represented by a diamond shape object in the display, would have their own spheric regions representing the ranges within which communication can occur and successful radio exchanges would necessitate an overlap between spheres of the desired parties. Their spheres would be displayed in different colours for the differentiation of the parties. If no overlap between the spheric regions occur, radio exchanges cannot be successful. As the variables of the work domain change states, the spheric regions change shape, thus changing the distance within which successful communication can occur. Figure 9 shows the details of viewport 1(only a two-dimensional display is shown here; however, viewport 1 is intended to have a three-dimensional representation).

[3] The "parent aircraft" refers to the aircraft acting as the frame of reference for the area.

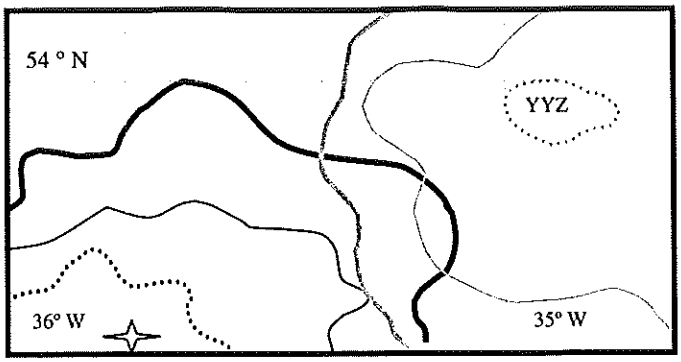


Figure 9. Details of viewport 1 displaying the Purpose view.

Viewport 2 – "Communication Theory" Display. This display is located in the upper left corner of the screen to the right of viewport 1 as shown in Figure 8a. It involves the depiction of information transfer represented in terms of Venn diagrams where the work domain's information loss, noise, and transmission capabilities are displayed as shown in Figure 10. A set representing the entropy at the source joining a set representing the entropy at the destination is shown; the intersection depicts the transmitted information and the shaded region represents the entropy loss and noise present in the domain. Such a display can allow operators to easily perceive the clarity of the domain and the possible transfer of information (made explicit in terms of percentage of transfer) in the communication channel. Also, given changes in the domain's states, the display parameters would change accordingly. Figure 10 shows the details of viewport 2.

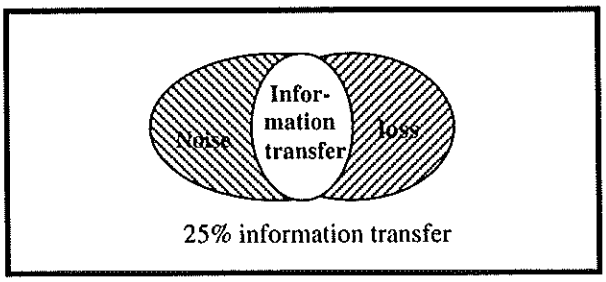


Figure 10. Details of viewport 2 displaying the Communication Theory view.

Viewport 3-a – "Radiophony: Attenuation" Display. The attenuation display is located in the middle left of Figure 8a, underneath viewport 1. It displays a three-axis graph where distance, in kilometers, is the variable on each axis (Figure 11). Three spheric envelopes, one for each radio band, are plotted on the graph showing the possible distance within which radio frequencies possess enough strength for transmission. The parent aircraft would be considered as the point of origin in the graph. Figure 11 shows the details of viewport 3-a (similar to viewport 1, only a two-dimensional display is shown here but viewport 3-a is intended to have a three-dimensional representation).

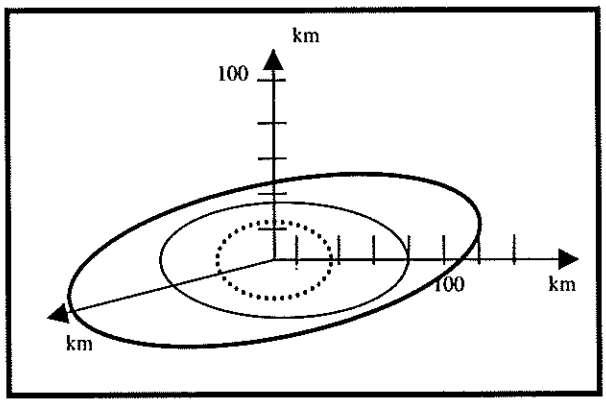


Figure 11. Details of viewport 3-a displaying the Attenuation node of the Radiophony means-end level.

Viewport 3-b – "Radiophony: Refraction/absorption/propagation/interference generation" Display. The viewport is located in the middle of the screen to the right of viewport 3-a. This display integrates four functions of the radiophony level in one graph: refraction, absorption, propagation, and interference generation. The graph has, as its x-axis, the time of day (0 to 24 hrs), and as its y-axis, the radio frequencies of aircraft communication grouped in the three radio frequency bands (as shown in Figure 12). The dashed line on the graph represents the lowest useful frequencies (LUHF) and the bold line, the critical frequencies. The frequencies falling under the LUHF, i.e., region A in Figure 12, are frequencies which are not useful for radio communication due to the strong absorption and noise levels given the area of concern. The frequencies falling between the LUHF and the

critical frequencies (region B) travel under ionospheric propagation while the ones in region C travel via tropospheric propagation. Also, regions of static interfering with radio waves are displayed in the graph as region of disturbances by ill-defined spots or bands in the display. Figure 12 shows the details of viewport 3-b.

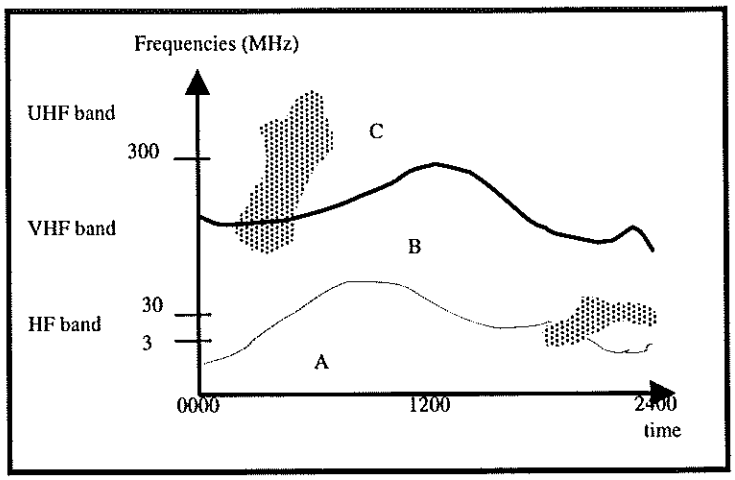


Figure 12. Details of viewport 3-b displaying the Refraction/Propagation/Attenuation/Interference generation nodes of the Radiophony means-end level.

Viewport 3-c – "Radiophony: Signal transduction" Display. The display is located at the upper right of the screen as shown in Figure 8a. This view displays the process of transduction by showing the translation of speech into electrical energy by the inscription of an electrical signal in the window as speech is being inputted (Figure 13-1). The same display is also located at the upper right of the interface underneath viewport 3-g. The details of the display are presented in Figure 13-1.

Viewport 3-d – "Radiophony: Frequency generation" Display. The display is located in the upper right of the screen, underneath viewport 3-c, as shown in Figure 8a. This view displays the process of frequency generation by showing the production the radio wave as a sinusoidal line in the window and the display is presented in Figure 13-2.

Viewport 3-e – "Radiophony: Modulation" Display. The display is located in the upper right of the screen, to the right of viewports 3-c and 3-d, as shown in Figure 8a. This view displays the process of modulation by showing the modulated radio wave as it is

produced through the integration of the audio and radio signal. The details of the display are shown in Figure 13-3.

Viewport 3-f – "Radiophony: Interference reduction" Display. The display is located between viewport 3-e and 3-g, at the upper right corner of the interface as well as to the right of viewport 3-h. Both are represented by the filtering of noisy signals into smoother signals. The details of the display are illustrated in Figure 13-4.

Viewport 3-g – "Radiophony: Radiation" Display. The display is located in the upper right of the screen, next to viewport 3-f, as shown in Figure 8a. This view displays the process of radiation by showing waves travelling away from the point of focus. This view shows continuous activity as the process is undertaken. The display is presented in Figure 13-5.

Viewport 3-h – "Radiophony: Extraction" Display. The display is located in the upper right of the screen, below viewport 3-d, as shown in Figure 8a. This view displays the process of extraction by showing waves travelling towards the point of focus. This view also shows continuous activity as the process is undertaken. Figure 13-6 presents the details.

Viewport 3-i – "Radiophony: Demodulation" Display. The display is located in the upper right of the screen, next to viewport 3-f, as shown in Figure 8a. This view displays the process of demodulation by showing the separation of the audio and radio signal as it occurs. Figure 13-7 shows the details.

Viewport 3-j – "Radiophony: Frequency conversion" Display. The display is located in the upper right of the screen, underneath viewport 3-c to the right of viewport 3-i, as shown in Figure 8a. This view displays the process of frequency conversion by showing the recovery of electrical energy. Figure 13-8 illustrates the display.

The ten displays represented by viewports 3-c to 3-j are grouped as a window for each of the radios. Therefore, three windows are represented on the EID interface.

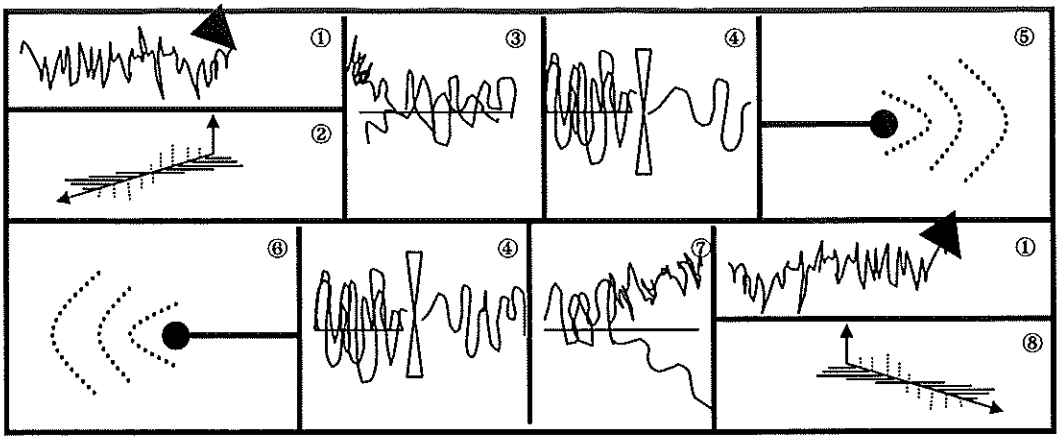


Figure 13. Details of viewports 3-c to 3-j relating to means-end nodes of the Radiophony level (signal transduction (1 on the display), frequency generation (2), modulation (3), interference reduction (4), radiation (5), extraction (6), demodulation (7), and frequency conversion (8).

Viewport 4-a – "Equipment" Display. The display spans two columns and is located at the bottom left of the screen, below viewports 3-a and 3-b, as shown in Figure 8a. This display presents the environmental elements of the work domain in a topographic format: terrain elevations through concentric circles denoting the height of the features are illustrated as well as meteorological information represented as ill-defined shaded regions of either rain, atmospheric disturbances, snow, etc. Figure 14 shows the details of the display.

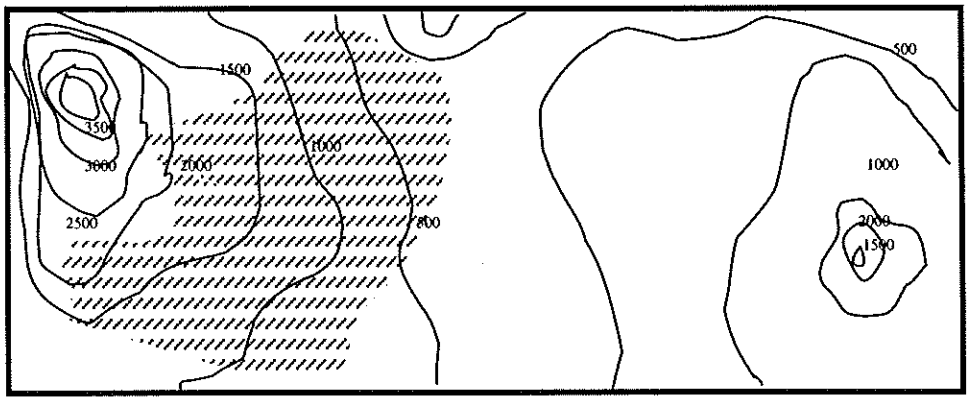


Figure 14. Details of viewport 4-a displaying the Equipment level information (environmental elements).

Viewport 4-b – "Equipment" Display. The display is located in the middle of the screen as shown in Figure 8a. The three radios, UAM-1, VFM-2, and UAM-3, are shown in viewport 4-b, their components, and their connections. A brief description of the radio components follows with their designator in Figure 15 in brackets (only one of the three radios is shown in Figure 15). Starting with the upper left of viewport 4-b, one sees the microphone (1) connected to the correcting network (2). The correcting network is also connected to the oscillator (3) and both these components are attached in parallel to the modulator (4) that provides input to the filters (5). Annexed to the filters is the antenna (6). The demodulator (7) and speaker (8) are also shown on the display. A highlighted icon for each element presents the active state of these parts.

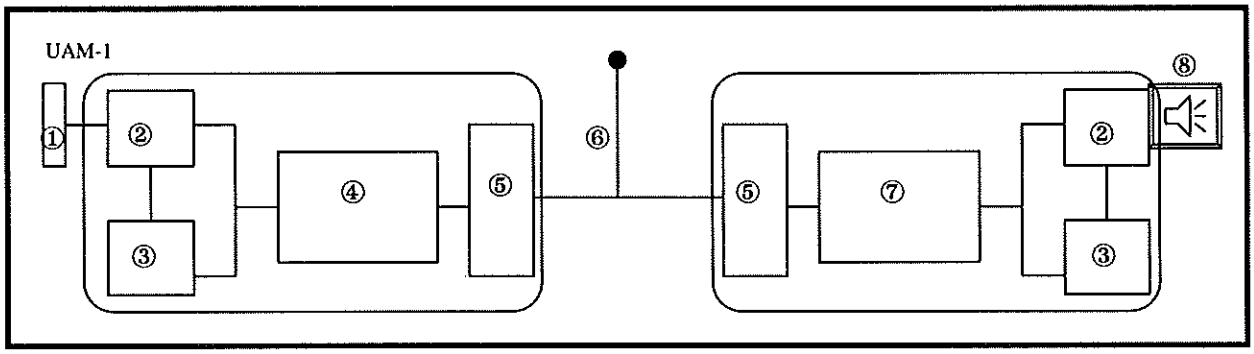


Figure 15. Details of viewport 4-b displaying the Equipment level information (technical elements).

EID-based Interface's Operational Capabilities

Figure 16 shows the EID display in its entirety. The selection of a radio involves pointing the trackball cursor to the specific radio on the display in viewport 4-b. The same action is done for the selection of the frequencies but in viewport 3-b.

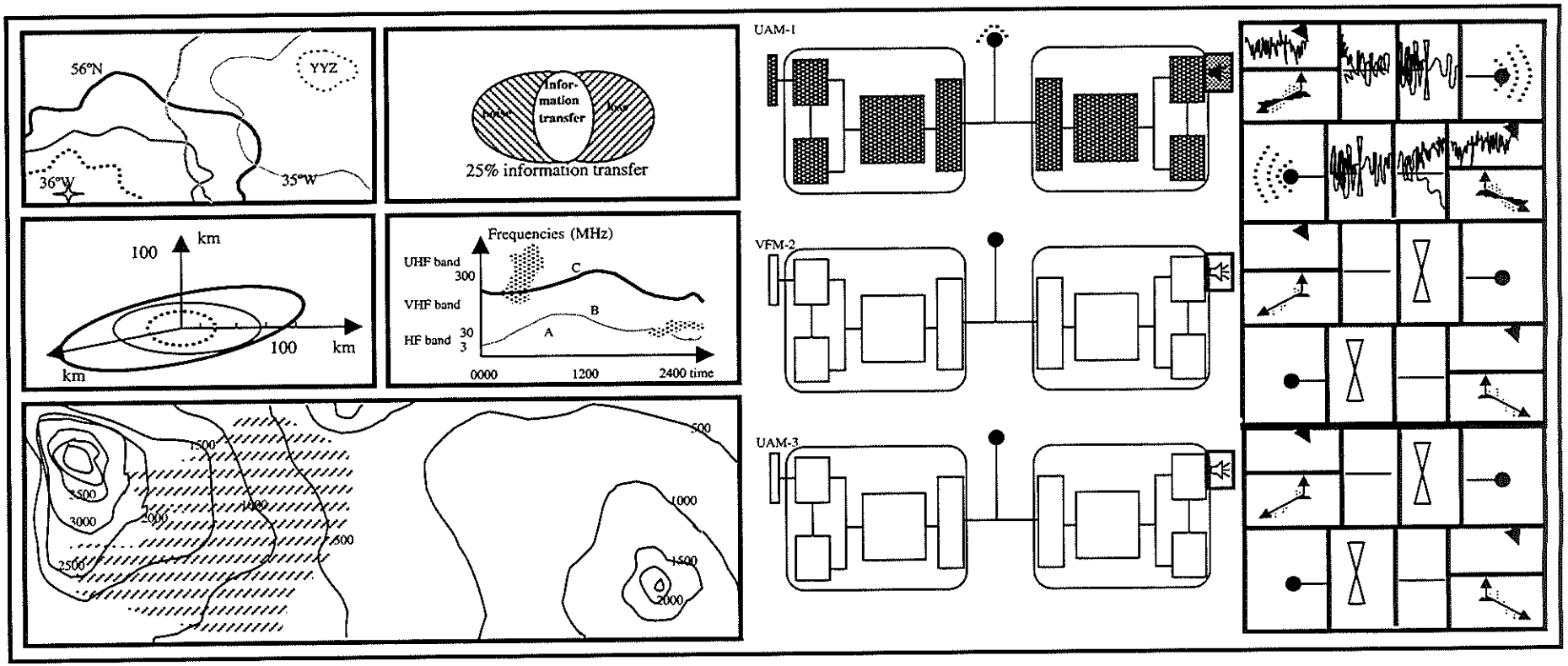


Figure 16. EID-based CDU interface for communication management. Note that this interface presents radio UAM-1, in the upper right corner, being active while the other two are not.

Summary

An EID-based interface for the CDU was developed. For each means-end level, variables were identified and classified as directly sensed, derived analytically, derived via heuristics, or not able to be sensed. The classification was necessary in order to provide a one-to-one mapping of the semantics of the domain into a representational form. Each level of the AH were represented visually and the interface resulted with seven main display regions presented in parallel on the screen. A trackball is used as a control to allow for direct manipulation to occur.

The next section now looks at the PCT analysis for the radio management and describes the procedures followed for the development of the information requirements necessary for a PCT-based CDU interface.

DEVELOPING A PCT-BASED ANALYSIS FOR RADIO SYSTEMS

A PCT-based analysis was performed using the tables suggested by Farrell and Chery (1998). In order to fill the columns of the tables necessary for the analysis, data from various sources were gathered. Documentation with respect to radio communication standard operating procedures (Fechet, Eddy, Lear & Bloch, 1942; Brown, 1975; Canadian Marconi Company, 1995b), military communications (Hyde, 1990; Ricci, & Schutzer, 1986), and control display units (Canadian Marconi Company, 1995a) were used for the development of the analysis. Also necessary were discussions with subject matter experts (Philip Farrell, personal communication, June, 1997; Ian Mack, personal communication, June 1997; Ronald Ebbers, personal communication, June, 1998), a military pilot (Peter Schiedler, personal communication, 25 June, 1997) and a familiarisation visit to Borden Canadian Forces Base to board a Griffon helicopter equipped with two control display units. All of this information was necessary in order to have an accurate and as complete as possible representation of the behaviours involved in the tasks of the operators and the functions of the CDU.

The perceptual goal that started the analysis was "to perceive that the radio communications are maintained". This particular goal was chosen because it encompasses the operator's high level objective and represents the system functionality that the designer wants to affect in the interface design of the CDU for communication management.

The stopping criterion that was used for the analysis was based on the stopping rule proposed by Annett and Duncan (1967) (cited in Diaper, 1989) which consists of the P x C principle (where the value of P and C represent the probability and cost of inadequate performance, respectively). The P x C "value" was conceptualized in this

work as low level control loops representing the need to fulfill the perceptual goals of pressing keys and visualising displays. The further decomposition of these motor and sensory activities would not be productive or useful for the purpose of interface design (Dix, Finlay, Abowd, & Beale, 1998).

The procedure which was used to perform the analysis was the development of the operator's goals. These were identified from the different sources of information mentioned above in a descriptive fashion (i.e., what the goals of the operators are, as opposed to what they should or could be). Then, it was necessary for the analyst to identify the sensory information which could yield matching perceptions. From there, possible error values were stated and behaviours that could accommodate such errors resulted. Controls and displays were then proposed.

In order to expand the loops from high to lower levels, the behaviours became the goal states of lower level control loops and the same exercise was performed iteratively. Also, the lower level perceptions became the high level sensory information allowing the perception/action loop to be closed. The full annotation of the PCT-based analysis is found in Appendix I.

Summary

A PCT-based analysis was performed using the PCT-based tables as suggested by Farrell and Chery (1998). Data from various sources was gathered in order to fill in the columns of the tables; then, interface displays and controls were proposed for each table in order to accommodate for the fulfillment of the goal stated for each table.

The subsequent section presents a description of the resulting interface incorporating the PCT-based requirements.

DESIGN OF A PCT-BASED CONTROL DISPLAY UNIT

The design of the interface was performed by implementing the display and control specifications yielded by the PCT analysis. Even though no design guidelines are prescribed by the PCT framework, the Department of Defense human engineering design guidelines were followed for the CDU interface (U.S. Department of Defense, 1996).

Implementation of the Requirements

This section presents the control and display requirements involved in each control loop (Table 8). The goal state of each loop is presented for each row with its respective control(s) and display(s) also listed in Table 8.

PCT Interface: General Description

The layout of the PCT-based interface is presented in Figure 17. The CDU has a rectangular screen which displays textual and colour-coded information yielded by the PCT-based analysis. The screen, delimited by the thick gray line in Figure 17, is divided into three display regions vertically aligned from each other representing the characteristics of three distinct radios. All three regions provide the same consistent type of information for each radio (radio UAM-1 and 3, and VFM-2). Only one radio field is described in detail as the same information pertains to the other two. Moreover, the interface has three horizontal display text boxes to the right of the primary screen, one for each of the three display regions. The CDU is also equipped with an alphanumeric keyboard at the bottom of the interface and possesses controls vertically spanning the left and right of the screen as well as at the top of the device for the selection of menu items or particular features (Figure 17).

Table 8. PCT information requirements for each control unit of the analysis (annotated by their goal state).

Goal State	Control Requirements	Display Requirements
To perceive that communications are maintained	Ability to control ❑ communication mode	Ability to display ❑ communication mode
To perceive that communications are exchanged	Ability to control ❑ communication reception ❑ communication transmission	Ability to display ❑ communication reception ❑ communication transmission
To perceive that communications are being monitored	Ability to control ❑ operator's monitoring activities ❑ establishment of a radio link	Ability to display ❑ operator's monitoring activities ❑ establishment of a radio link
To perceive that a specific radio link is established	Ability to control ❑ status of the radio link (active/standby)	Ability to display ❑ status of the radio link (active/standby)
To perceive that a specific radio link is set	Ability to control ❑ radio ❑ frequency ❑ security state	Ability to display ❑ radio ❑ frequency ❑ security state
To perceive that a message between communicating partners is adequately interpreted	Ability to control ❑ message content ❑ message adequacy	Ability to display ❑ message content ❑ message adequacy
To perceive that a desired radio is set	Ability to control ❑ radio setting	Ability to display ❑ radio setting
To perceive that a desired frequency is set	Ability to control ❑ frequency setting	Ability to display ❑ frequency setting
To perceive that the security is set	Ability to control ❑ security setting	Ability to display ❑ security setting
To perceive that the message content is completely received by the recipient	Ability to control ❑ message repetition	Ability to display ❑ message reception by recipient (acknowledgement)
To perceive that the message content is clearly understood by the recipient	Ability to control ❑ message content	Ability to display ❑ "understanding state" of the recipient ❑ message content
To perceive that the radio communication channel is clear	Ability to control ❑ channel clarity	Ability to display ❑ channel clarity

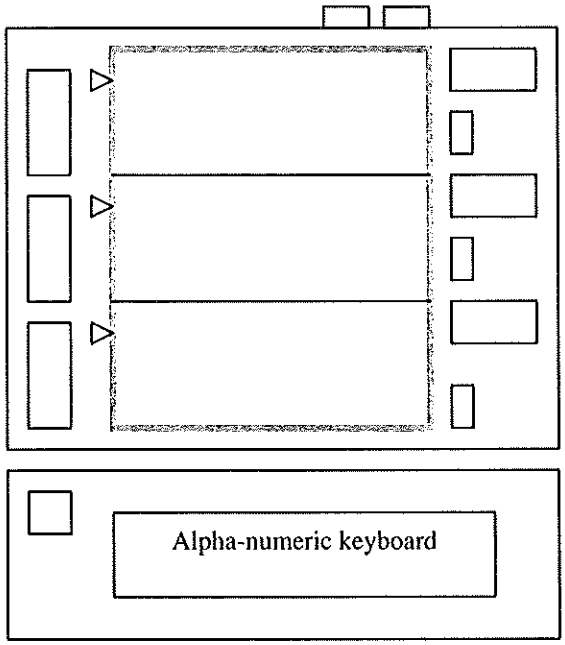


Figure 17. PCT-based CDU interface for communication management.

The organisation of the design requirements satisfies the U.S. Department of Defense guidelines 5.1.1.1 (relationship), 5.1.1.2 (design), 5.1.2.1.1.4 (consistency), 5.1.2.1.1.1 (sequence), and 5.1.2.3 (arrangement within groups) (listed in Appendix II) (U.S. Department of Defense, 1996).

PCT Interface: Specifications

The requirements are described showing their relationships with the PCT-based analysis and are organised per goal state (which corresponds to the headings below) for each PCT table used for the analysis. The requirements are numbered in the text for their cross-reference with the corresponding figures.

"To perceive that communications are maintained". To satisfy this operator goal state, a key (1) situated at the bottom left region labeled "comm" is designed allowing operators to be in a communication mode (Figure 18). Also, the complementary display

becomes the specific arrangement of the display regions while in communication mode which this section describes in greater detail.

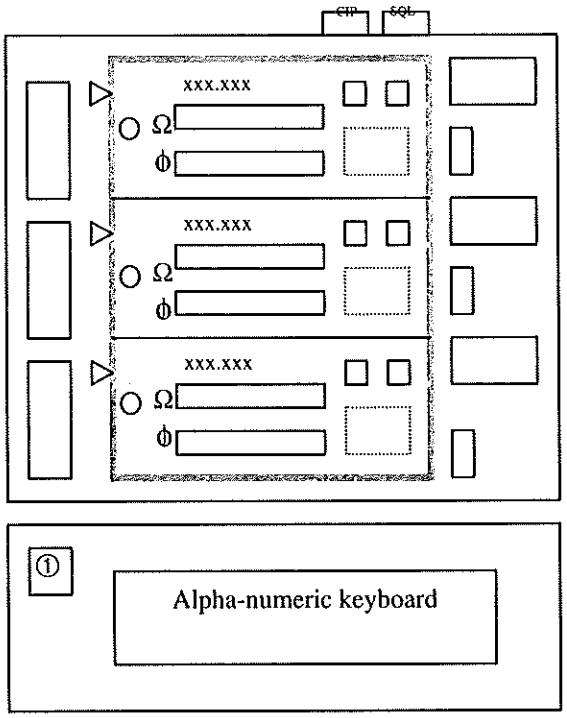


Figure 18. PCT-based CDU interface displaying the communication mode layout and the "comm" key (1)

<u>"To perceive that communications are being monitored".</u> To satisfy this operator goal, it is believed that communication activities should be undertaken and that possibilities for radio link establishment should be made available. At this high level in the analysis, establishment of a radio link can be performed by depressing the square key (2) labeled *A/S* (Figure 19a). The perception of link establishment can be generated by having the periphery of the radio field surrounded by a solid line (Figure 19a). The link can alternatively be put on standby via the depression of the same key (2). The radio field remains neutral in this case and a display field situated within the radio field at its bottom right (shaded area in Figure 19b) reads "stdby".

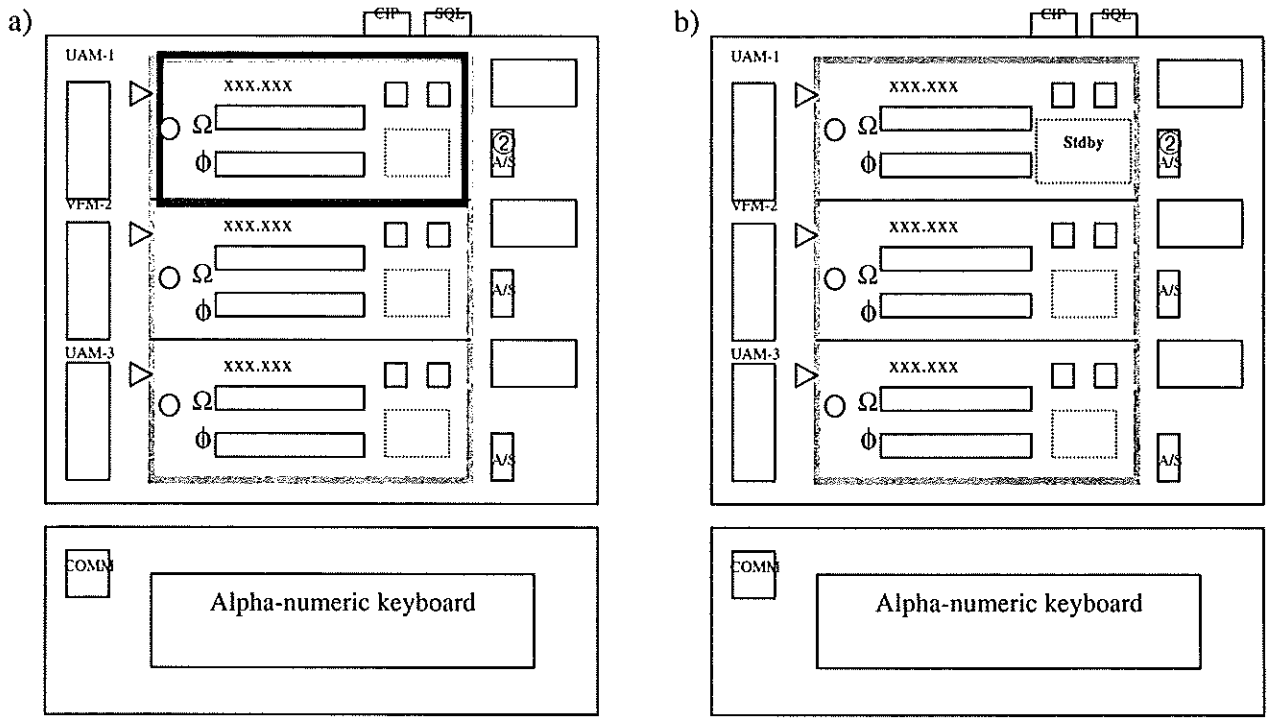


Figure 19. PCT-based CDU interface illustrating the "A/S" key (2) and the activated radio field in a) and the "stdby" display field shaded in b).

"To perceive that a specific radio link is established". To satisfy this operator goal, the above paragraph holds as well.

"To perceive that a specific radio link is set". To satisfy this operator's goal, a radio, frequency, and security state controls and displays are designed. These controls can easily be distinguished from the each other by their shape, size, and their spatial relationship vis-à-vis their corresponding displays, which can be advantageous for the tactile discrimination of the keys and therefore would not oblige operators to adopt a head-down configuration in the cockpit for CDU entries. The radio control is designed as a rectangular key (3) having a radio type labeled above it (4) (Figure 20). To its immediate right, a smaller triangular key (5) can also be found pointing towards the frequency field (seen as xxx.xxx) (6) for its selection. In the middle of the interface, at

the upper border of the screen lies the security control (CIP) (7) and vertically aligned to it are colour-coded indicators (8) in each radio field corresponding to each radio for their security state (Figure 20).

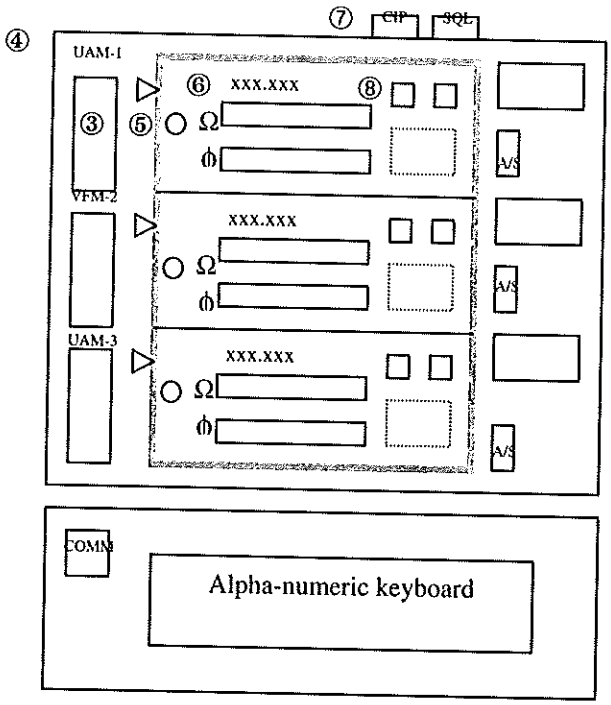


Figure 20. PCT-based CDU interface illustrating the radio control (3), its label (4), the frequency control (5), the frequency field (6), the cipher control (7) and indicator (8).

<u>"To perceive that a desired radio is set".</u> To satisfy this operator goal, the radio control (3) described above is made available at all times. Its depression leads to a dashed black line surrounding the radio field (Figure 21), which spans the upper middle of the interface (Figure 21), for the operator to perceive that the particular radio is being set.

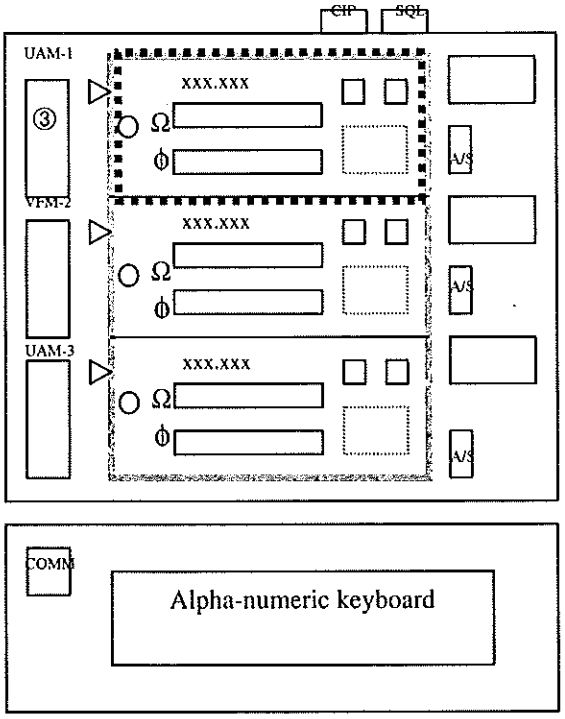


Figure 21. PCT-based CDU interface illustrating the radio control (3) and the radio field surrounded by a dashed black line advising of its selection for radio setting.

"To perceive that a desired frequency is set". To satisfy this operator goal, the frequency control (5) described above is made available at all times. Its depression leads to a dashed black line surrounding the frequency field which is located in the upper left of the menu (Figure 22). Moreover, the alphanumeric keyboard spanning the majority of the lower bottom of the interface is made available at all times for the entry of frequency numbers and/or call signs.

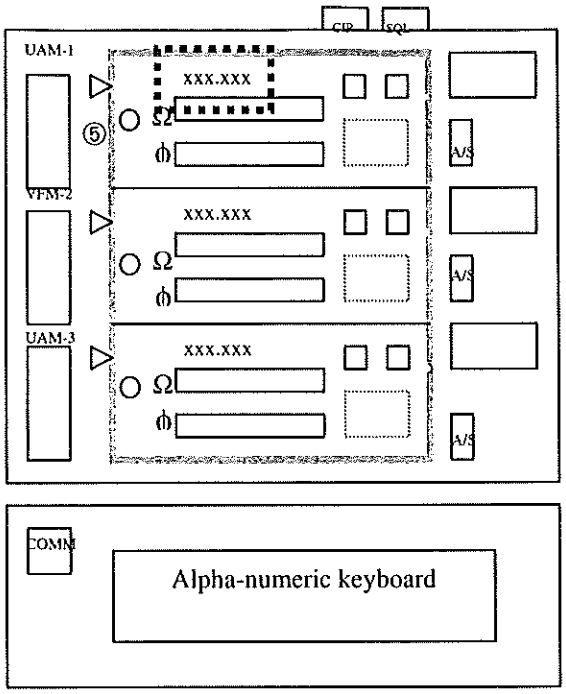


Figure 22. PCT-based CDU interface illustrating the frequency control (5) and the frequency field surrounded by a dashed black line advising of its selection for frequency setting.

"To perceive that a desired security is set". To satisfy this operator goal, the security control (7) described above is made available at all times. Its depression leads to the activation of the security indicator (8) (Figure 23).

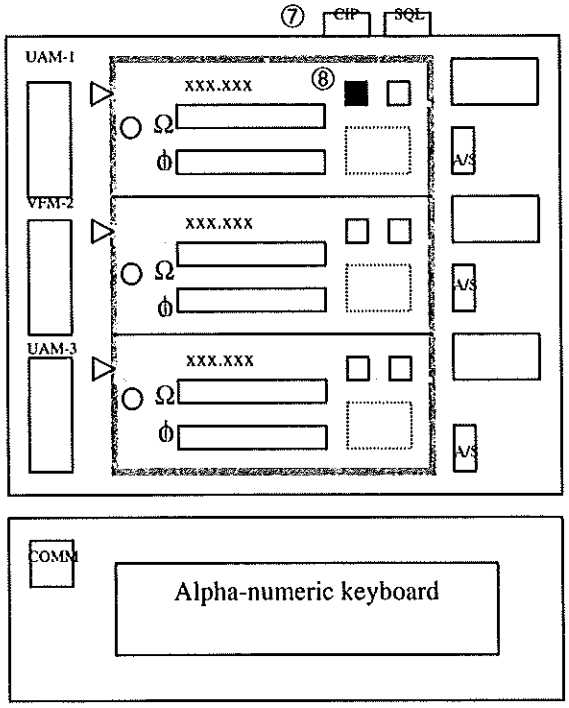


Figure 23. PCT-based CDU interface illustrating the security control (7) and its indicator (8).

"To perceive that the message content is completely received by the recipient".

To satisfy this operator goal, a colour-coded circular acknowledgement indicator (9) is placed underneath the frequency field in the radio field signifying that the message was completely received by the recipient (Figure 24). Repeating the message would be necessary if the indicator would not be active following message transmission (an active state is represented by the indicator being green).

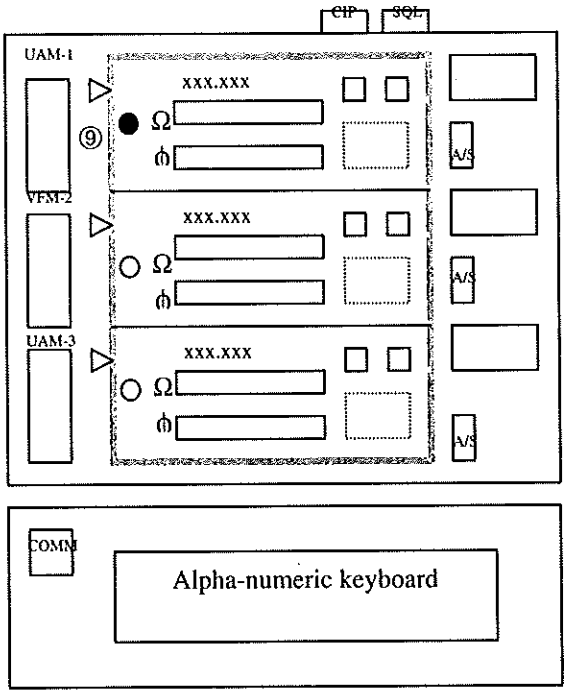


Figure 24. PCT-based CDU interface illustrating the circular acknowledgement indicator (9) for recipient's message acknowledgement.

"To perceive that the message content is clearly understood by the recipient".

To satisfy this operator goal, a rectangular text box (10) is made available at the upper right of the interface for the transcription of the incoming and/or outgoing radio message annotations (Figure 25). Messages which are inadequate from a syntactic standpoint have part of the text underlined in the text box.

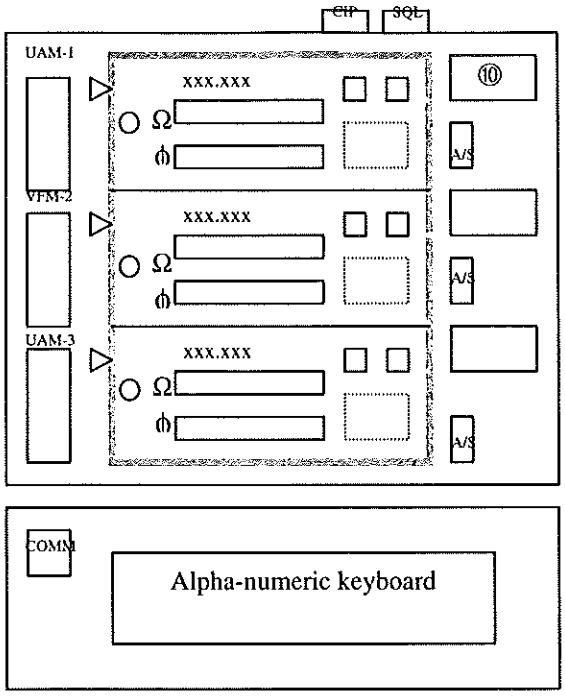


Figure 25. PCT-based CDU interface illustrating a text box (10) for the transcription of incoming and outgoing radio messages.

<u>"To perceive that the radio communication channel is clear".</u> To satisfy this operator goal, two rectangular status bars are shown in the middle of the radio field, one for transmission labeled with the symbol " Ω " and the other for reception labeled with "ϕ" (Figure 26) (these two symbols were chosen arbitrarily to represent the transmission and reception status). Their continuous display of activity shows how clear the channel is: a solid bar demonstrates that the channel is clear while a channel prone to background noise or static would be displayed on the status bar as well through discontinuous activity. Also, a control, the squelch key (SQL) (11), situated in the middle of the interface, at the upper border of the screen at the right of the security control (CIP) (7) is designed and vertically aligned to it are colour-coded indicators (12) in each radio field corresponding to each radio for the depiction of their squelch state. Depressing the squelch key leads to the activation or inactivation of the function.

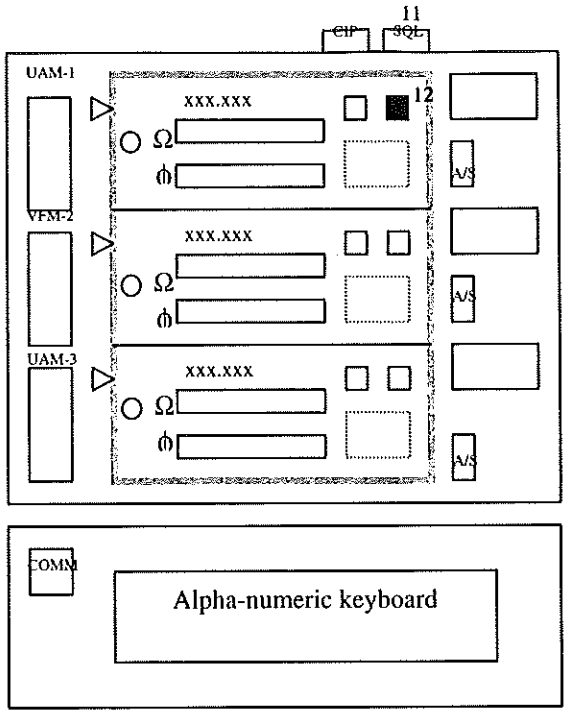


Figure 26. PCT-based CDU interface illustrating the transmitting status bar (Ω) and the receiving one (ϕ). Also shown are the squelch control (11) and its highlighted indicator (12).

Summary

The PCT-based interface requirements were implemented in a CDU design and the relationship between the requirements found in the analysis and the design was shown. The PCT-based interface possesses three display regions which are consistent with each other as they provide similar information for each of the three radios. The bottom region of the interface consists uniquely of controls allowing entry and editing of data.

Now that both analyses have been performed and that two interface designs incorporating each framework's information requirements were described, one can proceed to their comparison contrasting their own contributions. The following section presents qualitative remarks on the application of EID and PCT for the CDU interfaces specifically looking at the information requirements yielded by both frameworks. These requirements are also reviewed against the requirements of the current CDU for the appreciation of the value added by both frameworks.

EID- & PCT-BASED INFORMATION REQUIREMENTS: QUALITATIVE REMARKS

For this part, the information requirements are discussed from two different viewpoints and are contrasted against the controls and displays of the current CDU interface. First, the informational basis (interface content) is reviewed under three subgroups for EID and PCT:

- *New requirements*: the ones that are disclosed by the frameworks and not present on the current CDU,
- *Existing requirements*: the ones that are disclosed by the frameworks but already present on the current CDU,
- *Missing requirements:* the ones that are not disclosed by the frameworks but present on the current CDU.

Secondly, the interface structure is discussed as well.

Application of EID

The EID framework provided a list of interface requirements. They are grouped under the three labels described above.

New requirements. The majority of the EID requirements are new and thus no major overlap exists between the current and the EID interface. The requirements yielded by EID have a very different nature than the ones present on the current CDU. The EID requirements relay the functioning of the work domain in different representational descriptions. As mentioned earlier in the thesis, the requirements have a strong ecological approach looking at the principles governing the work domain and its components. This description of the radio communication domain is therefore heavily based on radio engineering and radio wave propagation theorems and is

independent of operators' actions and goals. The interface thereby leads to a deeper knowledge of the work domain, giving operators the possibility to cope with situations which were not anticipated.

Existing requirements. Only two information requirements (radio and frequency parameters) were yielded by the EID framework that were already present on the current interface. Given that the current design has a task-based approach, such a finding was not surprising. Furthermore, even if some hardware parameters are on the current CDU, none were found on the EID CDU interface. One can attribute that to the fact that the abstraction hierarchy modelled the communication space and not the CDU per se as a work domain.

Missing requirements. None of the current requirements were disclosed by the EID framework. Only information relevant to the identified work domain purpose is uncovered by EID, and given that several requirements are missing, it can be seen as a limitation. An activity analysis could help the analyst make note of missing specifics and complement the EID-based information requirements. An activity analysis depicts the actions performed on the work domain and allows to focus on the domain functions and components which are specific to operator's tasks (Rasmussen, Pejtersen & Goodstein, 1994). It then permits the work situations to be defined and relate the work domain requirements for the interface to the activities of the operator (Rasmussen et al., 1994).

Application of PCT

Similarly to EID, the PCT framework led to the exposure of control and display requirements. They are grouped under the three labels as well.

New requirements. Seven PCT requirements are not already present on the current CDU interface: e.g., link status: active/stdby, message content, message adequacy, clarity of channel, communication reception and transmission, and message acknowledgement. Because PCT focuses on what operators need to perceive for control stability, it provides a framework for designers to instantiate particular displays which let particular perceptions be generated by users. These perceptions can "close" the perception/action loop, assuring feedback. These seven new requirements make the feedback more explicit on the interface.

Existing requirements. The rest of the PCT requirements were present on the current CDU but relayed in a different visual form. This high degree of overlap was anticipated since the current CDU interface was designed using a task-based approach. Therefore, a great deal of similarity with the PCT requirements and the current design was to be expected.

Missing requirements. Various requirements were not yielded by the PCT framework. Some of the requirements present in the current CDU directly stated or were involved with hardware parameters for each radio (e.g., encryption units, DF capabilities, modulation, offset, etc.). Unsurprisingly, PCT did not disclose that information given that it does not look at the hardware of the device but at operators' goals. The necessity to look at the constraints of the device before looking at behavioural aspects could lead to the enrichment of the PCT requirements.

Other "missing" requirements dealt with the navigational capabilities of the interface (e.g., altn, prv/next, rtn). PCT did not disclose those either. Navigation issues involve design decisions relating to interface form and not content. Because the interface form was not evaluated in this thesis, these concerns are not addressed further.

Also PCT led to a re-structuring of some information requirements. For instance, in the current interface, the guard frequency is given "special considerations" by having its own control and display. However, one cannot know which radio is tuned to the guard frequency unless one goes deeper in the communication pages. In the PCT design, the guard frequency is considered just like the other frequencies and therefore, resolves such a concern. Moreover, the different modes of the communication links currently present on the current CDU interface (maritime, manual, scan, emergency, comm list, and have quick) were not disclosed by the PCT analysis. These different modes do not operationally change the way the links are established but join these links in functional groupings.

Interface Structure

For EID, the abstraction hierarchy provides the structure of the information via means-ends relationships. Such a depiction of the work domain has been shown to be representative of people's reasoning (Vicente & Rasmussen, 1992). Despite the fact that CDU operators are not extensively trained on radio engineering principles, it is believed that the high-order information of importance to the work domain presented in a structural means-end relationship will facilitate problem-solving activities. Empirical studies with military pilots would be necessary in order to validate the above statement.

The PCT structure of feedback at all hierarchical levels makes low-level control loop requirements visible at high levels thereby avoiding the need to undertake extra actions like with the current interface (e.g., the security setting of a radio channel can be known by accessing the radio page for the current CDU interface). Also, other requirements may be present but hidden in the menu structure which causes pilots to navigate through another communication page (e.g., squelch). This also requires pilots

to know where pertinent information is located in the menu pages. For the PCT interface, only one main page is necessary. Moreover, the PCT-CDU parameter states are readily seen which offloads the pilots' memory by making them visible, allowing pilots to remain in the loop and aware of the device's behaviours.

Information Requirements: Overall

With respect to the EID interface, the PCT requirements were clearly distinct and no major overlap between the requirements of the two frameworks was found. Given that they are based on different approaches, it is not surprising to see the extent to which the requirements differ since EID incorporates a work domain analysis while PCT a control task analysis. Also, it is important to mention that the PCT requirements were identified and a PCT interface designed prior to the EID analysis and interface design. One can see that the EID analysis still provided a new set of information requirements but failed to identify the ones uncovered by the PCT framework, even with the analyst' full knowledge of them. This shows that indeed both frameworks provide a distinctive sets of requirements for design.

Interfaces Differences

Several differences can be noticed with the two interfaces, not only with respect to their content but with their form as well. These interface differences reflect the differences present in the two frameworks. The representation of the requirements followed two EID principles (one-to-one mapping and direct manipulation) and some Department of Defense (DoD) guidelines for the EID and PCT interfaces, respectively. In order to make the interface forms more comparable, one would need to either apply the attributes of the EID or DoD criteria to both interfaces in order to minimise the differences present in their representational form. Even though the interface form was

not the parameter under study in this thesis, it is important to be aware that such a concern needs to be addressed when performing comparative evaluations. Table 9 shows the main differences between the EID and PCT interface form.

Table 9. Some main differences between the EID and PCT interface form.

EID interface	PCT interface
Emphasis on graphics	Emphasis on alpha-numerics
Use of trackball	Use of keys
Integrated controls/direct manipulation	Separated controls/key presses
Integrated display information (HF, VHF, UHF)	Separated display information

Summary

In itself, both EID and PCT have each contributed to the richness of the informational basis of the CDU interface. They provided information requirements which were not currently present and both provided a systematic way to structure information (via means-end relationships and explicit feedback at all control loop levels). However, it was shown that it would be better for them to be used in conjunction with other frameworks as they did not seem to disclose as much information requirements as needed.

The following section now addresses the effectiveness of the information requirements uncovered by EID and PCT via the performance of an analytical evaluation. Both interfaces are compared in their ability to support particular radio activities using different task scenarios.

EID- & PCT-BASED CONTROL DISPLAY UNITS: ANALYTICAL EVALUATION

Several documents in the human factors literature report the design process as having a top-down approach starting from user information requirements to prototype development (Vicente, 1990; Rasmussen et al., 1994; Rubin, 1994; Dix et al., 1998). Several steps as well as multiple evaluation stages are involved in design and the multiple phases of evaluation yield valuable insights enabling the modification of the design as necessary (Rouse, 1984).

Only the initial stage of the design process, user information requirements, is performed and evaluated in this research. Several design criteria have been identified by Rouse (1984) and claimed as appropriate for the evaluation of interfaces (Vicente, 1990; Rasmussen et al., 1994). The criteria are effectiveness, understandability, and compatibility.

Rouse considers an effective system as one that "supports an operator (or a crew) in a manner that leads to improved performance, results in a difficult task being less difficult, or enables accomplishing a task that could not be otherwise accomplished" (Rouse, 1984, p. 3-7). Hence, Rouse attributes effectiveness as a measure of the functionality of the system and such a parameter is evaluated via analytical evaluations which directly support this objective (Rasmussen et al., 1994).

For issues of understandability, "one is concerned with the nature of communications between operators and the system" (Rouse, 1984, p. 3-9). The main concern for this criterion is the form in which the functionality of the system is relayed to the operator and the depiction of what operators need to know in order to understand the messages designers want to convey. Such a parameter is evaluated empirically

since operators are necessary for the assessment of the proper implementation into a representational form of the functionality (Rasmussen et al., 1994).

Thirdly, compatibility involves the capability of the interface to fall within the operators abilities and limitations (Rouse, 1984). For instance, operators need to be able to read text displayed to them, reach the controls, etc. Similar to understandability, compatibility is evaluated empirically (Rasmussen et al., 1994).

In all, it is quite important during the design process of interfaces to satisfy the three criteria described above. Not only should an interface possess necessary features, but it should also be understandable and usable by operators. In this thesis, only the first criterion, effectiveness, is assessed via an analytical comparison for the EID- and PCT-based CDU interfaces. Several constraints such as the availability of resources as well as time did not favour the evaluation of the other two criteria. Further work would be needed.

Analytical evaluations.

Analytic evaluations, as previously mentioned, are concerned with the effectiveness of an interface (degree to which an interface supports the achievement of design objectives) using a qualitative approach. As Vicente reports (1990, p. 260), "effectiveness is related to the determination of interface content and structure (i.e., semantics), not form (i.e., syntax)". Analytical evaluations aim at assessing the functionality of an interface as to whether or not it can encompass the necessary information needed for operators to do their tasks (Rouse, 1984; Rasmussen et al., 1994). Such an endeavour must be determined before understandability and compatibility (i.e., interface form: e.g., issues of colours, font used, digital vs. analog representation, influences of user's experiences, and preferences) are assessed (Vicente,

1990). In addition, Rouse (1984) claims that analytical evaluations are important and necessary to insure the development of a functional system. At this initial stage of the CDU design, the design requirements are then evaluated from an analytical point of view. It is noteworthy to mention that the scope of this thesis only involves looking at the evaluation of the functionality of the interfaces given the two different requirements analyses. It is also important to mention that a fundamental distinction exists between functionality and usability: functionality refers to what a product can do while usability refers to how the functionality is implemented. Insight can be gained as to the efficiency of the frameworks in yielding information supporting operator's tasks through the assessment of functionality.

Objectives of the CDU Evaluation for Effectiveness

Rubin (1988) reports that there can be two evaluative objectives one can assess when evaluating interfaces:

- Assessment of interface capabilities, and
- Assessment of the ability to diagnose problems with the interface.

The assessment of the interface capabilities involves the evaluation of the design with respect to the user's requirements while the diagnostic activities supported by the interface involve the "investigation (of) interaction failures" between the operator and the interface (Rubin, 1988, p. 137). The above two evaluative objectives were used for the interface evaluation of the CDU.

Analytical evaluation of the CDU. In order to pursue an analytical evaluation, multiple scenarios ranging from familiar to complex situations are needed (Rouse, 1984). For the CDU, ten tasks situations from a realistic mission scenario were used (the tasks can be found in Appendix III; Canadian Marconi Company, 1995b) to see if

the necessary information yielded by EID and PCT is sufficient and appropriate for task completion. The scenario contains radio tasks that need to be completed under different circumstances: radio exchanges under normal operations, under environmental disturbances[4], and under technical failures[5]. The ability or inability of each interface to support these different scenarios was examined, as well as the assistance provided in problem-solving. This allows the evaluation of the effectiveness of each interface for task completion.

The analytical evaluation technique that is performed in this thesis is the cognitive walkthrough which is a commonly used technique in the human-computer interaction literature. The next section describes what is involved with this technique, how it is performed, as well as its advantages and limitations.

Cognitive Walkthrough

The cognitive walkthrough is a method of evaluating interfaces analysing mental processes required of operators to undergo their tasks (Lewis & Wharton, 1997). It specifically examines the interface capabilities for effectiveness as opposed to the interface characteristics falling under understandability and compatibility issues (heuristic evaluations). Both types of evaluations are necessary within interface evaluation as one type can uncover problems that the other can miss and vice-versa. Moreover, walkthroughs encourage analysts to undergo detailed thinking of the procedures involved in the tasks and assess whether or not the interface can support their completion. Therefore, the main objective of the walkthrough is to provide feedback to designers for the identification of possible functionality problems and to suggest reasons for these problems. This evaluation technique allows the analyst to step

[4] These situations involve the effect of terrain features on the propagation of the radio waves.
[5] These situations involve the effect of technical failures on radio communications.

through the actions necessary for users to perform their tasks on the interface and allows the analyst to determine, at an early design stage, tasks which can or cannot be accommodated by the interface.

The cognitive walkthrough method has been seen as quite effective for the identification of problems (as it finds about 40% or more of them) and it is less effortful than user testing (Lewis & Warton, 1997). However, some limitations can be found with regards to this method. First, designers can act as evaluators of their interface. Even if it is thought that designers can effectively perform the evaluation because they would make better judgements in the analysis, the inability for them to see problems with their own design is more likely than if the evaluation was performed by a second party (Lewis & Wharton, 1997). Also, the walkthrough, being task-specific, is restricted by the tasks and scenarios chosen during the evaluation. Possible problems with the interface might be missed due to this fact. It is also recommended to perform walkthroughs with more than one evaluator, but the downfall is that such an activity would necessitate more resources which can be an important constraint when evaluating interfaces.

Procedures for the cognitive walkthrough. What is needed to perform a cognitive walkthrough is a detailed description of the interface, a task scenario, as well as explicit assumptions about the target population and context of use (Lewis & Warton, 1997; Dix et al., 1998). Then, four questions are to be addressed for the actions to be performed on the interface. For each question, the analyst is required to record possible problems with their rationale, reasons, and assumptions. The questions are the following:

- "Will the user be trying to achieve the right effect?" (Lewis & Wharton, 1997, p. 722). This question attempts to assess the operator's action at this

point of the interaction given their background and knowledge and whether they have the possibility of choosing the correct actions.

- "Will the user notice that the correct action is available?" (Lewis & Wharton, 1997, p. 722). As Lewis and Wharton (1997) claim, "users will not perform actions that they do not know they can do. Actions associated with obvious interface features like menus or buttons will not be problematic (...) but actions like double-clicking a part of the diagram that is not apparently a button may not be discovered" (Lewis & Wharton, 1997, pp. 722-723).
- "Will the user associate the correct action with the desired effect?" (Lewis & Wharton, 1997, p. 722). This question deals with the possibility for users to know that the controls and displays in question are the ones they are looking for to complete their task.
- "If the correct action is performed, will the user see that progress is being made?" (Lewis & Wharton, 1997, p. 722). Will users be aware that the correct action was performed?

Cognitive walkthrough of the EID and PCT Interfaces

The assumptions made for the evaluations are that the operators are familiar with the military communication standard operating procedures, have a good knowledge of the roles and functions of the CDU for communication management, and have had training on either the EID or PCT interface. With regards to the context of use, it is assumed that the CDU is used in order to perform secondary tasks (the flying task being the primary one).

Procedures. Ten task situations were taken from the mission scenario presented in Appendix III. Given that most of the tasks require the same actions (i.e., establishing a radio link) but have different radio parameters (i.e., using a different radio or a different frequency), the task situations presented in Appendix III are grouped under three main categories which are each evaluated:

i) simple communication tasks (task situations 1,3,4,5,7,8,9: refer to Appendix III),

ii) complex communication tasks involving environmental concerns (task situations 2 and 6), and

iii) complex communication tasks involving technical concerns (situation 10).

Cognitive walkthrough of the EID Interface

Simple communication tasks. For the EID interface, the particular actions necessary for the establishment of radio links are the ones presented below and each action from the operators results in a response from the CDU shown on the interface (as shown in the figures).

- Clicking on the frequency of choice using a trackball (a CDU response follows the action via the highlight of the selected frequency as a thick dashed line in the graph in viewport 3-b as shown in Figure 27).

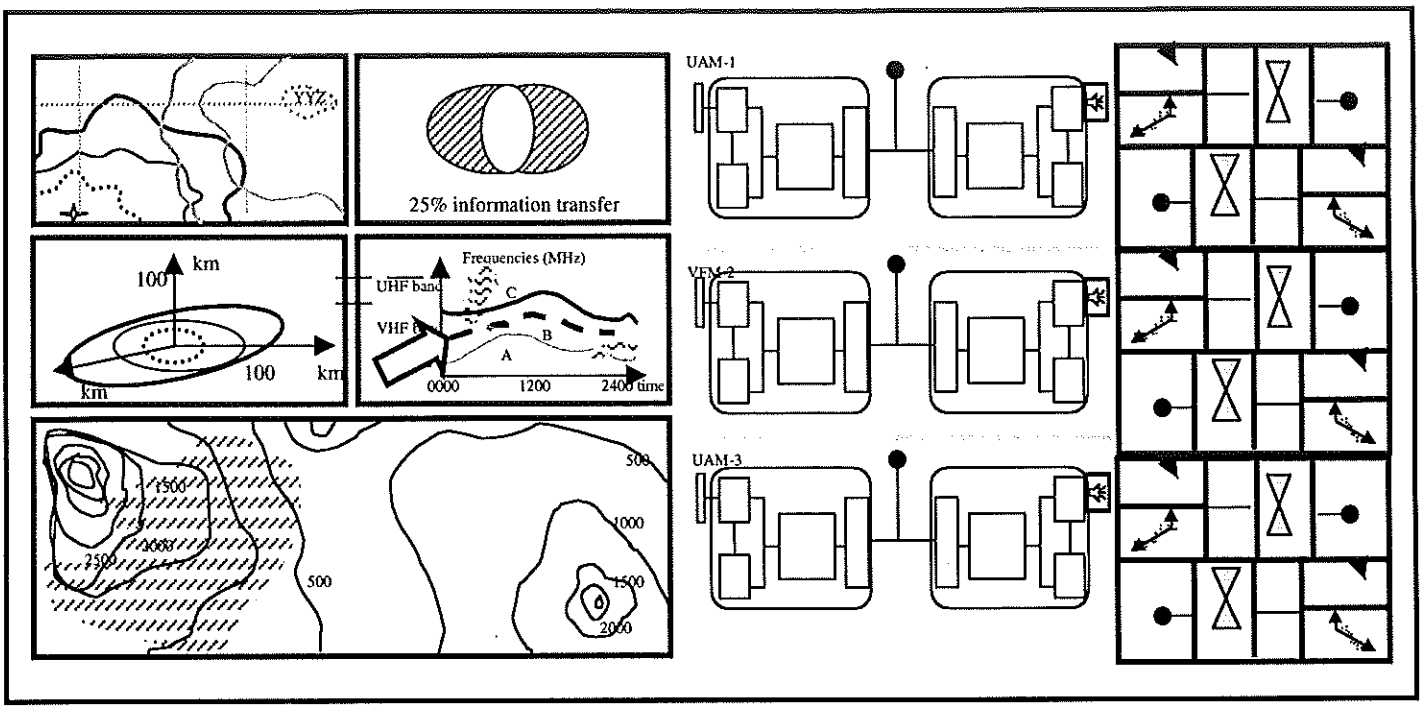


Figure 27. Response of the EID interface to the clicking of the frequency of choice in viewport 3-b. The trackball cursor is also displayed as the white arrow.

- Clicking on the "radiation" display (viewport 3-g) using the trackball (a CDU response can be shown on Figure 28 as the selection of the feature can be seen on the selected display by its highlight).

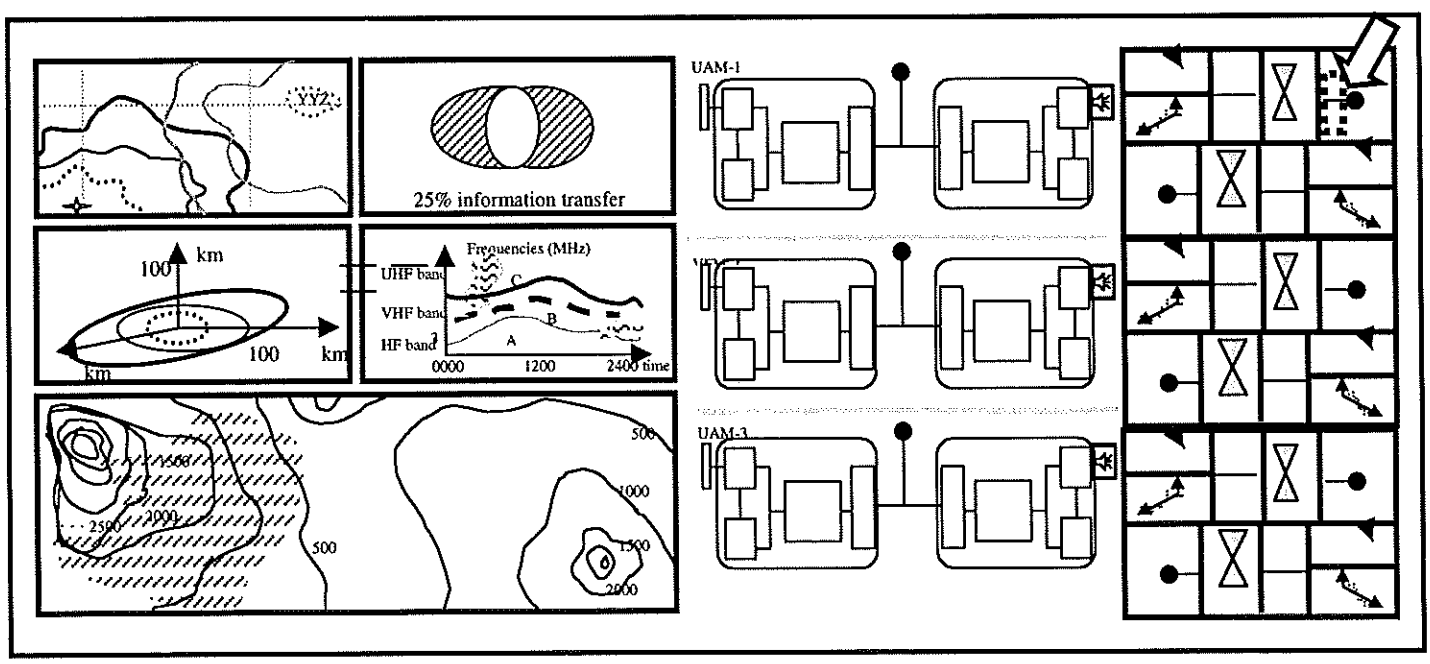


Figure 28. Response of the EID interface to the clicking of the "radiation" display in viewport 3-g. The trackball cursor is also shown as the white arrow.

- Engage in verbal communication (a CDU response can be seen through the activation of the corresponding functions of the radiophony level (e.g., signal transduction, frequency generation, interference reduction, modulation – viewports 3-c, 3-d, 3-e, and 3-f respectively as shown in Figure 29. Also, the activation of the radio components would be seen e.g., microphone, correcting network, oscillator, modulator, filters, and antenna).

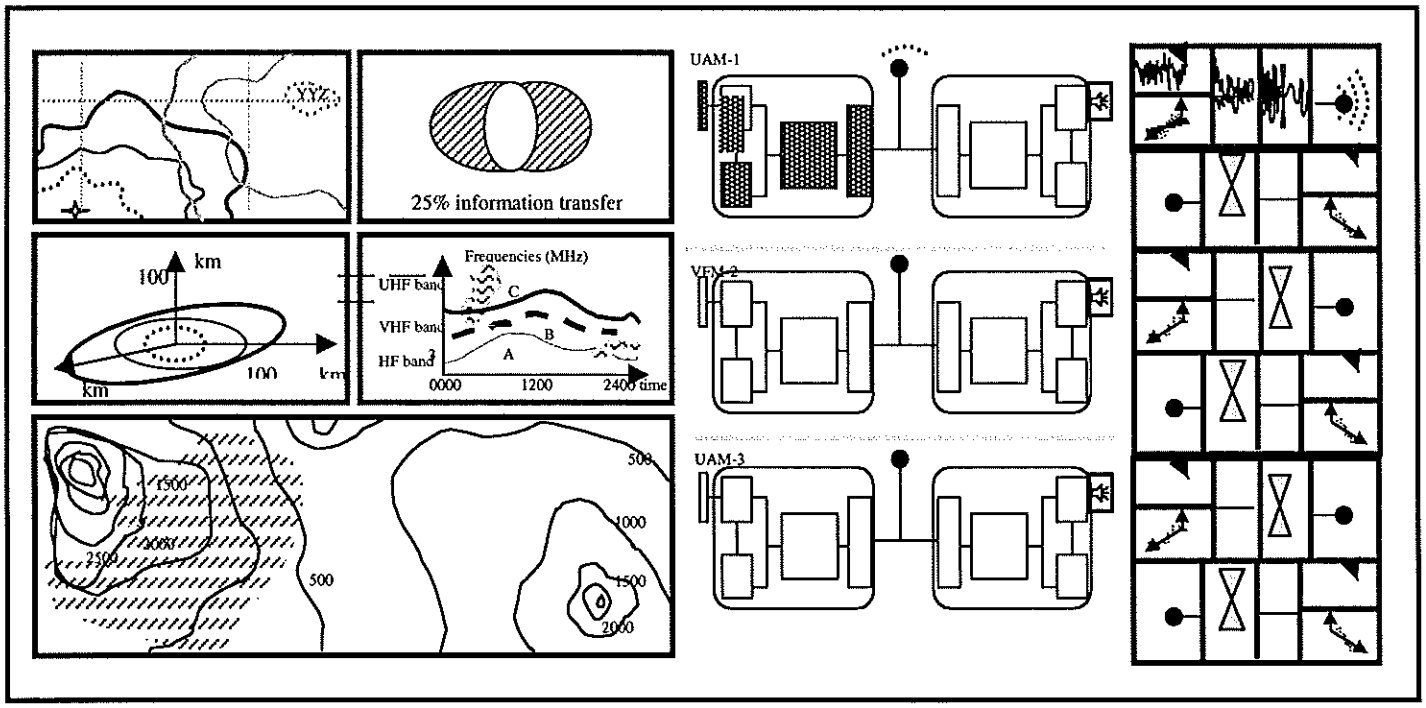


Figure 29. Response of the EID interface to message transmission.

- Reception of message acknowledgement (following the transmission of a message, the reception of a message by the originator would be shown on the display via the depiction of activity of the interference reduction, demodulation, frequency conversion, and signal transduction displays – viewports 3-h, 3-i, 3-j, and 3-c respectively (Figure 30). The radio parts would also be active, e.g., the antenna, filters, demodulator, correcting network, oscillator, and speaker).

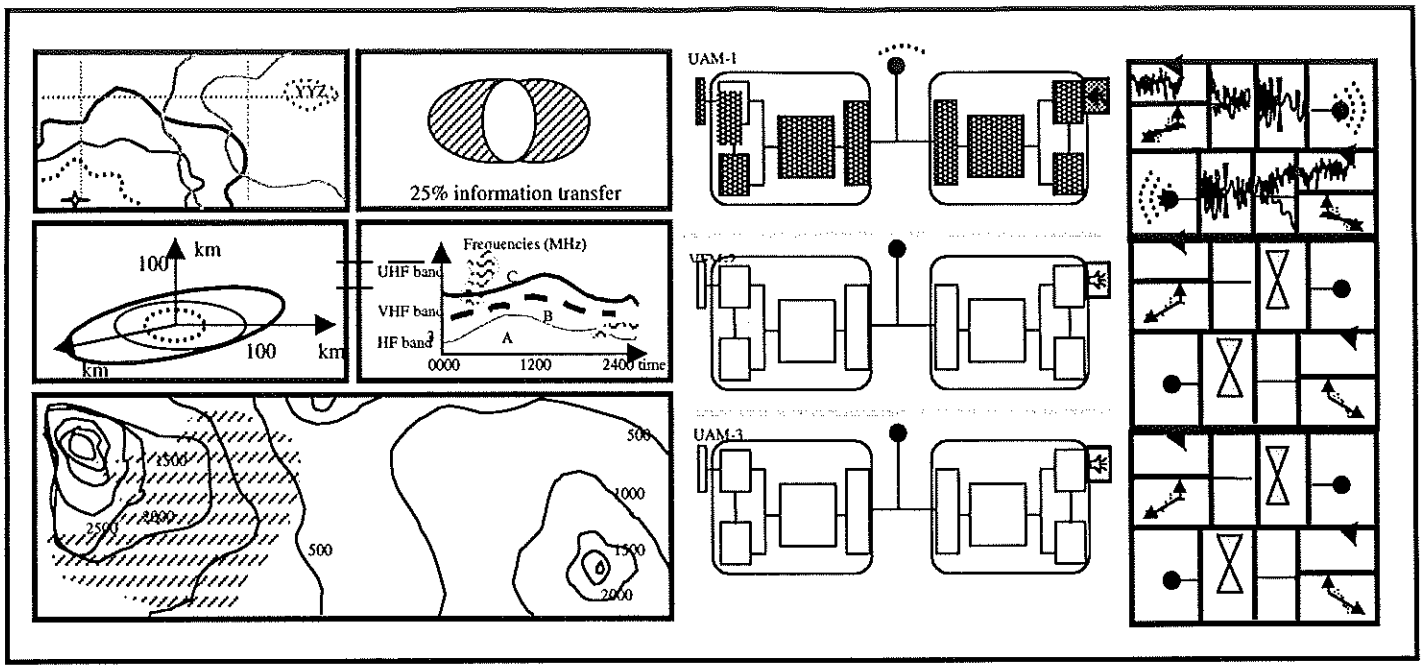


Figure 30. Response of the EID interface to message reception.

The four questions of the walkthrough as presented in Table 10 are now addressed for the EID interface.

Table 10. The four questions for the cognitive walkthrough analysis (Lewis & Wharton, 1997).

1. "Will the user be trying to achieve the right effect?"
2. "Will the user notice that the correct action is available?"
3. "Will the user associate the correct action with the desired effect?"
4. "If the correct action is performed, will the user see that progress is being made?"

1. For the EID interface, provided adequate training, and given that the control is explicit, it is likely that users try to achieve the right effect since they would know that the display would allow direct manipulation to occur and thereby allow them to select a radio frequency by means of the trackball.
2. The trackball is available and visible at all times on the device and the displays are as well.

3. The trackball is the only effector available for the EID interface. No other means of interacting with the display (such as touch screen or voice input, etc.) leads to a response from the device. Also, upon slightly turning the trackball, the moving cursor can be seen following the trackball trajectory as the nature of direct manipulation displays involves rapid feedback of the actions. However, not every element of the interface can be acted upon as some of them are constraints of the work domain no one can have control over, while others are variables of the domain. It is possible that only a thorough knowledge of the domain by the operator can, over time, lead to a better appreciation of what the constraints are as well as the variables of the domain for task completion.
4. Once the action is undertaken, a response from the CDU follows. It is reasonable to assume that the user would recognise it as successful completion of the action.

Complex communication tasks: environmental concerns. The particular actions necessary for the establishment of radio links are the same as for the simple communication tasks.

In the case where environmental problems affect successful communication, a particular note should be made for the EID interface. For the tasks involved in this category, the EID displays would show that the work domain would impede radio communication between the originator and recipient(s) because of environmental constraints (Figure 31 shows how the EID display would illustrate the work domain

parameters for the situation involved in task situation 2 assuming that mountainous features would be the culprit – see Appendix III).

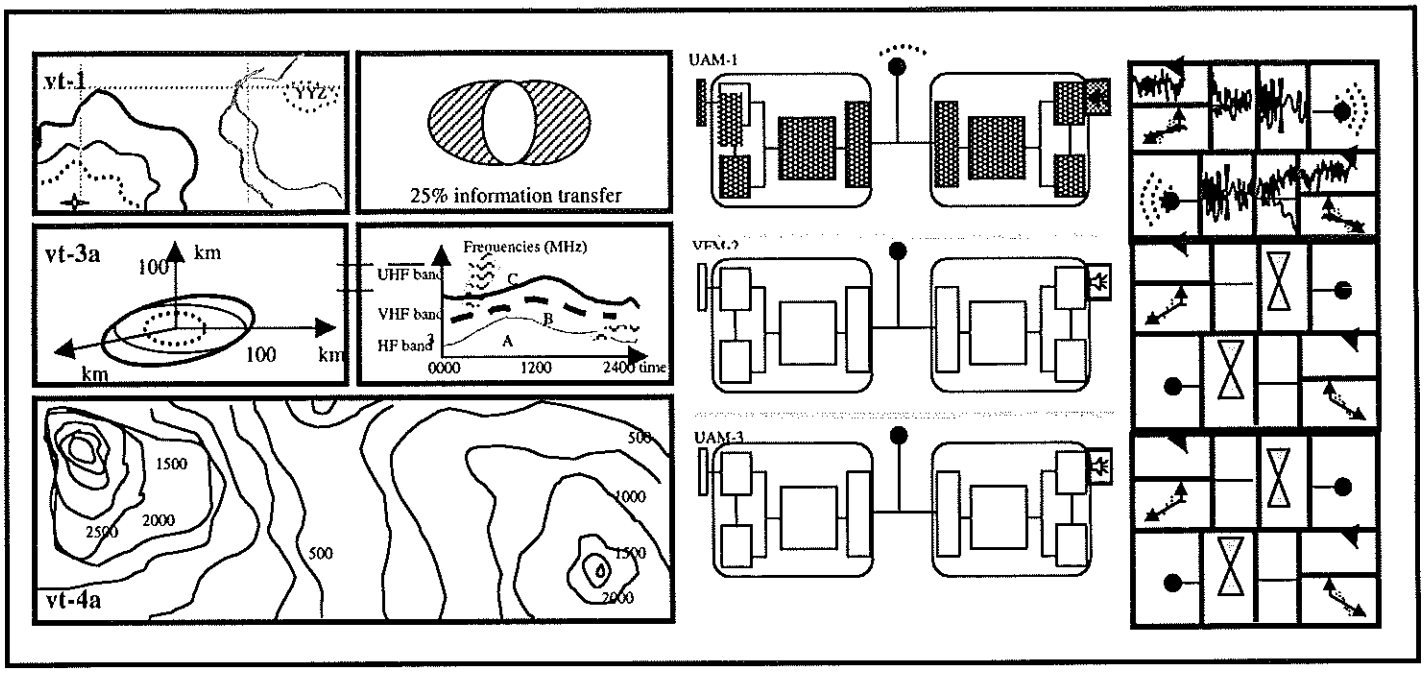


Figure 31. EID displays illustrating the work domain states for task situation 2 (Appendix III).

The purpose view (viewport 1 – "vt-1" in Figure 31) relays the inability for the parent aircraft to contact "YYZ" which is displayed by the fact that no sphere overlap exists between the parent aircraft (shown as the diamond object in "vt-1") and "YYZ". The range of communication is quite limited as shown by the closeness of the spheres in the attenuation view (viewport 3-a – "vt-3a" in Figure 31) and the region is seen as very mountainous in viewport 4-a ("vt-4a" in Figure 31) with the many topographic lines revealing the terrain elevation. The interface also shows that unsuccessful communication is not due to technical failures from the parent aircraft as its components and functions are satisfactory. It is therefore plausible to say that pilots would try to be within the range of successful

communication by changing their navigational position thereby satisfying their goal, given the domain's constraints and select an appropriate frequency. They would then have the necessary information to allow diagnostic activities in cases where communication is not possible. Therefore, if this were to be the case, the "complex task" can be treated as if it were a "simple task". Nonetheless, experimentation with users would be needed to validate the statement to see if in fact, pilots would undertake another frequency selection and change their position. However, the capability of the interface to display such a distinction is still a valuable information requirement by showing the global capabilities of the domain.

Complex communication tasks: technical concerns. Similarly to the above situation, the EID interface would display the global capabilities of the domain and show that some constraints of a technical nature may impede radio communication from the message originator to recipient(s). Also, technical problems originating from the aircraft could be detected by the highlighting of one of the radio's components and/or the inability of one of the processes (displays of viewports 3-c to 3-j) to occur. Their diagnosis, however, would not be possible given that the components are not further detailed. Also, if a technical failure were to be from another party, as task situation 10 demonstrates, the purpose view of that parent aircraft would show that the party in question would not be able to communicate since no spheres surrounding it would be present (see Figure 32). However, the parent aircraft would not be able to know what the problem is aside from detecting the technical nature of the disturbance in the work domain.

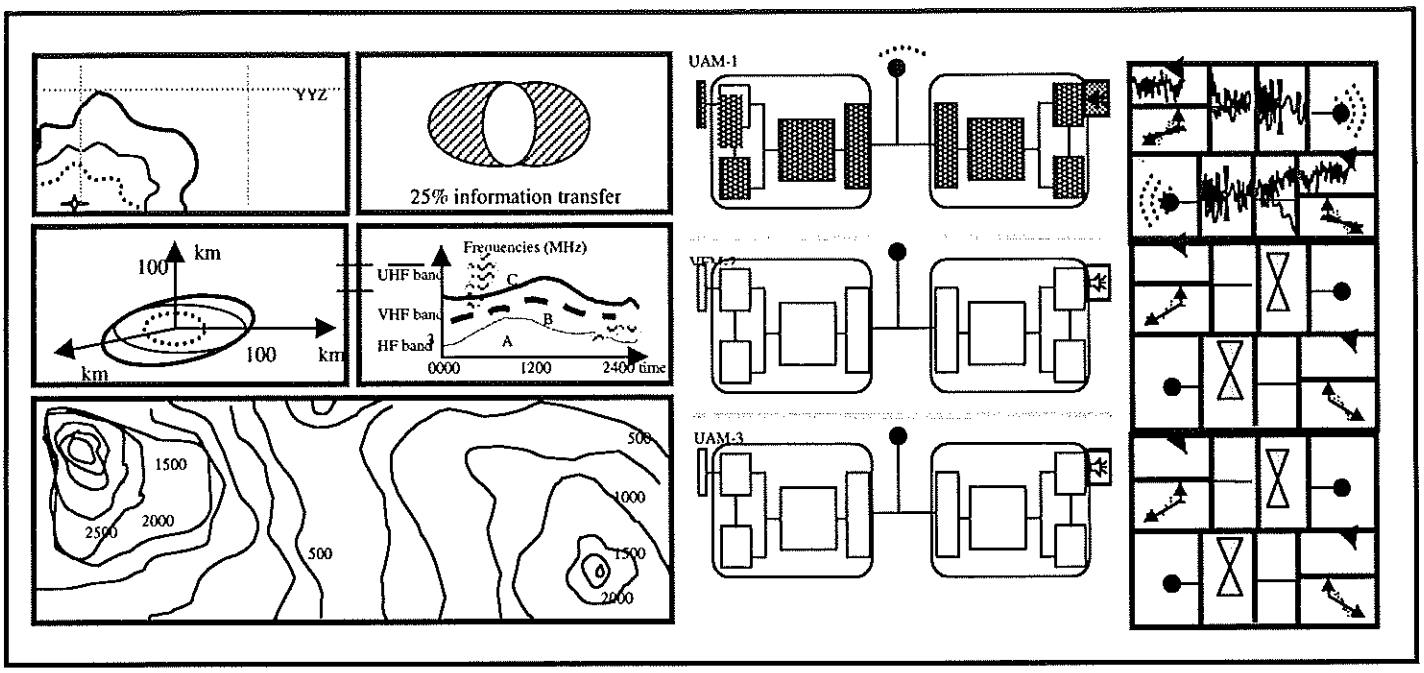


Figure 32. EID displays illustrating the work domain states for task situation 10 (Appendix III).

Cognitive walkthrough of the PCT interface

Simple communication tasks. For the PCT interface, the particular actions necessary for the establishment of radio links are listed below and each action from the uses results in a response from the CDU (the CDU response to every action is shown in the figures).

- Key press of the radio key (a CDU response following this action is illustrated in Figure 33. As shown in the figure, pressing the radio key leads to dashed line surrounding the radio field).

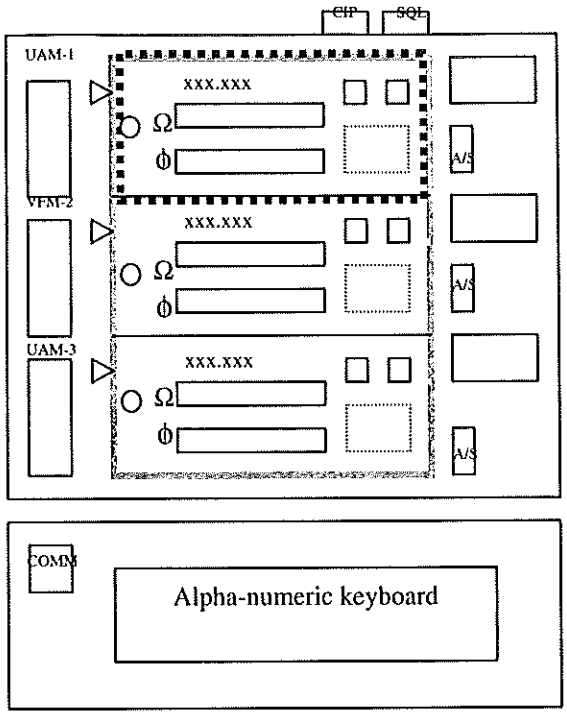


Figure 33. Response from the PCT interface following radio UAM-1 key press.

- Key press of the frequency key (a CDU response following this action is illustrated in Figure 34. The frequency field is also surrounded by a dashed line following the key press).

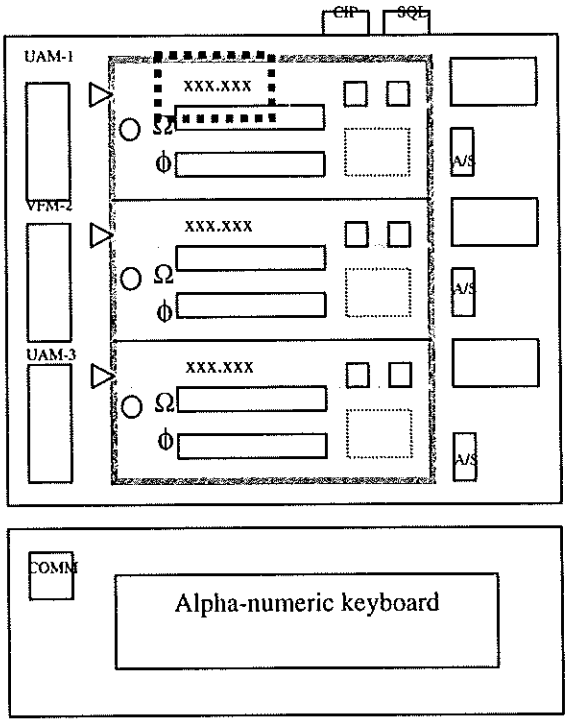


Figure 34. Response from the PCT interface following the frequency key press.

- Key press of the frequency numbers on the keyboard followed by the enter key (a CDU response following this action is illustrated in Figure 35. Pressing the alphanumeric keys leads to the inscription in the frequency field of the corresponding data).

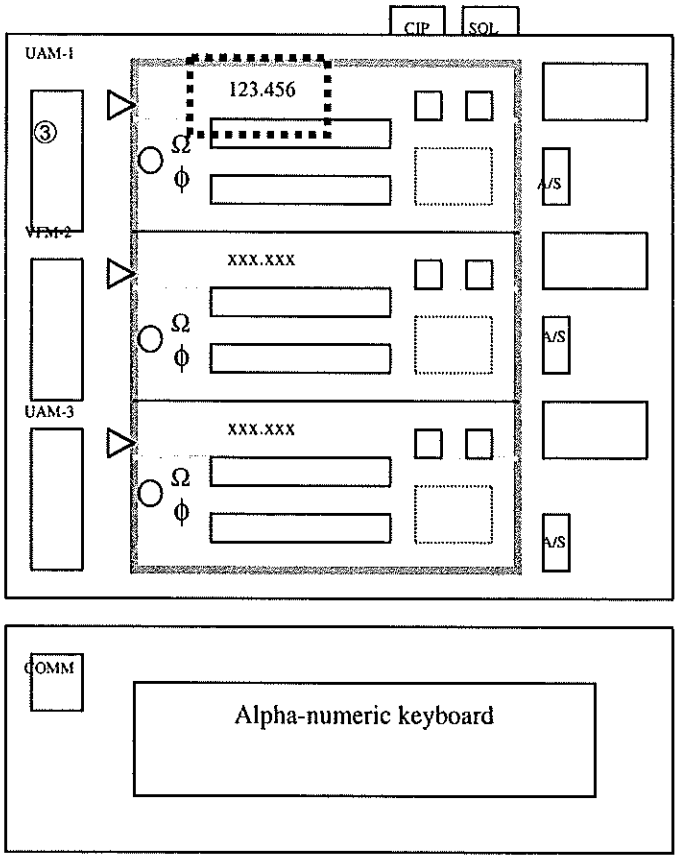


Figure 35. Response from the PCT interface following alphanumeric key entries.

- Key press of the active/stdby key (a CDU response following this action is illustrated in Figure 36. As illustrated, the response to this action leads to a solid green line surrounding the periphery of the radio field in question).

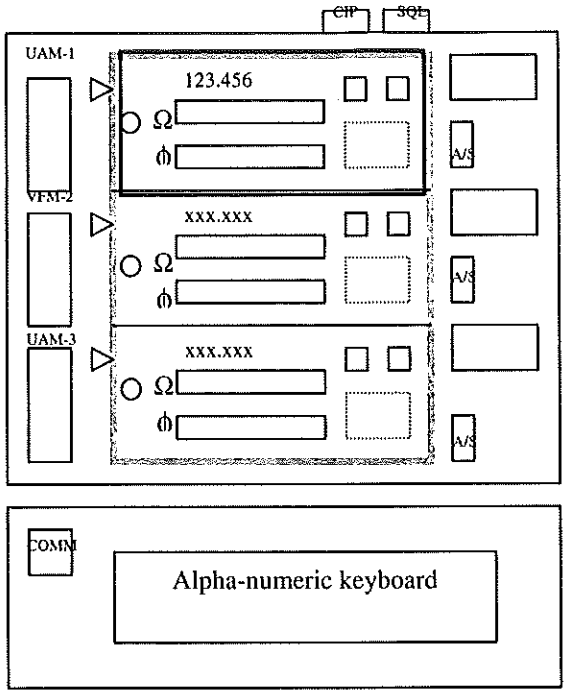


Figure 36. Response from the PCT interface following the A/S key press.

- Engage in verbal communication (a CDU response following this action is illustrated in Figure 37. Verbal communication from the originator leads to the transcription of the message in the textbox situated next to the active radio field on the interface as shown in Figure 37. Also, the status bars show the transmission and reception processes as channel clarity).
- Reception of message acknowledgement (a CDU response following this action is illustrated in Figure 38. The acknowledgement indicator located underneath the frequency field becomes activated once a message is acknowledged by the recipient.).

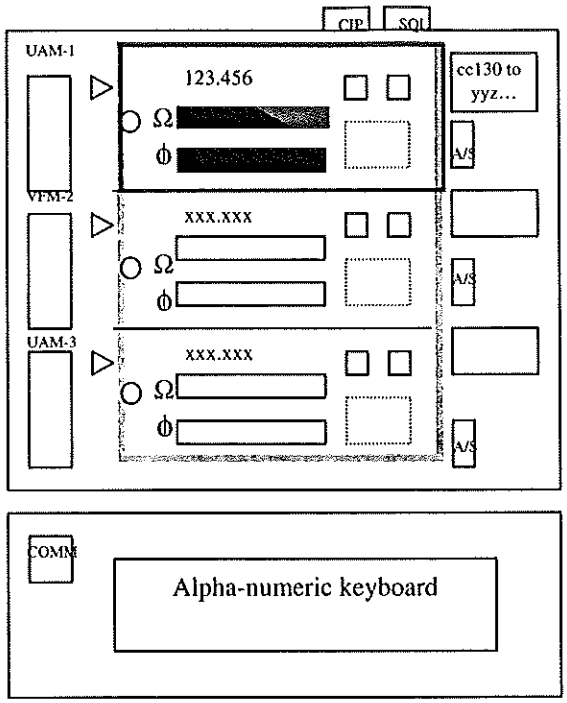


Figure 37. Response from the PCT interface following message transmission.

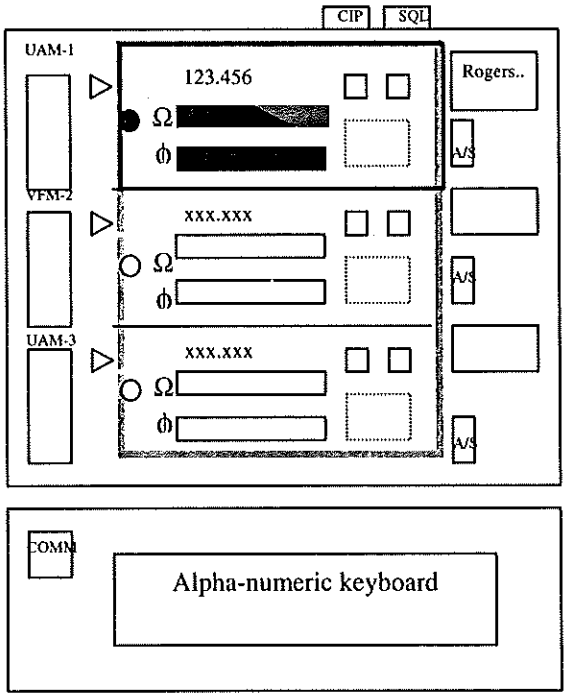


Figure 38. Response from the PCT interface following message acknowledgement by the recipient.

The four questions of the cognitive walkthrough (from Table 10) are now addressed.

1. For the task sequence using the PCT interface, given that the controls are made explicit and available on the interface at all times, it is more than likely that the users would be trying to achieve the right effect.

2. The radio, frequency controls, alphanumeric keys, active/standby key, and "enter" key are available and visible at all times on the device.

3. The frequency control is shaped pointing to the frequency field. The radio control spans the width of the radio field while the active/standby key is next to its display field. It is believed that the control/display proximity can easily show their relationship. Also, the radio controls have the radio type written on top of each key allowing anyone familiar with radio terminology (including CDU users) to identify that they are indeed radios. An identifying label on the active/standby key also allows users to identify the key function.

4. Once the action is undertaken, a response from the CDU follows. It is reasonable to assume that the user would recognise it as a successful completion of the action.

Complex communication tasks: environmental concerns. The particular actions necessary for the establishment of radio links are the same as the ones listed for the simple communication tasks. The only difference here is the response from the CDU interface for the last action that would be different, as Figure 39 shows. The acknowledgement indicator would remain inactive meaning that communication was either not received by the recipient or that communication from the recipient to the originator is not possible. However, the interface would not let the user know which of the circumstances apply nor why.

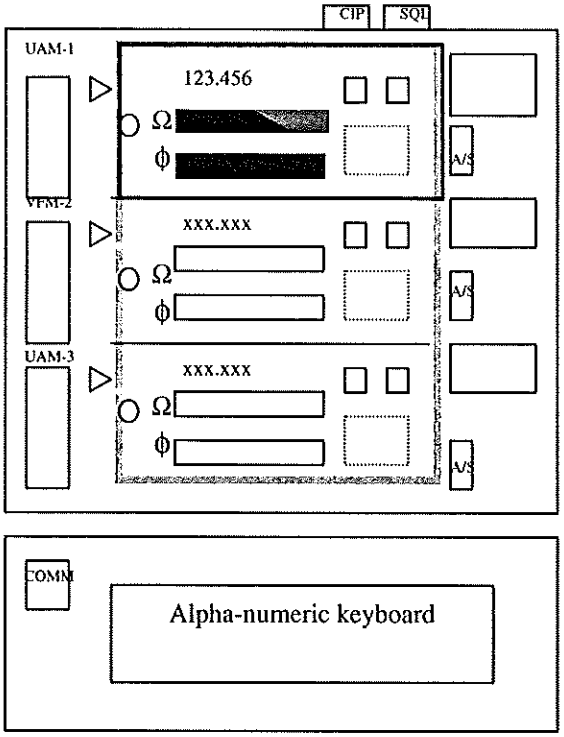


Figure 39. Response from the PCT interface in the case where communication is not received by the recipient or where communication from the recipient is not possible.

Complex communication tasks: technical concerns. Similarly to the above situation, the PCT interface provides feedback that the message was either not completely received by the recipient or that the message could not be received by the originator (Figure 39). Because they would receive the same feedback on the interface for the same circumstance, operators would not be able to discriminate between technical and/or environmental concerns impeding radio communications.

Results of the Cognitive Walkthrough Analyses

Table 11 summarises the findings of the walkthroughs for the EID and PCT interfaces and distinguishes between their support of tasks under normal and abnormal circumstances.

Table 11. Results of the capabilities of the EID- and PCT-based CDU interfaces as evaluated by the cognitive walkthrough analyses[6]

	Normal Situations	Abnormal Situations			
		Technical concerns		Environmental influences	
		Detection	Diagnosis	Detection	Diagnosis
EID-based CDU interface	√	√		√	√
PCT-based CDU interface	√	x		x	

EID-based CDU Interface. The walkthrough demonstrated that the EID-based CDU interface was able to provide support of the normal situations presented in the scenario for the establishment of radio links. It can also support the detection of problems in abnormal situations and allows the discrimination of the nature of the problem between technical and environmental concerns that were present in the mission scenario (task situations 2, 6, and 10 – Appendix III). However, the EID interface could not support the diagnosis of technical problems but could support the diagnosis of environmental concerns.

PCT-based CDU Interface. The walkthrough demonstrated that the PCT-based CDU interface was able to support the normal situations presented in the scenario for the establishment of radio links. It can also support the detection of the problems of a

[6] Legend for Table 11. The "√" symbol denotes that the interface supports the evaluative criterion. The "x" symbol denotes that the interface supports the detection of a problem but cannot allow distinguishing between the nature of the fault. Whenever the cell is left blank, the information requirements yielded by the framework do not support the user for the particular condition given the described scenario.

technical or environmental nature that were present in the mission scenario, but it does not allow for their discrimination. Consequently, the diagnosis of these problems remains unsupported by the interface.

Summary

Analytical evaluations are used for the assessment of interface effectiveness which is the evaluative criterion of interest in this thesis. The analytical evaluation technique used was the cognitive walkthrough which is a method for analysing operator's mental processes. It consists of four questions analysts need to answer and it provides designers feedback as to the interface capabilities in supporting the completion of a sequence of tasks.

A cognitive walkthrough was performed for the EID and PCT interfaces and the analyses showed that both interfaces allowed operators to complete the establishment of radio links. Also given the presented scenarios, the support of radio exchanges under normal circumstances, and the detection and diagnosis of technical and environmental concerns were assessed.

The analyses demonstrated that both interfaces allowed radio tasks accomplishment during normal and abnormal operations. However, the EID interface supported the detection of technical and environmental concerns as well as the diagnosis of problems of environmental nature only. The PCT interface was able to support the detection of technical and environmental problems but was unable to support their diagnosis.

DISCUSSION

The results are discussed with respect to the interface effectiveness during normal and abnormal situations. They are also reviewed against the expectations that were stated earlier in the thesis regarding frameworks falling within the realm of work domain- and task analyses techniques for EID and PCT, respectively. Finally, some implications for interface design are made and the thesis limitations are presented to then finish off with concluding remarks.

Interfaces Effectiveness

Normal Operations. The task situations describing normal operations were supported by both interfaces. For the EID interface, the normal conditions of the work space were made explicit on the displays; however, the displays and the control do not seem to intuitively prescribe the user particular types of action needed to be performed to establish a radio link as the PCT interface did. To reiterate, the interface presents the work domain but not the tasks themselves. Even though the assumption is that training would be provided, it could be difficult for operators to use the interface as is because the displays do not explicitly distinguish between the work domain's constraints and parameters that operators can manually control using the interface. The acquisition of knowledge of the work domain's functioning by operators might alleviate this concern.

The PCT interface seems to demonstrate easier procedures due to its user-friendliness and its compatibility with the current standard operating procedures. This is not surprising, given that the PCT paradigm is an approach that partly models tasks necessary to achieve operators' goals.

Abnormal Operations – Environmental Disturbances. The EID interface seems to support the detection and diagnosis of environmental disturbances well. It does so by

displaying the higher level constraints of the work domain which incorporate meteorological/terrain information. In this case, pilots can then readily obtain information as to the reason why certain frequencies might not reach the desired destination and therefore autonomously decide to communicate through another radio channel. Current procedures, when meteorological/terrain features impede successful radio communication, include the involvement of air traffic centers for the disclosure of other radio frequencies, allowing exchanges given the current conditions. This demonstrates that in fact the work domain is distributed and its different constraints levels are delegated to operators having different work functions (e.g., Air Traffic Controller (ATC) dealing with higher order properties of the work domain, while pilots deal with lower order properties, as shown in Figure 40). Cooperation between the ATC and pilots is necessary for the coordination of activities between the two parties leading to particular courses of action (use of other channels, traffic centers acting as radio relay, etc.). A display showing the entirety of the work domain to operators might then support this coordination of activity between air traffic controllers and CDU operators.

PCT's feedback instantiation in the interface conveyed the presence of a fault which is manifested by an unstable control loop (a non-zero perceptual error). It is not surprising to see the PCT-CDU's inability to support diagnostic activities since the framework emphasizes the actions, goals, and perceptions necessary to perform tasks and not on the constraints allowing these actions to occur. Thus, any broken constraints could not be shown either. It is current practice when abnormalities arise to follow emergency standard operating procedures (whenever they are available), or for operators to improvise a solution on-line or neglect the problem whenever the situation is not life-threatening. Other radios are used and depending on the nature of the

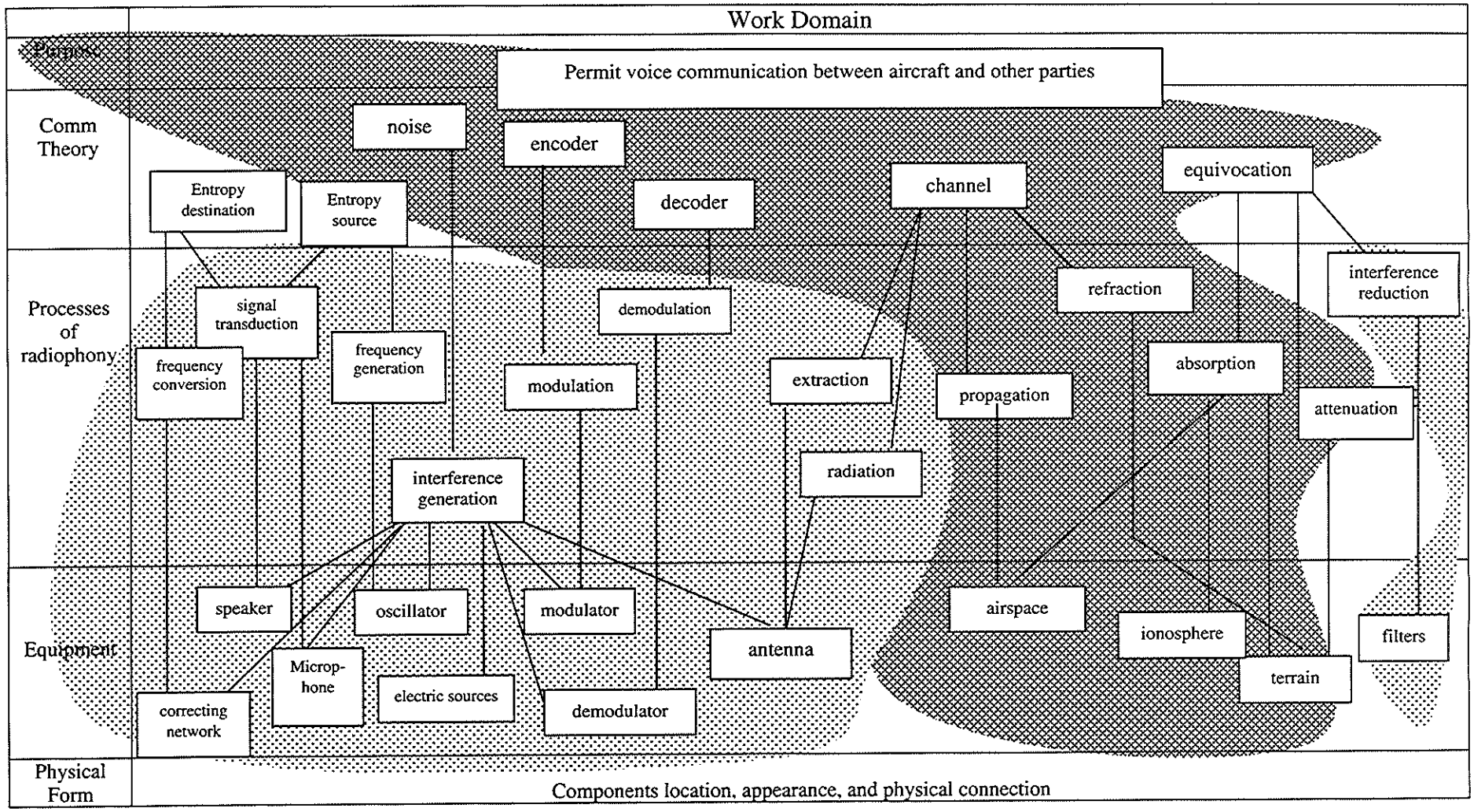


Figure 40. Depiction of the distribution of the work domain for radio communications. Air traffic controllers tasks currently involve the higher levels and functions shaded in the darker gray while operators deal with the lower levels and functions shaded in the lighter gray.

mission, emergency landings can be performed. Incorporating diagnostic related goals within the PCT analysis would, in principle, provide requirements supporting this type of activities. The PCT-based interface did not seem to support the diagnosis of meteorological disturbances with the interface. As can be seen on the interface, no higher-order information related to weather or physical influences on radio waves propagation is conveyed. Therefore, it is not possible for the interface to relay proper information to operators to support problem solving. Other resources would be necessary to infer the abnormality.

Abnormal Operations – Technical Concerns. Both interfaces supported the detection of technical problems although both did not seem to support any diagnostic activities with respect to the fault.

For EID, the presence of a fault is manifested by the changes in the representations of the different means-end views (recall that the different means-end views are different representations of the domain). The diagnosis of the problem might not be fully supported since the abstraction hierarchy modelled the communication work domain and not the CDU itself as a work domain. The ability to troubleshoot specific CDU problems remains unsupported, given that the CDU as a work domain was not analysed. The incorporation of the CDU as a work domain in conjunction with the radio communication space needs further exploration.

The PCT interface did not seem to support the diagnosis of technical failures for the same arguments presented for the environmental disturbances.

Theoretically-based Predictions Revisited

The findings of this thesis corroborate with the claims stated by Vicente (1999). Indeed, the EID-based information was able to accommodate scenarios including

unanticipated circumstances. However, as anticipated, the EID interface provided little procedural guidance with respect to task completion.

On the other hand, the PCT-based requirements provided that guidance for the performance of tasks; however, the interface could not adequately provide the necessary assistance for diagnostic activities during unanticipated circumstances.

Implications for Design

Ecological Interface Design. EID has important implications for the allocation of responsibilities among workers. The abstraction hierarchy representation led to the realisation that the radio communication domain is distributed among workers. In all, procedural changes would have to be addressed if the EID interface were to be implemented. As reported by Degani and Wiener (1998), successful management of flight operations requires compatibility between the procedures and the device itself. This implies that an EID interface requires a review of the procedures currently in place in the aviation community.

Moreover, the display of the work domain goes beyond communication and provides a global picture similarly to a navigation aid. It allows one to have knowledge of certain weather conditions affecting communication and discloses aircraft position information that can assist in flight planning. The idea of integrating the radio communication domain and the navigational work domain would be an interesting one to pursue.

The feasibility of the implementation of the EID interface to a cockpit needs to be extensively studied as several concerns are raised: space considerations, integration of EID information with other current cockpit displays, sensors availability, feasibility of the integration of data from different sources into a mobile aircraft, etc. EID requires

the measurement of several variables which can be sensed by various centers; however, their amalgamation to the aircraft could be more challenging, given the limited technology currently available in the cockpit. In the case of the radio communication domain, many variables need to be sensed. These variables can be parameters from remote locations which can be fixed or mobile and other variables are related to the aircraft subsystems. There needs to be a way for the aircraft to receive remote information since it may be highly unfeasible for an aircraft to perform such sensing independently. Digital data communication technology, which consists of a network allowing air-to-ground and ground-to-ground information transfer, can provide a way to mitigate that matter and solve the issues of gathering high level information from the radio domain in the cockpit. The difficulty of sensing parameters from different locations, to assess conditions of equipment distant from the aircraft, and to assess meteorological information could be alleviated by this growing technology.

Perceptual Control Theory. The PCT interface, on the other hand, being compatible with current standard operating practices, would seem to be easily implemented in the cockpit. Also, the addition of the new requirements would seem feasible; however, some research would need to directly address the matter.

Thesis limitations

Some limitations can be identified in this thesis. First, with respect to the evaluation of the interface, only one criterion was assessed, notably effectiveness. Issues of understandability and compatibility were beyond the scope of this project. However, their assessment is a necessity for a complete interface evaluation.

In the same line of thought, both frameworks' limitations can be found in their application in this thesis: EID, being work-domain centered, was not aimed at modelling attributes related to operators such as the tasks they perform, the possible strategies they use, and their competencies. The potential information identified by these attributes could lead to necessary and useful interface requirements. Moreover, EID interfaces are also susceptible to uncertain data in sensing the work domain's variables (Vicente & Rasmussen, 1992). Thus, the information relayed by the interface may be distorted by noise. Until better sensor technology becomes available, such a shortfall has to be kept in mind. Also, difficulties were experienced in gaining insights through discussion with radio engineers for the verification of the EID analysis. Nevertheless, various documents on the topic were gathered and converging statements from numerous sources were used as a basis for the accuracy of the EID analysis.

With regards to PCT, operator's behaviours, perceptions, and goals were described within a control theory template while no systematic description of the environment was prescribed. As demonstrated by EID, a thorough description of the environment (or work domain) can lead to useful interface requirements. Also, operators' goals which were unintentionally omitted cannot be accommodated by the interface, thereby limiting the interface capabilities.

CONCLUDING REMARKS

The research presented in this thesis showed that EID and PCT both have strengths and weaknesses as Vicente (1999) would predict: EID relays high order information useful in abnormal situations. The prevalence of these abnormalities in radio communication remains undocumented; however, the inability to use radio communication can be fatal. Also, the EID design poorly supports radio communication procedural execution and would necessitate training and a probable change in current standard operating procedures.

On the other hand, PCT does not aid in diagnosis although it leads to intuitive procedures and line of actions needing to be performed in normal situations. Nonetheless, prescribed actions for use in abnormal cases are not supported on the interface and pilots have to rely on experience, the use of emergency standard operating procedures whenever available, and air traffic centers to cope with such eventualities.

It would seem beneficial to integrate the EID- and PCT- based information requirements for the Griffon CDU interface (Miller & Vicente, 1998, in press, acclaim the benefits of integrating work domain- and task analysis techniques for interface design). This thesis showed that both frameworks bring their own distinctive set of design requirements necessary for effective performance in human-machine systems.

REFERENCES

Bourbon, W. T. (1990). On the accuracy and reliability of predictions by control-system theory. Perceptual and Motor Skills, 71(3.2), 1331-1338.

Bourbon, W. T. (1996). On the accuracy and reliability of predictions by Perceptual Control Theory: Five years later. The Psychological Record, 46(1), 39-47.

Brown, G. D. (1975). Flight guide radio. Melbourne, Australia: FTC Ltd.

Burns, C. M. (1998). The effects of spatial and temporal proximity of means-end information in ecological display design for an industrial simulation. Unpublished doctoral dissertation, University of Toronto, Toronto, ON.

Canadian Marconi Company. (1995a). Screen definition document for the canadian forces tactical transport helicopter Control/Display Unit (CDU) (Contract No. 826000. Document no. 147-A60331-005). Kanata, ON.

Canadian Marconi Company. (1995b). Human Engineering System Analysis Report (HESAR) of canadian forces search and rescue helicopter missions (DSS Contract No. W711-4-7221/01-XSE. Document no. 1000-1090). Kanata, ON.

Chery, S., and Vicente, K. J. (1999). Ecological interface design – applications. Manuscript submitted for publication.

Davies, K. (1965). Ionospheric radio propagation. Washington, DC: US Government Printing Office.

Degani, A., and Wiener, E. L. (1998). Procedures in complex systems: the airline cockpit. [On-line]. Updated 2 June 1998. June 10, 1999. http://olias.arc.nasa.gov/personnel/people/asaf_degani/Asaf_publ/Degani_Wiener.html.

Dinadis, N., and Vicente, K.J. (1999). Designing functional visualizations for aircraft systems status displays. The International Journal of Aviation Psychology, 9(3), 241-269. Submitted for publication.

Dix, A., Finlay, J., Abowd, G., and Beale, R. (Eds.). (1998). Human-computer interaction (2nd ed.). London, England: Prentice Hall.

Farrell, P. S. E., and Chery, S. (1998). PTA: Perceptual control theory based Task Analysis. In Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting (pp. 1314-1318). Santa Monica, CA: Human Factors and Ergonomics Society.

Fechet, J.E., Eddy, M.F., Lear, W., and Bloch, A. (1942). Radio in airmanship. New York, NY: National Aeronautics Council Inc.

Hajdukiewicz, J. R., Doyle, D. J., Milgram, P., Vicente, K. J., and Burns, C. M. (1998). A structured approach for patient monitoring in the operating room. In Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting (pp. 1038-1042). Santa Monica, CA: Human Factors and Ergonomics Society.

Henny, K. (Ed.). (1938). Principles of radio (3rd ed.). New York, NY: Wiley.

Howie, D. E. (1996). Shaping expertise through ecological interface design: strategies, metacognition, and individual differences. Unpublished master of applied science thesis, University of Toronto, Toronto, ON.

Hyde, J. P. (Ed.). (1990). Military air and space communications. Virginia: AFCEA International Press.

King, R., W., P., Mimno, H., R., and Wing, A. (1945). Transmission lines, antennas, and wave guides. New York, NY: McGraw Hill.

Lewis, C., and Warton, C. (1997). Cognitive walkthroughs. In M. G. Helander, T. K. Landauer, and P. V. Prabhu (Eds.), Handbook of human-computer interaction (2nd completed revised ed.) (pp. 717-732). Amsterdam, The Netherlands: Elsevier.

Marken, R.S. (1999). PERCOLATe: Perceptual Control Analysis of Tasks. Manuscript submitted for publication.

Marken, R. S. (1997). The nature of behavior: control as fact and theory. [On-line]. Last modified 27 June 1997. April 22, 1999. http://home.earthlink.net/~rmarken/Chapter1.html.

McRuer, D. T., and Jex, H. R. (1967). A review of quasi linear pilot models. IEEE Transactions on Human Factors in Electronics, HFE-S, 3, 231-249.

Menzel, D. H. (1948). Elementary manual of radio propagation. New York, NY: Prentice-Hall.

Miller, C.A., and Vicente, K.J. (in preparation). Task "versus" work domain analysis techniques: a comparative evaluation.

Miller, C.A., and Vicente, K.J. (1998). Towards an integration of task- and work domain analysis techniques for human-computer interface design. In Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting (pp. 340-344). Santa Monica, CA: Human Factors and Ergonomics Society.

Powers, W. T. (1973). Behavior: the control of perception. Chicago, IL: Aldine.

Powers, W. T. (1997). A brief introduction to perceptual control theory. [On-line]. Last modified 12 May 1997. April 22, 1999. http://www.frontier.net/~powers_w/whatpct.html.

Rasmussen, J. (1985). The role of hierarchical knowledge representation in decisionmaking and system management. IEEE Transactions on Systems, Man, and Cybernetics, SMC-15, 2, 234-243.

Rasmussen, J., Pejtersen, A. M., and Goodstein, L. P. (1994). Cognitive systems engineering. New York, NY: Wiley.

Ratcliffe, J. A. (1959). The magneto-ionic theory and its applications to the ionosphere. Cambridge University Press.

Ricci, J., and Schutzer, D. (1986). U.S. military communications. Maryland: Computer Science Press.

Rouse, W. B. (1984). Computer-generated display system guidelines: developing an evaluation plan (NP-3701, volume 2 Research Project 2184). Norcross: Search Technology Inc.

Rubin, J. (1994). Handbook of usability testing: how to plan, design, and conduct effective tests. New York, NY: Wiley.

Rubin, T. (1988). User interface design for computer systems. Chester, England: Ellis Horwood Ltd.

Shannon, C. E. (1949). The mathematical theory of communication. Urbana, IL: University of Illinois Press.

Shannon, C. E., and Weaver, W. (1964). The mathematical theory of communication. Urbana, IL: University of Illinois Press.

Sharp, T. D., and Helmicki, A. J. (1998). The application of the ecological interface design approach to neonatal intensive care medicine. In Proceedings of the Human Factors and Ergonomics Society 42th Annual Meeting (pp. 350-354). Santa Monica, CA: Human Factors and Ergonomics Society.

Sheperd, A. (1989). Analysis and training in information technology tasks. In D. Diaper (Ed.), Task analysis for human-computer interaction (pp. 15-55). England: Ellis Horwood Limited.

Stone, E. W. (1926). Elements of radio communication (3rd ed.). New York, NY: Van Nostrand Company.

Terman, F. E. (1947). Radio engineering (3rd ed.). New York, NY: McGraw Hill.

U.S. Department of Defense. (1996). Department of defense design criteria standards: human engineering (MIL-STD-1472E). Washington, DC.

Vicente, K. J. (1990). Ecological interface design as an analytical evaluation tool. In Proceeding of the Topical Meeting on Advances in Human Factors Research on Man-Computer Interactions: Nuclear and Beyond (pp. 259-265).

Vicente, K. J. and Rasmussen, J. (1990). The ecology of human-machine systems II: mediating "direct perception" in complex work domains. Ecological Psychology, 2 (3), 207-249.

Vicente, K. J. and Rasmussen, J. (1992). Ecological interface design: theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, SMC-22, 589-606.

Vicente, K. J. (1995). Ecological interface design: a research overview. Analysis, design, and evaluation of man-machine systems. (Postprint volume from the sixth IFAC/IFIP/IFORS/IEA symposium). Cambridge, MA: Pergamon.

Vicente, K. J. (1999). Cognitive work analysis: towards safe, productive, and healthy computer-based work. Mahwha, NJ: Erlbaum.

Xu, W. (1996). Externalizing a work domain structure on a hypertext interface using an abstraction hierarchy: supporting complex search tasks and problem-solving activities. Unpublished doctoral dissertation, Miami University, Oxford, OH.

APPENDIX 1. PCT-BASED ANALYSIS FOR RADIO COMMUNICATIONS.

Table 1

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e = 1 - p$	• listing of logic statements • determine behaviour values if $e = 0$ then $b = 0$ *i.e., do nothing* if $e = 1$ then $b = 1$ *i.e., exchange or monitor*	$b = \{o_1, o_2\}$ *output variables* o_1 = do comm exchanges o_2 = do monitoring activities *possible values* $o_1 \rightarrow 0$ or 1 $o_2 \rightarrow 0$ or 1	• ability to control communication reception • ability to control communication transmission	
Goal "To perceive that radio communications are maintained." $g = 1$					Environmental Variable(s) Inputs/outputs lower levels
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = s_1 \parallel s_2$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = comm. exchanges s_2 = comm. monitoring *possible values* $s_1 \rightarrow 0$ or 1 *i.e. no exchange or exchange* $s_2 \rightarrow 0$ or 1	• ability to display comm reception • ability to display comm transmission	

Table 1.1

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e = \{1\text{-}s_1, 1\text{-}s_2,\}$	• listing of logic statements • determine behaviour values if e={1,0} then b={1,0} *i.e., set radio link* if e={0,1} then b={0,1} *i.e., initiate communication* if e={1,1} then b={1,1} *i.e., set radio link and initiate* if e={0,0} then b={0,0} *i.e., do nothing*	$b = \{o_1, o_2\}$ *output variables* o_1 = set radio link o_2 = initiate communication *possible values* $o_1 \rightarrow 0$ or 1 $o_2 \rightarrow 0$ or 1	ability to control • establishment of radio link • transmitting/ receiving status	
Goal "To perceive that radio communications are being exchanged." g = {1,1}					Environmental Variable(s) Inputs/outputs lower levels
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1, s_2\}$ $p = s_1(1) = s_1 \oplus s_2$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = radio link s_2 = a message *possible values* $s_1 \rightarrow 0$ or 1 *i.e. no link or link* $s_2 \rightarrow 0$ or 1 *i.e. no message or message*	ability to display • radio link is/is not established • transmitting/ receiving status	

Table 1.2

Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls
$e = \{1\text{-}s_1, 1\text{-}s_2, 1\text{-}s_3\}$	• listing of logic statements • determine behaviour values if e={1,0,0} then b={1,0,0} *i.e., set radio link* if e={0,1,0} then b={0,1,0} *i.e.,listen for communication* if e={1,1,0} then b={1,1,0} *i.e., set radio and listen* if e={0,0,1} then b= {0,0,1} *i.e., monitor radio* etc.	$b = \{o_1, o_2, o_3\}$ *output variables* o_1 = set radio link o_2 = listen for communication o_3 = monitor *possible values* $o_1 \rightarrow 0$ or 1 $o_2 \rightarrow 0$ or 1 $o_3 \rightarrow 0$ or 1	ability to control • establishment of radio link • message content • monitoring activities

Goal	Environmental Variable(s)
"To perceive that communications are being monitored." g = {1,1,1}	Inputs/outputs lower levels and from the originator

Perception	Integration Processes	input/sensation	Interface Displays
$p = \{s_1, s_2\}$ $p = s_2(\mathbf{1}) = s1 \oplus s2 \oplus s3$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = radio link s_2 = a message *possible values* $s_1 \rightarrow 0$ or 1 *i.e. no link or link* $s_2 \rightarrow 0$ or 1 *i.e. no message or message* $s_3 \rightarrow 0$ or 1 *i.e., no monitoring or monitoring activities*	ability to display • radio link is/is not established • message content • monitoring activities

Table 1.1.1 (or 1.2.1)

Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls
$e=\{1-s_1, 1-s_2, 1-s_3, 1-s_4\}$	• listing of logic statements • determine behaviour values if e={0,0,0,0} then b={0,0,0,0} *i.e., do nothing* if e={1,0,0,0} then b={1,0,0,0} *i.e., set radio* if e={0,1,0,0} then b={0,1,0,0} *i.e., set frequency* if e={0,0,1,0} then b={0,0,1,0} *i.e., set security* if e={0,0,0,1} then b={0,0,0,1} *i.e., set link status* etc.	$b = \{o_1, o_2, o_3, o_4\}$ *output variables* o_1 = set desired radio # o_2 = set desired frequency o_3 = set desired security o_4 = set desired link status *possible values* $o_1 \rightarrow 0$ or 1 *i.e. null or set desired radio type* $o_2 \rightarrow 0$ or 1 $o_3 \rightarrow 0$ or 1 $o_4 \rightarrow 0$ or 1	ability to control • radio # • frequency • security settings • link status

Goal	Environmental Variable(s)
"To perceive that a specific radio link is established." $g = \{1,1,1,1\}$	Inputs/outputs lower levels

Perception	Integration Processes	input/sensation	Interface Displays
$p = \{s_1, s_2, s_3, s_4\}$ p= **(1.1 and 1.2)** $= s_1 \oplus s_2 \oplus s_3 \oplus s_4$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = radio type (UAM1, VFM-2, UAM-3) s_2 = frequency (operational radio frequencies) s_3 = security (on / off) s_4 = link status (active/standby) *possible values* $s_1 \rightarrow 0$ or 1 (not desired radio/desired) $s_2 \rightarrow 0$ or 1 $s_3 \rightarrow 0$ or 1 $s_4 \rightarrow 0$ or 1	ability to display • radio type • frequency • security settings • link status

Table 1.1.2 (or 1.2.2)

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e=\{1-s_1, 1-s_2\}$	• listing of logic statements • determine behaviour values • if e={1,0} then b={1,0} *i.e., set message content* if e={0,1} then b={0,1} *i.e., set message adequacy* if e={1,1} then b={1,1} *i.e., set message content and adequacy* if e={0,0} then b={0,0} *i.e., do nothing*	$b = \{o_1, o_2\}$ possible output values $o_1 \rightarrow 0$ or 1 null or set message content $o_2 \rightarrow 0$ or 1 null or understand the message	ability to control • message content • message adequacy	
Goal "To perceive that a message between communicating partners is adequately interpreted $g = \{1,1\}$					Environmental Variable(s) Inputs/outputs from the recipient
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1, s_2\}$ $p=s_2$**(1.1 and 1.2)** $= s_1 \oplus s_2$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = message content s_2 = message adequacy *possible values* $s_1 \rightarrow (0,1)$ i.e., no content, content $s_2 \rightarrow (0,1)$ i.e., no adequacy, adequacy	ability to display • message content • message adequacy	

Table 1.1.1.1 (or 1.2.2.1)

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e=\{1-s_1\}$	• listing of logic statements • determine behaviour values if $e = \{0\}$ then $b = \{0\}$ *i.e., do nothing* if $e = \{1\}$ then $b = \{1\}$ *i.e., set a desired radio*	$b = \{o_1\}$ *possible values* $o_1 \rightarrow 0$ or 1 null or set desired radio	ability to control • radio setting	
Goal "To perceive that a desired radio type is set." $g = \{1\}$					Environmental Variable(s) Inputs/outputs from the CDU
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1, s_2\}$ $p = s_1$ **(1.1.1 and 1.2.1)** $= s_1$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = radio type where the type can be UAM1. UAM3, VFM 2. *possible values* $s_1 \rightarrow 0$ or 1 *i.e., not desired radio or desired radio type*	ability to display • radio setting	

Table 1.1.1.2 (or 1.2.2.2)

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e=\{1-s_1\}$	• listing of logic statements • determine behaviour values if $e = \{0\}$ then $b = \{0\}$ *i.e., do nothing* if $e = \{1\}$ then $b = \{1\}$ *i.e., set a desired frequency*	$b = \{o_1, o_2\}$ *possible values* $o_1 \rightarrow 0$ or 1 null or set desired frequency	ability to control • frequency setting	
Goal					Environmental Variable(s)
"To perceive that a desired frequency is set." $g = \{1\}$					Inputs/outputs from the CDU
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1, s_2\}$ $p = s_1$ (**1.1.1 and 1.2.1**) $= s_1$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = frequency x where x is part of the set of operational radio communication frequencies *possible values* $s_1 \rightarrow 0$ or 1 *i.e. not desired frequency/desired frequency*	ability to display • frequency setting	

Table 1.1.1.3 (or 1.2.1.3)

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e=\{1-s_1\}$	• listing of logic statements • determine behaviour values if $e = \{0\}$ then $b = \{0\}$ *i.e., do nothing* if $e = \{1\}$ then $b = \{1\}$ *i.e., set desired security*	$b = \{o_1, o_2\}$ *output variables* o_1 = set desired security *possible values* $o_1 \rightarrow 0$ or 1	ability to control • security setting	
Goal					Environmental Variable(s)
"To perceive that the security is set to desired setting. $g = \{1\}$					Inputs/outputs from the CDU
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1\}$ $p = s_3$ (1.1.1 and 1.2.1) $= s_1$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = security setting (on or off) *possible values* $s_1 \rightarrow 0$ or 1 *i.e., not desired security state/set on desired security state*	ability to display • security setting	

Table 1.1.1.4 (or 1.2.1.4)

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e=\{1-s_1\}$	• listing of logic statements • determine behaviour values if $e = \{0\}$ then $b = \{0\}$ *i.e., do nothing* if $e = \{1\}$ then $b = \{1\}$ *i.e., set desired activation link status*	$b = \{o_1, o_2\}$ *output variables* o_1 = set desired activation link status *possible values* $o_1 \rightarrow 0$ or 1 $o_2 \rightarrow 0$ or 1	ability to control • link activation setting	
Goal "To perceive that the activation link status is set to desired setting. $g = \{1\}$					Environmental Variable(s) Inputs/outputs from the CDU
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1\}$ $p = s_4$ (**1.1.1 and 1.2.1**) $= s_1$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = link activation status (active or standby) *possible values* $s_1 \rightarrow 0$ or 1 *i.e. set on desired link status*	ability to display • link activation setting	

Table 1.1.2.1

Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls
$e = 1 - p$	• listing of logic statements • determine behaviour values if $e = \{0\}$ then $b = \{0\}$ *i.e., do nothing* if $e = 1$ then $b = 1$ *i.e., request for message repetition*	$b = o_1$ *output variables* *possible values* $o_1 \rightarrow 0$ or 1 null or request for message repetition	ability to control • repetition of message

Goal	Environmental Variable(s)
"To perceive that a message content is completely received by the recipient. $g = 1$	Inputs/outputs from the recipient

Perception	Integration Processes	input/sensation	Interface Displays
$p = s_1$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = message reception *possible values* $s_1 \rightarrow 0$ or 1 *i.e., no reception or reception*	ability to display • message reception by recipient

Table 1.1.2.2

	Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls	
	$e = \{1\text{-}s_1, 1\text{-}s_2\}$	• listing of logic statements • determine behaviour values if $e = \{0,0\}$ then $b = \{0,0\}$ *i.e., do nothing* if $e = \{1,y\}$ then $b = \{1,y\}$ *i.e., clarify message* *where* $y \rightarrow 0$ or 1 if $e = \{0,1\}$ then $b = \{0,1\}$ *i.e., request clarification*	$b = \{o_1, o_2\}$ *output variables* *possible values* $o_1 \rightarrow 0$ or 1 null or clarify message $o_2 \rightarrow 0$ or 1 null or request clarification	ability to control • message content	
Goal "To perceive that a message content is clearly understood by the recipient. $g = \{1,1\}$					Environmental Variable(s) Inputs/outputs from the recipient
	Perception	Integration Processes	input/sensation	Interface Displays	
	$p = \{s_1, s_2\}$ $p = s_2$ **(1.1.2)** $= s_1 \oplus s_2$	• identify input variable • determine input value • generate perception vector	*input variables* s_1 = message clarity s_2 = content understanding *possible values* $s_1 \rightarrow 0$ or 1 $s_2 \rightarrow 0$ or 1	ability to display • message content • understanding state of the recipient	

Table 1.1.2.2.1

Perceptual Error	Decision-Making Processes	output/behaviour	Interface Controls
$e = \{1 - s_1 \parallel 1 - s_2\}$	• listing of logic statements • determine behaviour values if $e = \{0,y\}$ then $b = \{0,0\}$ i.e., do nothing where $y \rightarrow]0, 1[$ if $e = \{1,0\}$ then $b = \{1,0\}$ i.e., select a clear channel if $e = \{1,1\}$, then $b = \{1,1\}$ i.e., select a clear channel and set squelch state	$b = \{o_1 \parallel o_2\}$ $o_1 \rightarrow 0$ or 1 null or select clear channel $o_2 \rightarrow 0$ or 1 null or set squelch	ability to control • selection of a clear channel • squelch state

Goal	Environmental Variable(s)
"To perceive that the radio communication channels are clear." $g = \{1,1\}$	Inputs/outputs from the CDU and the radio domain conditions

Perception	Integration Processes	Input/sensation	Interface Displays
$p = \{s_1 \parallel s_2\}$ $p = s_1$ **(1.1.2.2)** $= s_1 \parallel s_2$	• identify state variable • determine state value • generate perception vector	*state variables* s_1 = clarity of the channel s_2 = squelch state (on/off) *possible values* $s_1 \rightarrow [0, 1]$ *is a continuous variable going from no clarity to channel clarity* $s_2 \rightarrow 0, 1$ not desired squelch state/desired one	ability to display: • clarity of channel • squekh state

APPENDIX II. DEPARTMENT OF DEFENSE HUMAN ENGINEERING GUIDELINES FOLLOWED FOR THE DESIGN OF THE PCT CDU INTERFACE (U.S. DEPARTMENT OF DEFENSE, 1996).

5.1-- Control-display integration

5.1.1-- General Criteria

5.1.1.1-- Relationship: "The relationships of a control to its associated display and the display to the control shall be immediately apparent and unambiguous to the operator. A control should be located adjacent to (normally under or to the right of) its associated display and positioned so that neither the control nor the hand normally used for setting the control will obscure the display" (DoD design criteria standard -- human engineering (MIL-STD-1472E)).

5.1.1.2--Design: "Control-display relationships shall be apparent through proximity, similarity of groupings, coding, framing, labeling, and similar techniques"

5.1.2-- Position relationships

5.1.2.1-- Functional grouping: "Functionally related controls and displays shall be located close to each other and arranged in functional groups, e.g., power, status, test"

5.1.2.1.1--Functional group arrangement

5.1.2.1.1.1--Sequence: "Functional groups of controls and displays shall be located to provide for left-to-right (preferred) or top-to-bottom order of use, or both"

5.1.2.1.1.3-- Functional group marking: "Functional groups may be set apart by outlining with contrasting lines which completely encompass the groups. Where such coding is specified by the procuring activity, and where gray panels are used, noncritical functional groups (i.e., those not associated with emergency operations) shall be outlined with a 1.5 mm(1/'16 in) black border (27038 of FED-STD-595), and those involving emergency or extremely critical operations shall be outlined with a 5 mm (3/16 in) red border (21136 of FED-STD-595).(...)."

5.1.2.1.1.4--Consistency: "Location of recurring functional groups and individual items shall be similar from panel to panel. Mirror image arrangements shall not be used"

5.1.2.2-- Location and arrangement: "If an operator must use many controls and displays, they shall be located and arranged to aid in identifying the controls used with each display, the equipment component affected by each control, and the equipment component described by each display"

5.1.2.3-- Arrangement within groups: "Controls and displays within functional groups shall be located according to operational sequence or function or both"

5.1.2.3.6--Separate panels: "When related controls and displays must be located on separate panels and both panels are mounted at approximately the same angle relative to the operator, the control positions on one panel shall correspond to the associated display positions on the other panel. The two panels shall not be mounted facing each other."

5.2--Visual Displays

5.2.1.3.4-- Redundancy: "Redundant information shall not be displayed to a single operator unless it is required to achieve a specified reliability.

5.2.2.1.18-- Color Coding: "With the exception of aircrew station and training equipment applications, transilluminated displays shall conform to the following color coding scheme, in accordance with Type I - Aviation colors of MIL-C-25050. Light transmitted by the color filters should be visible through laser protective (or other) eyewear required to be worn by the user.

d) GREEN shall be used to indicate that the monitored equipment is in tolerance or a condition is satisfactory and that it is all right to proceed (e.g., "in-tolerance", "ready", "function activated").

5.2.6.9-- Electroluminescent displays

5.2.6.9.2-- Alphanumeric character and symbol sizes: Alphanumeric characters shall be upper case.

APPENDIX III. REALISTIC SCENARIO AND TEN TASK SITUATIONS USED FOR THE ANALYTICAL EVALUATIONS OF THE EID AND PCT BASED CDU INTERFACES

Realistic Scenario

Situation

The events described in this scenario take place along the east coast of Labrador. It is early fall of the year 2010 and the world strategic situation is generally one of peace and increasing wealth.

The Canadian Coast Guard vessel Sir Wilfred Grenfell is completing a routine actic patrol and is enroute back to St. Johns, Newfoundland. The current position of the vessel is 60°10'N 63°00'W, about 60 nautical miles off the East coast of Labrador, proceeding southeast at 12 knots. The weather is poor, with winds from the north at 10 knots gusting to 20 knots, a temperature of 3°C and drizzle reducing visibility as little as 1/8 mile in places. At the same time, an advanced technologies SAR helicopter prepares to take off from a fuel cache at Nain, Labrador for a flight to Kuujuaq, Labrador where the crew plans to spend the night before continuing their mission checking northern fuel caches. The weather at Nain is ceiling 300ft and visibility 1/2 mile, temperature is 0°C and the winds are out of the northeast at 10 knots. The weather at the intended destination has improved over the last hour to a ceiling of 3000 feet and 10 miles visibility, and is forecast to remain VMC for the next 12 hours before a new weather system arrives.

The time is 1800 hrs and the helicopter crew is eager to get airborne and on their way. There is a full crew complement of two pilots, a flight engineer (FE) and two SAR technicians (SAR technicians) onboard. The aircraft captain (AC) occupies the right seat.

As the radio operator aboard the Sir Wilfred Grenfell prepares for the upcoming shift change, she hears a distress call on an HF radio distress frequency. The transmission is from CF-BBI, a commercial passenger aircraft enroute from Iceland to Edmonton, Alberta. The aircraft, with 14 persons onboard, has lost one of its two engines and is unable to maintain altitude. Having been forced into a slow descent, the situation is now worsening because the aircraft has entered a layer of several icing. The pilot reports the aircraft position as 60°00'N 61°00'W. The radio operator notes the time of the distress call, marks the reported position on her chart and advises the captain of the ship. The captain attempts contact with the aircraft and is able to ascertain that the aircraft is now at 8000 feet and losing altitude steadily at about 300 feet per minute. The pilot has radar operating, and has decided his best course of action is to try and reach the nearest point on the coast of Labrador. At that point, if he is still unable to maintain altitude, he intends to ditch the aircraft in one of the inlets where water conditions will offer a better chance for survival. He advises the sir Wilfred Grenfell that he believes he can make it to a point near Whale Island, and the coat guard ship changes course to proceed to that position at maximum speed. The captain of the ship calculates that it will be five hours before he can be in the vicinity.

The sir Wilfred Grenfell contacts the Marine Rescue Sub-Center (MRSC) St. Johns and advises them of the situation. MRSC had monitored the call from BBI and is coordinating a response with the Rescue Coordinator Center (RCC). RCC is in the process of tasking the advanced technologies SAR helicopter, soon to be designated Rescue 57.

Mission

Rescue 57 is contacted shortly after departure from Nain, advised of the situation and tasked to proceed to the expected location of the CF-BBI at maximum speed in order to provide whatever assistance is necessary. HF and VHF frequencies are passed to rescue 57 and the pilot attempts to contact CF-BBI without success. He requests and receives clearance to climb to 10 000 feet and change course. Rescue 57 informs Air traffic control (ATC) of the tasking and advises that a revised flight plan will be passed shortly. ATC acknowledges and passes the latest weather for the search area. The AC passes control to the copilot and commences flight planning for the new task. The pilot designates a waypoint for steering on the onboard navigation system. The copilot turns toward the waypoint and continues climbing to the transit altitude of 10000 feet. The AC and crew confirm the serviceability of the search systems and continue to monitor for other traffic and weather. The copilot levels the helicopter at 10000 feet, sets the torque for maximum cruise speed, and maintains steering to the waypoint. The AC reports to ATC the flight level and position, and passes an estimate for the search area. He requests a flight plan revision, which is rapidly approved by ATC. He conducts the navigation

accuracy checks, noting and logging the GPS FOM and the ONS geometry and SNR. He selects voice communications and transmits his ETA for the search area to RCC via Halifax Military.

Periodically the AC attempts contact with CF-BBI and the Sir Wilfred Grenfell using both HF and VHF. The AC of rescue 57 calculates that they will be able to remain in the distress vicinity for only one hour and 30 minutes unless they can find a source of fuel closer than Kuujuaq. To refuel and return will be a three hour round trip. He enters the mission computer database to find fuel cache locations on the east coast of Labrador. He notes that there is a fuel cache at Saglek, close to their intended rendezvous. Ironically, the fuel cache is scheduled for its annual check by Rescue 57 the next day, and has not been reported on since the previous summer. The condition of this cache is therefore questionable. While the AC of rescue 57 is considering his options for refueling, RCC contacts Rescue 57 on HF and advises that the Sir Wilfred Greenfell has fuel and is equipped for Helicopter In Flight refueling (HFIR). The AC considers that the HFIR will maximise the time that the SAR helicopter can remain on scene and offers a better chance for success than the cache. He mentally decides that this will be the option he will pursue if necessary. He decided that he will retain sufficient fuel to proceed to the Saglek cache should the HFIR be unsuccessful, however. At 1840 hrs Rescue 57 is still unable to make contact with Sir Wilfred Grenfell. Halifax Military responds to Rescue 57 's call on HF to the Greenfell and offers assistance as a radio relay. Rescue 57 asks

Halifax Military to relay a request to SIr Wilfred Grenfell for a HFIR at approximately 2020hrs. At this point, all stations hear a call from BBI loud and clear over the HF radio. BBI states that they have identified an inlet directly ahead of them on radar at range of 6 miles. They are at 500 feet and still unable to maintain altitude, and are setting up to ditch as close as the north side of the inlet as possible.

Crew composition/Assumed air vehicle

Transit

1837 RCC advises Rescue 57 that te Sir Wilfred Grenfell is HFIR capable.

1840 Rescue 57 is unable to contact the Sir Wilfred Grenfell on HF. The AC receives contact from Halifax Military, and asks them to relay to Sir Wilfred Grenfell a request for a HFIR at 2020 hrs local. He advises that they require approximately 2500 pounds of jet fuel.

1841 BBI transmits intentions to ditch in inlet ahead, and gives position report of 59°23'N 63°25'W.

1850 RCC contacts rescue 57 to advise that the CG ship will be ready to HFIR at 2020 hrs, and will be monitoring VHF-FM Ch 16 for control and VHF-AM 123.1 MHz for safety. RCC also advises that the CG ship will be broadcasting NDB frequency 410KHz with the ident letter 'J' to assist in identification and navigation.

1855 The AC and Lead SAR tech conduct their respective pre-search briefings discussing the situations and possible courses of action on arrival at the scene. The AC

anticipates that lacking further updates to the situation, the plan will be to descend on arrival and conduct search of the closest inlet to the last reported position of BBI, favouring the northwest shore, and recording video information of all search sensors. If a crash site is found on that pass, he expects to have just enough fuel to land and drop off the SAR technicians, or hoist them down if no landing spot is available. He advises that the SAR technicians should take survival gear for a possible extended stay. If no crash site is found on the first pass, he advises that the helicopter will immediately depart for the CG vessel and attempt a HFIR. If the HFIR is unsuccessful. the helicopter will have to depart the scene to the Saglek fuel cache. The AC tells the cabin crew that he wants them to review the search sensor videos during the transit to the CG vessel to see if they can detect any signs of the distress aircraft. As always, he explains that the mission may not go as predicted and all crewmembers should be prepared for on-the-spot changes to the plans if required.

1910 As rescue 57 transits the last 50 NM to the distress location the crew continues electronic search procedures, including maintaining a listening watch on all distress frequencies. The aircraft continues to conduct regular fuel checks, and requests the latest weather forecast for the search area from ATC, and further information about the distress aircraft form RCC.

Initial Search

1928 As rescue 57 approaches on scene the predescent checks are completed and the AFCS is programmed for the automatic descent to terrain following altitude at 500 feet. No ELT or radio contact has been received. The AC provides a SITREP to RCC via Halifax Military. RCC advises rescue 57 to pass further reports to Sir Wilfred Grenfell. The radar is painting a contact approximately 40 NM north east which is confirmed by IFF squawk to be the Sir Wilfred Grenfell. Radio contact is made with the Sir WG on channel 19, and a radio check completed on 123.1 MHz. The HFIR arrangements are confirmed. The AC of Rescue 57 examines the map display and observes a number of inlets in the immediate vicinity. Two of them appear to be the most likely candidates based on their positions relative to the last GPS fix passed by BBI. The AC selects the most northernly and begins a descent to enter the inlet at the south western end to commence the search. All sensors are confirmed ready and recording modes selected. The sensor displays located in the cabin provide the cabin crew with means to conduct an effective aided visual search. The cockpit sensor displays provide the pilots with a clear daylight view of a sector ahead of the aircraft. The aircraft enters the inlet at 60knts groundspeed. The terrain following radar maintains a comforting silence.

Task situations

Ten communication tasks can be seen within this search and rescue scenario and are used for the evaluation of the interfaces. The situation is described from the mission scenario and the corresponding communication tasks are specified below.

1. Situation: "Rescue 57 is contacted shortly after departure from Nain, advised of the situation and tasked to proceed to the expected location of the CF-BBI at maximum speed in order to provide whatever assistance is necessary."

   Task: The pilot of Rescue 57 receives a message from the Rescue Coordinating Center (RCC) and exchanges on HF 123.55 mHz.

2. Situation: "HF and VHF frequencies are passed to Rescue 57 and the pilot attempts to contact CF-BBI without success."

   Task . Rescue 57 was assigned to communicate on 123.25 (HF) and 234.65 (VHF) with CF-BBI. As the excerpt shows, communication was unsuccessful; nowhere in the mission scenario is there mention of the reason why. Several hypotheses can be formulated.

- The region between Nain and the crash site is separated by a very mountainous area which could possibly affect the trajectory of the radio waves. The Torngat Mountains chain is at this location where terrain elevation goes from 1850 feet to 5320 feet above sea level - a topographic map of the area is provided (Department of Energy, Mines, and Resources, 1974). The terrain can lead to the refraction of radio waves in different directions (depending on the angle of incidence of the waves and the direction of the plane of the surface) with HF frequencies. This situation could have redirected the wave in an undesirable direction.

- The VHF frequency communication could be unsuccessful because of the receiver of CF-BBI being below the Rescue 57's line-of-sight. This would render communication between the two parties impossible on such frequency.
- There could be technical problems with CF-BBI's VHF receivers enabling the radios to receive frequencies on these bands. (The scenario later shows the successful reception by CF-BBI's HF radio; this is why technical problems with the HF receiver are ruled out).

It would be a plausible statement to say that one of the first two hypotheses are applicable in this case since the pilot is assigned to change the path of the aircraft as well as increase the altitude. This allows the receiver of CF-BBI to be within line-of-sight and prevents the elevated terrain to bounce the waves in undesirable paths.

3. Situation: "(the pilot) requests and receives clearance to climb to 10 000 feet and change course. Rescue 57 informs Air traffic control (ATC) of the tasking".

   Task . Rescue 57 communicates with the air traffic controller at frequency 123.45.

4. Situation: "The AC reports to ATC the flight level and position, and passes an estimate for the search area".

   Task . Rescue 57 communicates with the air traffic controller at frequency 123.7.

5. Situation: "He selects voice communications and transmits his ETA[1] for the search area to RCC via Halifax Military."

   Task . Rescue 57 communicates with RCC with frequency 123.75.

6. Situation: "Periodically the AC attempts contact with CF-BBI and the Sir Wilfred Grenfell using both HF and VHF."

   Task . Rescue 57 sends radio transmission to CF-BBI on HF 123.55 and VHF 234.56, and to SWG on HF 123.56. Inability to successfully transmit radio messages in similar to the reasons presented above.

7. Situation: "While the AC of rescue 57 is considering his options for refueling, RCC contacts Rescue 57 on HF and advises that the Sir Wilfred Greenfell has fuel and is equipped for Helicopter In Flight Refueling (HFIR)."

   Task . Rescue 57 is receiving communication from RCC on HF frequency 123.45.

8. Situation: "Halifax Military responds to Rescue 57 's call on HF to the Greenfell and offers assistance as a radio relay. Rescue 57 asks Halifax Military to relay a request to Sir Wilfred Greenfell for a HFIR at approximately 2020hrs."

   Task . The inability of Rescue 57 to get in touch with SWG compels Halifax Military to become an intermediary in the communication between the two parties. Rescue 57 is communicating with Halifax Military on HF frequency 123.6

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[1]Estimated Time of Arrival.

9. Situation: "At this point, all stations hear a call from BBI loud and clear over the HF radio."

   Task . Rescue 57 receives communication on HF frequency 123.1.

10. Situation: "Rescue 57 transmits the helicopter's ETA of 1930 hrs for the area to BBI, but there is no response".

   Task . Rescue 57 transmits to BBI on HF frequency 123.5 unsuccessfully. A plausible explanation is a technical problem with BBI's HF radio; as the scenario mentions, transmission from there part ceased while the aircraft was 500feet above ground and unable to maintain altitude. Inability to be within line-of-sight or to redirect HF waves to a point where no communication is possible would seem very unlikely since Rescue 57 was in the vicinity of the crash site (as per the map).

References

Canada. Survey and Mapping Branch. – Ottawa: Ontario, Quebec. – 6th ed. -Ottawa: The Branch, © 1974. – 1 map. – scale 1:500 000. – Hebron-Cape Territok. – N.T.S., No. 14 N.W.

Canada. Survey and Mapping Branch. – Ottawa: Ontario, Quebec. – 7th ed. -Ottawa: The Branch, © 1974. – 1 map. – scale 1:500 000. – George River. – N.T.S., No. 24 N.E.

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