7 Analyzing the Cognitive System From a Perceptual Control Theory Point Of View

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ABSTRACT

The starting point for the design of any complex system should be analysis. For systems where human functions are predominantly "cognitive," the method of analysis should capture this essentially human activity. Traditionally human engineering analyses have been based on a hierarchical decomposition of system missions, functions and tasks. Perceptual Control Theory (PCT) provides a theoretical framework for guiding this process. PCT reorients the approach from a serial function analysis, function allocation, task analysis process, to a hierarchical goal analysis. The hierarchical goal analysis combines the previously separate processes into one. With PCT it is inescapable that goals at all levels are candidates for assignment to an agent (human or machine).

Two new analyses emerge from the PCT framework. The first, a stability analysis, looks to see if certain external variables can be simultaneously under multiple control. If conflicting goals or incompatible internal perceptual, cognitive, or machine functions, could cause these multiple control situations to be unstable, then the designer has to find a way to separate control or otherwise ensure stability. The second analysis looks at the upward flow of information in the system. Each goal is examined to see how information existing at the

subgoal level flows up to the level above. Both analyses potentially identify new goals that must be accommodated by interface design.

7.1 INTRODUCTION

A closed, negative loop gain, feedback system is an error-correcting system. The inverse of this proposition is that all error-correcting systems can be reduced to a closed-loop, negative-gain, feedback system. If these propositions are true, and the human is seen as exhibiting error-correcting behavior, then William T. Powers' claim that all human behavior occurs as a result of a perceptually driven, goal-referenced, feedback system (Powers, 1973b), should come as no surprise. This is the tenet of Perceptual Control Theory or PCT. At best, PCT provides a veridical explanation of how humans form and emit behaviors; at the very worst, PCT is a normative model of human behavior.

The PCT model suggests a multilayered system, with multiple goals providing the reference points for a hierarchical organization of control loops. These loops provide control at many levels—from the lowest levels of sensory processing, upward to the satisfaction of abstract goals such as the need for self-esteem and actualization. In PCT terms, an emitted action or behavior is in response to the presence of an error, or difference, signal. The emitted action is transmitted purposefully, with the intention of changing the state of the world so that the operator's perception can be made to match a desired state or goal, which reduces the error signal to zero. It is a fundamental thesis of PCT that it is the perception that is controlled, not the behavior.

The starting point for the design of any complex system should be analysis. For systems where human functions are predominantly "cognitive," the method of analysis should capture this essentially human activity. Traditionally human engineering analyses have been based on a hierarchical decomposition of system missions, functions, and tasks analysis (MIL–HDBK–46855A, 1999). A method is proposed in this paper, based on PCT, for conducting this type of HFE analysis. PCT provides a theoretical framework for guiding this process, and reorientates the approach from a serial process of function analysis, function allocation, task analysis, to a unified process of hierarchical goal analysis. The hierarchical goal analysis combines the previously separate processes into one. With PCT the fact that goals at all levels are candidates for assignment to an animate or inanimate agent, is inescapable. Two emergent properties have been identified with PCT:

- The need to consider stability in multiagent systems, and
- The need to consider both the upward and downward flow of information in the system.

It is important to understand the context within which the proposed method is intended to function. A PCT-based analysis is intended to serve front-end Human Factors Engineering (HFE) analysis requirements, as outlined in documents such as MIL–HDBK–46855A (1999) or in IEEE–1220 (1994). The output of this process feeds the specification of human systems design requirements that must encompass each of the domains specified by the U.S. DoD for human systems integration in their Department of Defense (DoD, 1991). These domains are as follows:

- **Manpower:** The number of military and civilian personnel required and potentially available to operate, maintain, sustain, and provide training for systems.
- **Personnel:** The cognitive and physical capabilities required to be able to train for, operate, maintain, and sustain materiel and information systems.
- **Training**: The instruction or education, and on-the-job or unit training required to provide personnel their essential job skills, knowledge, and attitudes.
- **Human Factors Engineering:** The integration of human characteristics into system definition, design, development, and evaluation to optimize human-machine performance under operational conditions.
- **System Safety:** The design features and operating characteristics of a system that serve to minimize the potential for human or machine errors or failure that cause injurious accidents.
- **Health Hazards:** The design features and operating characteristics of a system that create significant risks of bodily injury or death; prominent sources of health hazards include acoustics energy, chemical substances, biological substances, temperature extremes, radiation energy, oxygen deficiency, shock (not electrical), trauma, and vibration.

In this sense, the proposed method sits above the level of many of the specific tools or techniques that might contribute to the mechanics of a top-level analysis. For example, in the cognitive task analysis literature some methods (e.g., cognitive work analysis, see Vicente, 1999) are intended to be comprehensive human systems analysis processes, while others are more limited in scope and are focused on specific aspects of the process, such as expert knowledge elicitation.

The structure of this paper is first to elaborate on the link between structured front-end HFE methods and systems engineering and then to present some basic ideas from the perceptual control theory paradigm that leads to an alternative form of analysis. The PCT-based systems analysis described is a method for conducting front-end human factors engineering analysis. In that it deals with the goals and knowledge of the humans in the system, it has an association with cognitive systems engineering, but it is equally concerned with the sensory, perceptual, and psychomotor requirements of the human machine interface. Finally, in discussion, the proposed PCT-based analysis method is compared to more traditional human factors engineering methods and to Vicente's (1999) Cognitive Work Analysis (CWA).

At first exposure to these ideas, it is not always obvious that PCT evokes all the power and knowledge of closed-loop control systems theory from engineering. Therefore, proponents of PCT do not argue from a purely descriptive position, but can apply what is known about closed-loop control behavior to human cognition. While many of the ideas contained in PCT are represented within other paradigms, it is their synthesis under PCT that is perhaps the main contribution of this method. It is argued that adopting the PCT approach to systems analysis does not usurp mainstream psychological theory or established tools like cognitive task analysis. PCT provides a framework within which these ideas may be embedded.

7.2 HUMAN SYSTEMS ANALYSIS

Engineering provides a technology base that bridges the gap between a body of scientific knowledge and the application of that knowledge to design. The engineering technology base consists of the methods, procedures, and tools for applying this pool of scientific knowledge to design. Engineering is divided into disciplines that draw on different science bases. The discipline known as Human Factors Engineering (HFE) fits naturally within this framework. HFE draws on a knowledge base of engineering principles and methods that is shared with other engineering disciplines, together with a specialist knowledge base that describes what we know about human capabilities and limitations. It is arguably the least mature of the engineering disciplines although possibly not the newest. Systems engineering appears to have largely emerged from the RAND Corporation during the 1950s and 1960s (Checkland, 1981, p. 136); HFE can trace its origins back at least to the 1940s (Green, Self, & Ellifritt, 1995).

Systems engineering has typically dealt with the constraints imposed by the technological side of the design equation, particularly with cost-benefit trade-offs of alternative design solutions, while human engineering has considered the constraints imposed by human capabilities and limitations. These disciplines meet at the human interface with the potential for some crossover where the transfer of information and human performance become necessary considerations in systems integration activities.

The goal of systems engineering analysis is the transformation of an operational need into a system configuration (Diamond, 1989). A key to systems engineering activities is the functional decomposition of a system to the level where candidate solutions can be identified (DoD, 1990).

The belief that large-scale systems development can benefit from a structured top-down approach to design, characterizes *hard* systems thinking in

Peter Checkland's terms (see Checkland, 1981, Chap. 5). While there may be disagreement about the best tactics for implementing this approach, the strategic issues are quite clear. A formal method of systems analysis typically involves (the following is reported in Checkland, 1981, p. 136, and is adapted from a 1955 report by Hitch from the RAND corporation):

- A statement of objective(s)
- Alternative design solutions
- The costs involved in the implementation of each solution
- Mathematical representations of the system, and
- Criteria relating objectives, costs, and resources required in implementing a preferred or optimum alternative.

7.2.1 Structured Analysis Techniques

As a set of methods and procedures, the classical systems engineering process as currently practiced (e.g., see IEEE–1220, 1994) specifically considers the constraints imposed by both the human and the environment on design. Early texts on systems engineering included human engineering as a topic with an emphasis on the "…man machine link" (Goode & Machol, 1957); however, structured techniques for analyzing human systems have been part of basic HFE practice for many years (e.g., Chaillet, 1967; McCormick, 1976; Meister, 1985; Van Cott & Kinkade, 1972; Woodson, 1981). Typical of these is the set of procedures described as Mission, Function, Task Analysis (MFTA).

MFTA represents a comprehensive top-down analysis that mirrors the process used by systems engineers (IEEE–1220, 1994) as shown in Figure 7.1. MFTA is appropriately used during the early stages of systems development, that is, during the concept development and feasibility phases. MIL–HDBK–46855A (1999) describes this process and provides guidance for how one might conduct this type of analysis. Fundamental is the concept that analysis and design are tightly linked, and that validation and verification are carried out at each step. MIL–HDBK–46855 specifies a structure, which includes, but is not restricted to:

- Scenario development and mission analysis
- Function analysis and allocation
- Equipment selection
- Task analysis (including critical task analysis), and
- Workload/performance analysis.

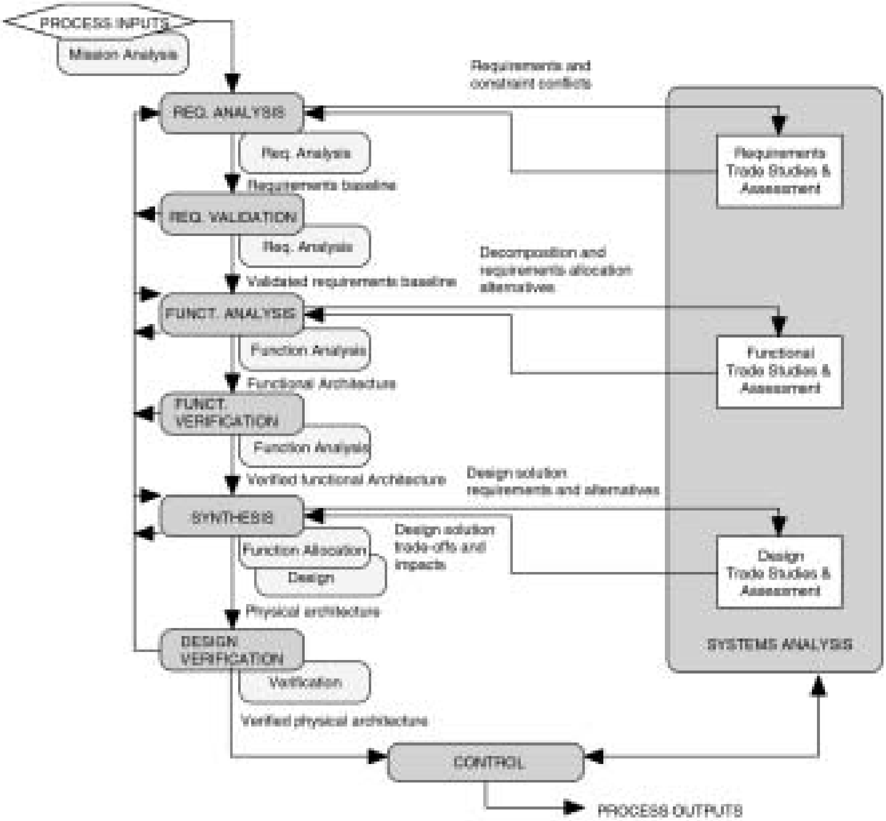

Figure 7.1: Relationship between the systems engineering (in dark gray) and human engineering processes (in light gray). (From IEEE–1220, 1994).

7.2.2 Domains of Analysis

Typically systems analysis will include (Van Cott & Kinkade, 1972, p. 4):

- The explication of system requirements and constraints
- The description of system functions
- Detailed descriptions of operational event sequences (including environmental conditions), and
- Detailed descriptions of component processes.

This suggests a two-dimensional, high-level, taxonomy for analysis that has, at least, both time and functional area aspects. For example:

7.2.2.1 Time-Based (While these categories have obvious relevance to vehicular systems, all systems demonstrate equivalent time-based phases from startup to shutdown, or from commissioning to decommissioning and disposal.)

- Prepare for mission
- Prepare for departure
- Departure
- Transition
- Mission
- Return
- Arrival
- Shutdown and secure

Each of these time-based components should then be broken out by functional area, as follows—

7.2.2.2 Functional Area-Based

- Primary mission
- Training (the need to design for embedded or on-the-job training)
- Abnormals
- Maintenance
- Sustain or replenish

To this list could be added team functions (i.e., behaviors and behavior modifications that emerge when individuals interact as team or group members, for example, see Annett & Cunningham, 2000). At a recent meeting between Canada, the Netherlands, and United Kingdom, the following tentative list of team behaviors was identified using the PCT structure as a framework (Belyavin, Cain, Lessens, & Hendy, 2000):

7.2.2.3 Team Coordination (optimize throughput, balance workload, minimize workload)

- Coordinate tasks
- Monitor task demand
- Establish priorities
- Allocate responsibilities (reactive)
- Take responsibility (proactive)
- Coordinate resources (manage the collective time-knowledge-attention equation)

- Monitor the load of team members
- Initiate load correction
- Monitor the knowledge of team members
- Initiate calibration of knowledge states
- Monitor the attentional locus
- Direct attention

7.2.2.4 Team Error Correction (support successful goal achievement)

- Monitor team goal achievement
- Provide feedback

7.2.2.5 Team Maintenance (maintain team health)

- Establish personal authority (establishing trust)
- Establish legitimate authority
- Motivate the team
- Monitor the affective state of team members
- Establish and maintain communication channels in human-human interactions
- Etc.

Without a formal structure such as this, it is possible that a designed system might serve the primary mission but not accommodate the requirements for departure and return, or on-the-job training and maintenance. The time-based dimension of this taxonomy imposes sequence at the top level of analysis but does not necessarily impose sequence at lower levels of the analysis, a criticism sometimes made of what are called traditional task analysis methods (e.g., p. 76 of Vicente, 1999).

The sequence of mission, function, and task analysis outlined above does more than support human factors engineering efforts. These analyses also provide information for the other four Human Systems Integration (HSI) domains. Thus, as with systems engineering, it can be argued that classic MFTA is ecological, in that the analyses describe the context and environment in which operators and maintainers perform their tasks.

7.2.3 Reliability of Human Systems Analyses

Currently the approach outlined in IEEE–1220 (1994) and MIL–HDBK–46855A (1999) has the advantage of many years of practice behind it and the availability of a plethora of tools for its implementation (e.g., http://dticam.dtic.mil/hsi/index.html; McMillan, Beevis, Salas, et al., 1989; Beevis, Bost, Döring, et al., 1999). Yet even though these methods and tools exist, design continues to have its failures, even for the most simple of everyday things (Darnell, 2000).

Design can break down from many factors. It may be that the customer was insensitive to human factors and did not emphasize their importance to the developer (Hendrick, 1990). It may be that the developer's personnel were untrained in human factors, or that their effort was focused on the final detailed design stage of development and was unable to influence the system concept (Beevis, 1987). It may be the failure of systems developers to actually use a comprehensive process of systems analysis (Beevis, et al., 1999, p. xxi–xxiii) that is at the heart of many design errors rather than the actual form of the analysis used. Or it may be that the tools used to implement these procedures are not sufficiently mature or that the methods and procedures are wrong or do not capture important emergent properties (Checkland, 1981, pp. 72–84). Then there are those who argue that traditional methods of analysis are doomed to failure for the analysis of complex open systems and, by implication, one might trace design failures to these flawed methods (Vicente, 1999, Chap. 3).

The Achilles heel of MFTA, as traditionally practiced, may not be in the overall structure of the method but rather in its implementation. In MFTA, interface design is generally done at the task or lowest level of analysis. As will be seen from the PCT hierarchical goal analysis described later in this paper, this limitation presents a number of problems. For example, the typical MFTA approach identifies operator tasks related to mission-specific functions. The functional decomposition does not identify crew functions because it is performed before functions are allocated to operators, maintainers, or machines. As a result, the analysis may not identify any functions or multi-operator tasks associated with crew coordination, consultation, resolution of ambiguity, etc., which can have an important bearing on crew compartment design (Beevis, Lessens, & Scuffle, 1996). Some other problems are identified by Vicente, albeit within the limited context of task analysis procedures in isolation.

7.3 PERCEPTUAL CONTROL THEORY

The basic perceptual control theory model for goal-directed human behavior, at a single level of abstraction, is shown in Figure 7.2. PCT, combined across all possible levels of abstraction, describes a hierarchical model of many processing layers (Hendy, East, & Farrell, 2000; Powers, 1973b, 1989, 1992a, 1992b).

True to its control heritage, a PCT loop consists of a set point (the perceptual goal), an input transformation process that maps incoming sensory

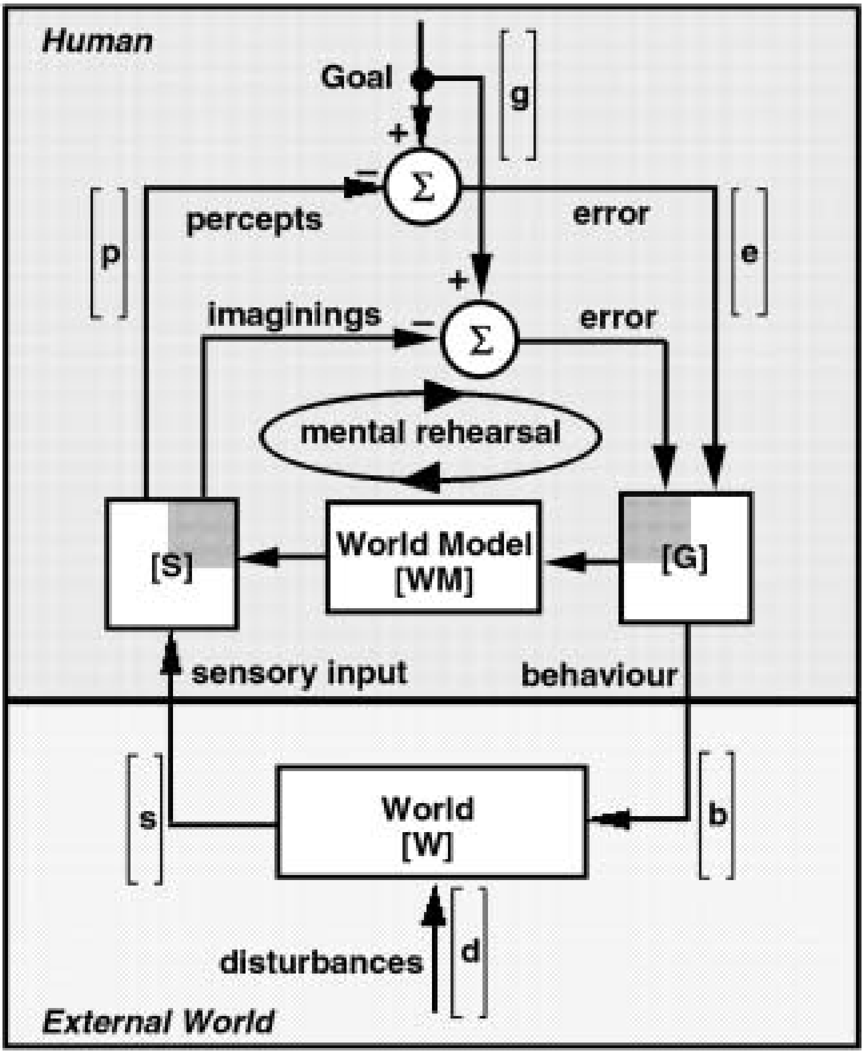

Figure 7.2: The Perceptual Control Theory model.

data into perceptual information, and an output transformation process that maps a difference or error signal into an output behavior. The loop is closed through its influence over a set of variables in the environment. PCT includes an inner loop, operating on or influencing internal memory structures. When this internal loop is exercised, no observable behaviors need be seen at the interface between the human and the world. The hierarchical nature of the PCT model is captured in a representational form by the use of a vector and matrix notation for the various system states and the transformation functions at the input and output sides of the loop.

Humans and machines interact and communicate with each other (human-human and machine-human) via their influence on various variables in the external world. Just as humans have goals that determine the set point of various control loops, machines have various references or programmed objectives that represent the goals of the system designers. Hence, the general structure of the PCT model applies to machines as well as humans. Teams and groups interact through their mutual influence on these external world variables. In Figure 7.3 a two-person team is shown operating on a common world environment represented by a complex environment function **W**. The concept shown in Figure 7.3 can be generalized to teams or groups of any number. Team members can be composed of any mixture of humans and machines.

From what we know of multivariate controllers (e.g., see Van de Vegte, 1986) we can predict how such systems might achieve stable control. In Figure 7.3 both operator *i* and operator *j* are initiating actions that operate on the shared world environment **W**. As both operators' actions affect the shared environment, their control loops are potentially cross-coupled with the potential for divergent or unstable behavior. As Powers (1992a) points out, the potential for conflict (i.e., the degree of coupling between *i* and *j*) depends both on the extent that *i* and *j* attempt to act on the same environmental variables, and to the extent that *i* and *j*'s perceptions are formed by linearly dependent transformations on these variables.

In situations where there is strong cross coupling, it is critical for stability that the goals and the perceptual (input) and behavioral (output) transfer functions are very closely matched. When controllers are coupled and the loop gains are quite different, the controller with the highest loop gain (authority gradient) will generally override the other.

Decoupling the loops implies that nonoverlapping roles and tasks have been defined for each of the agents. The need for an executive function (command, leadership) to oversee the allocation of roles and tasks, set common goals and establish common mental models is specific to the multicrew case. Information flow or communication between crewmembers, to execute this function, becomes an essential emergent property in this situation (Hendy, 1995, 1998). Note that the potential for multiagent instability comes only from mutual influence on external variables. No agent can directly influence the internal variables of another agent.

The constraints on human information processing, within the modules of the PCT loop, are described by the Hendy et al. Information Processing (IP) model (Hendy et al., 2000; Hendy, Liao, & Milgram, 1997). Together the IP/PCT models provide a strong integrating framework for analyzing and predicting human information processing behaviors (Hendy & Farrell, 1997).

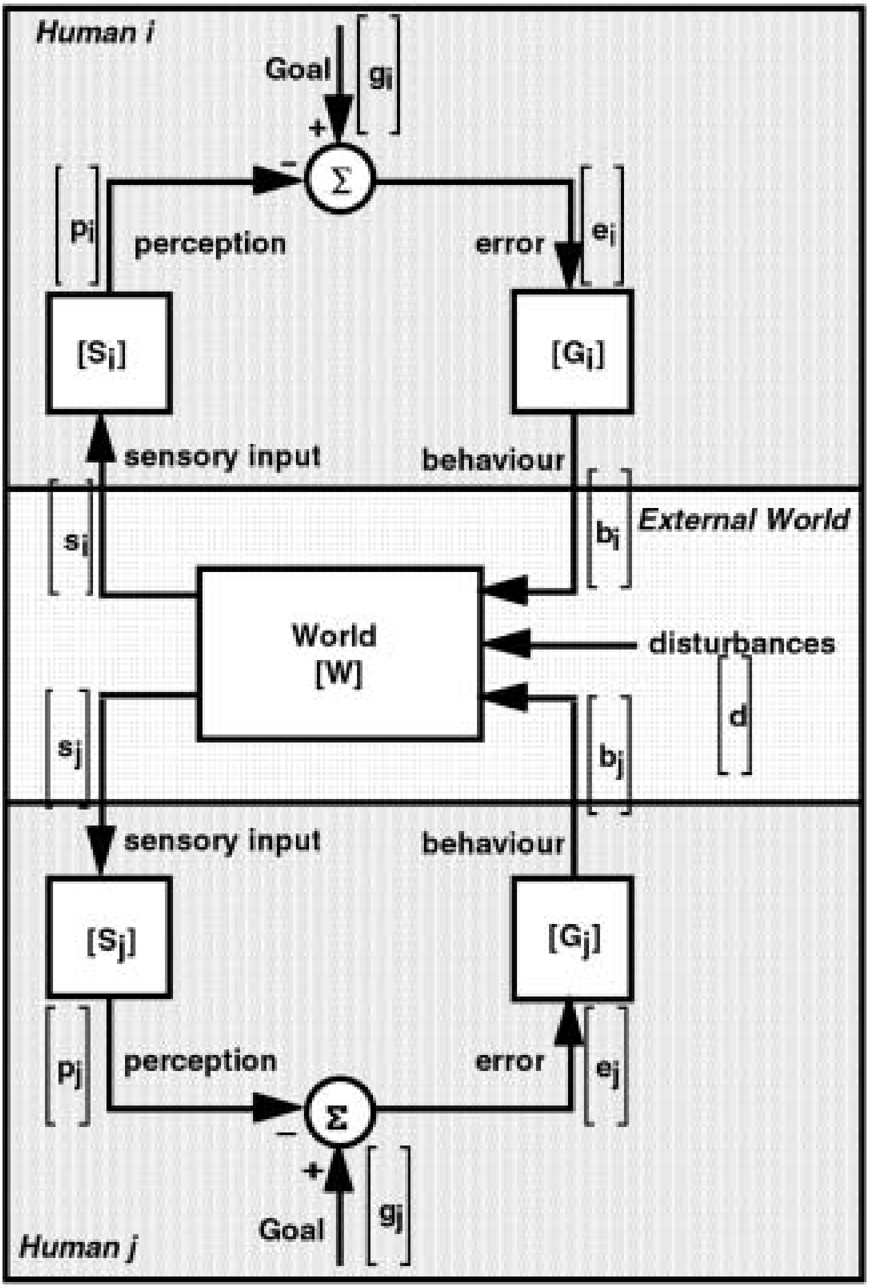

Figure 7.3: Multiple agents interacting through their influence on shared environmental variables.

7.3.1 Information Processing Models and PCT

Generally, a model is a representation that mirrors, duplicates, imitates, or in some way illustrates a pattern of relationships observed in data or in nature. In this way a model becomes a kind of mini-theory, a characterization of a process and, as such, its value and usefulness derive from the predictions one can make from it and its role in guiding and developing theory and research (Eysenk & Keane, 1990). Indeed, one of the purposes of building models is to make observations more comprehensible (Solso, 1991).

Cognitive psychologists are interested in the study of how we gain information about the external world. As Lachman, Lachman, and Butterfield (1979) assert (see also Neisser, 1967) cognitive psychology is about how people take in information, how they recode and remember it, how they make decisions, how they transform their internal knowledge states, and how they translate these states into behavioral outputs. Cognitive psychologists try to achieve this end by focusing on the internal psychological structures and operations that are involved in the transformation of information from stimulus to response (Roediger, Rushton, Capaldi, & Paris, 1984; Solso, 1991). Since the 1950s, this endeavor has been guided primarily by the information-processing paradigm (note that the Hendy et al., 1997, IP model is a specific example of this general class of model).

Rooted firmly in this framework, cognitive psychologists have viewed complex human behavior as the result of how a person transforms information between stimulus and response (Hintzman, 1978; Lachman et al., 1979; Reed, 1982; Simon, 1980). Guided by the IP paradigm, cognitive psychologists believe that information is transformed (i.e., processed) and analyzable across a series of processing stages during which specific operations are performed on incoming information. The response is assumed to be a result of the outcome of this series of stages and operations (Garner, Hake, & Eriksen, 1956; Hintzman, 1978; Knobel & Shaughnessy, 1999; Logan, Coles, & Kramer, 1996; Marr, 1982; Previc, Yauch, DeVilbiss, et al., 1995; Solso, 1991; Sternberg, 1969). The success of the IP paradigm in enhancing our understanding of complex human behavior has been demonstrated in such fields of research as lexical processing (Becker & Killion, 1977; Besner & Chapnik Smith, 1992; Herdman, Chernecki, & Norris, 1999), the effects of narcosis on divers (Fowler, Mitchell, Bhatia, & Porlier, 1989), the effects of closed-head injuries on information processing (Schmitter-Edgecombe, Marks, Fahy, & Long, 1992), and visual pattern recognition (Hughes, Layton, Baird, & Lester, 1984).

The prototypic cognitive model broadly divides the cognitive processes into three components or structures:

- Detection of stimuli
- The storage and transformation of stimuli, and

- The production of responses (Solso, 1991).

Cognitive psychologists then attempt to determine how information is modulated both within and between these structures. This "…cognitive architecture provides the missing theoretical integration, and is thus far broader in its scope than most theories…cognitive architectures are designed to capture the basic principles of operation built into the cognitive system" (Eysenk & Keane, 1990, p. 31). In addition to this basic architecture, Marr (1982) has stated that a model of information processing must have certain properties before a complex behavior can be fully understood. First, a model must be able to detail how different kinds of information (e.g., perceptual, higher order) map onto one another. Second, the model must detail how this information is represented. For example, is information coded as patterns of activation or as localized representations? Third, the model must provide a structure from which the above properties can operate. This third level involves the derivation of an algorithm from which the transformation of information is to take place. Consequently, the algorithm is dependent upon the manner in which information is represented (e.g., serial, parallel, connectionist, localist, etc). The development of these algorithms is further dictated by situation and task-specific attributes as well. As should be evident, model building, certainly within cognitive psychology, involves a progression from the conceptual to the computational. The discovery of these structures and what happens to information within and between these structures is particularly important because when a person has difficulty performing a task, the psychologist can then attempt to identify which stage is the primary source of this difficulty and then attempt to remedy it (Reed, 1982).

PCT both embodies and extends the traditional IP approach to understanding the underlying cognitive components to behavior. Structurally, PCT embodies the IP approach insofar as it broadly divides the cognitive system into three similar areas: perception (i.e., detection of stimuli), a goal stage which is integral in the storage and transformation of stimuli, and a response stage that initiates an overt behavior. Operationally, PCT outlines the transfer functions required to explain the manner in which stimuli are recoded and manifested into a response. Importantly, PCT together with the IP model emphasizes the importance of the time-constrained nature of the cognitive system within any behavioral context (Hendy & Farrell, 1997; Hendy, et al., 1997; Hendy & Lichacz, 1999). The cognitive system is assumed to be a limited-capacity processor having both structural and resource limitations (Eysenk & Keane, 1990). The IP model claims that all factors that have traditionally been seen as contributing to operator workload can be reduced to their effect on the amount of information to be processed or to their effect on the time available for processing. The IP model, through assumed limits on the rate at which information can be processed, determines the dynamic behavior of the perceptual control loop. When the rate of information processing demand exceeds the capability of the cognitive structure to respond, information remains unprocessed; in other words, it is shed. Error is attributed directly to the information shed. But the IP model is an adaptive model and asserts that the human information processor will adapt to excessive demands by a strategy shift, to either extend the time available before a decision has to be made, or to adopt a less information-intensive strategy that will reduce processing time. In an absolute sense, less information-intensive processing strategies will be less precise (this is the speed vs. accuracy trade-off), leading to longer goal achievement times unless the goal is relaxed to be consistent with the loss of precision. Errors due to the time-constrained behavior of the IP model will not be corrected by the perceptual control loop. Errors due to information shedding will only be reversed when the time pressure can be returned to acceptable values (say around 70–80%, see Hendy & Farrell, 1997).

PCT extends the traditional IP account of behavior by directly addressing the contributions that an individual's past experiences, expectations, and goals, as well as feedback make to the overall performance environment. Traditionally, the IP paradigm has been criticized for its assumption that stimuli impinge on an inactive and unprepared organism (Eysenk & Keane, 1990). Mental models and goals represent an important component of the PCT environment. PCT explicitly addresses the role(s) and manner in which mental models and goal states affect information processing and ultimately behavior. In PCT terms, transient errors are the inevitable result of imperfect mental models. Imperfect mental models produce transformations that resolve some, but not all, of the uncertainty in the error signal, and while an imperfect mental model may reduce the error signal (hence, it might be termed an appropriate mental model), it may not be optimum in the sense of producing fastest goal achievement (as determined by the settling time of the loop). Errors in the sensation-perception and action formation stages can be due to either a lack of the requisite knowledge in the first place, or to retrieval errors and biases from memory structures (including decision biases). In all cases, goal achievement should eventually be possible as long as the feedback loop remains intact (this translates to the management of attention and knowledge) and the system is error tolerant (a missile fired in error is unlikely to be recoverable). Feedback is essential to the adaptation of the loop and the gaining of new knowledge about a variable under perceptual control. Hence, to gain situation awareness about a particular world state, one must attend to, or control, that state.

In sum, PCT and the IP paradigm are not so dissimilar in that both share several basic characteristics: both view people as autonomous, intentional beings who interact with the external world; stimuli are acted upon by similar processes which manipulate and transform this information into symbols which relate to things in the external world and direct behavior; both specify the symbolic processes and representations which underlie performance on cognitive tasks; and both view the mind as a limited-capacity processor having both structural and resource limitations. More importantly, some might argue, as with the IP model, PCT provides researchers with a structure within which specific hypotheses can be tested, and enables them to predict events on the basis of the model.

7.4 PCT SYSTEMS ANALYSIS

The following procedure for systems analysis is firmly rooted in PCT, and therefore is based on the notion that humans and machines can be described in terms of a hierarchical control model. At all levels of abstraction, human activities will be directed to satisfying a hierarchical set of goals. Throughout this discussion it will be assumed that *goals* describe human set points, while the neutral term *objective* will be used to describe machine set points. Similarly *behavior* will be associated with human activity while machines will have *output.*

According to PCT the hierarchical structure of goals and objectives, from the highest level of abstraction to the lowest, represents the hierarchy of control loops that potentially will be active during the life of the system. Any goal/objective not served by a control loop has no influence over a variable in the external world, and will cause no behavior/output to be emitted. Alternatively, all system variables that are to be influenced must be associated with a goal or objective. It follows then that all goals and objectives must have the potential to be assigned to either a human in the system or to a machine. This will become a major point of departure between the PCT approach and more traditional function-task analysis (MIL–HDBK–46855A, 1999).

The described approach is shaped by and directly supports the implementation of the IP/PCT model (Hendy, 1997; Hendy & Farrell, 1997) within the Integrated Performance Modeling Environment (IPME http://199.170.148.19/toolsite/Tools/Shrtdesc/sindipme.htm) software. IPME is a tool for conducting front-end human engineering and human performance modeling for validation and verification analysis (in the past IPME has been used for traditional MFTA analyses but is entirely compatible with the shift to the PCT approach). This places PCT systems analysis within an integrated and comprehensive framework for HFE front-end analysis. Yet this linkage between PCT systems analysis and IPME could be broken while still retaining the integrity of the approach. If one was not wedded to IPME as an analysis tool, different data capture strategies could lead to the specification of the interface requirements.

7.4.1 Decomposing the Goal Structure

Some ground rules for performing a Hierarchical Goal Analysis (HGA) under this framework are as follows:

- Until assigned to human or machine all set points are generalized goals/objectives. When assigned to humans they become *perceptual* goals—they are what you want to *perceive*. (GOAL: *object of effort or ambition*: Sykes, 1982). Hence all PCT goal statements are of the form "I want to perceive [*goal statement in the form of a noun or noun clause*]." Goals are what drive *human* activity. It must be possible to assign all active goal/objective statements in an analysis, from the highest to the lowest levels, to a human or a machine in the system. Any goal/objective not assigned is not actively controlling—it is unlikely that a goal/objective will be achieved if it is not assigned to an agent within the system (it is possible that external disturbances could serendipitously drive a variable to a desired state).
- All control loops involve a variable that is influenced (coq: *controlled*) by the loop action, for example, the status of a mission, the temperature of a room, the altitude of the aircraft, the rotational speed of a propeller, etc. If there is a goal/objective, there must be an influenced variable. For humans these variables can be either internal (not directly observable by a third party) or external and therefore observable (see Figure 7.2). While the same can be said for the machine, human controllers can only know about those variables that are observable in the environment.
- Subgoals/subobjectives occur at the next level down in the hierarchy. They will be decomposed, in general, into even lower level goals/objectives. Decomposition into lower level goals follows a means-end hierarchy.

Table 7.1 demonstrates a hypothetical hierarchical decomposition of system objectives for a notional airborne platform. The decomposition is shown arbitrarily to be four layers deep; however, an analysis to any depth can be carried out by this method. It is also incomplete, as only one branch of the tree is shown. Starting with the two leftmost columns of Table 7.1, the analysis first identifies the highest-level objective and the associated variable that is to be influenced. The starting point for analysis is not arbitrary but can be reasonably set at the highest level variable that is to be controlled by the system under consideration. Information may flow from this level to and from higher-level external systems (often organizational or political) but no higher-level variables are *under the control of this system*. Each objective is then decomposed according to a means-end hierarchy until the lowest level of control is reached. Typically this will occur at the fourth or fifth level (c.f. Fig 4.2 of Beevis et al.,

Table 7.1: Hierarchical Goal Analysis Four Levels Deep

Goal/Objective (Level N)		Influenced ("Controlled") Variable	Assignment (Pick List)	Subgoals/Subobjectives (Level N-1)	
Level 1					
1	...the conduct of the mission	Mission occurring	Mission Commander	1.1	...aircraft being preflighted
				1.2	...aircraft taking-off and departing
				1.3	...aircraft ingressing to the mission area
				1.4	...aircraft conducting mission segment
				1.5	*...abnormal handled*
				1.6	*...restasking completed*
				1.7	...etc.
Level 2					
1.2	...aircraft taking off and departing	Flight status	Pilot Flying	1.2.1	...aircraft is prepared for TO
				1.2.2	...the aircraft rolling on the runway
				1.2.3	...the aircraft intersecting the outbound track and climbing to cleared altitude
Level 3					
1.2.1	...aircraft is prepared for take off	Preparedness for take off	Aircraft Commander	1.2.1.1	...the TO clearance has been received and understood
				1.2.1.2	...the pre-TO checklist has been completed
				1.2.1.3	...the departure has beeen planned
				1.2.1.4	...the TO brief has been prepared
				1.2.1.5	...the TO brief has been planned
				1.2.1.6	...the TO brief has been delivered and confirmed
				1.2.1.7	...etc.
Level 4					
1.2.1.1	...the TO clearance has been received and understood	Clearance status	Aircraft Commander	No lower levels in the analysis	
1.2.1.2	...the pre-TO checklist has been completed	Checklist status	Aircraft Commander	No lower levels in the analysis	

1999; and the Abstraction Hierarchy of Vicente, 1999, p. 157). For simplicity, the clause "I want to perceive," that might be associated with each goal/objective, is replaced by an ellipsis (…) in Table 7.1. The goal structure must reflect the environmental constraints identified in parallel system engineering studies. The effects of some constraints will be obvious while others will not be evident until more detailed interface specifications are developed.

Initially no assignment is made to a specific operator or machine. The assignment of objectives is a major engineering decision that fundamentally shapes the designed system. Note that an objective could be assigned to one or more human operators or machines. While not an exact science, there are tools for guiding this process (e.g., see Beevis et al., 1999, pp. 79–102). The assignment of objectives continues until the process is complete or until a decision has been made as to which variables are going to be left uncontrolled (i.e., without error correction), with their values determined entirely from the status of their lower level objectives. For example, if no one is actually responsible for, or is going to try to control, the conduct of the mission (the highest level objective in Table 7.1), this objective does not have to be assigned. The fact that all the sub-goals are being controlled may be sufficient. However, the requirement to address this type of issue is explicit in this process and therefore is traceable in the analysis.

Because all levels may be assigned to a human, all levels are potentially tasks in the vocabulary of MFTA. The formerly distinguishable processes of function and task analyses are now inseparable. There is now no point of demarcation between functions and tasks; hence, the hierarchical goal analysis combines what has traditionally been done under function and task analysis into a single process. This has major implications for design (as will be seen in discussing the requirements for an upward flow of information in the designed system) and clearly separates the PCT analysis from traditional MFTA. This structure supports the expansion of the analysis in either direction (up to higher levels or down to lower levels) at any time. There is no issue with representing all activities at the same level of abstraction as the decomposition proceeds (in traditional MFTA one might arrive at what was formerly described as the task level after three stages of decomposition in some branches, and at five stages in other branches). This creates difficulties with some analysis tools.

The top-level goals/objectives will generally represent the system at what might be seen as its functional purpose (conduct a particular mission), whereas the lower levels objectives generally serve an interaction at the level of the physical interface (tune a radio, release a weapon—c.f., the Abstraction Hierarchy of Vicente, 1999, p. 157). A fundamental difference between this approach and traditional MFTA is that the designer must make a decision, at each level of abstraction, as to what loops are going to be controlled. This means that goals/objectives may be assigned at all levels from the highest to the lowest. *Any goal/objective not assigned to an agent is not controlled.* Generally higher-level loops are satisfied by some combination of lower-loop activity (e.g., a logical sum of lower-loop states). *If feedback is broken at any level, there is no closed loop control, and if a loop is not controlled there is no direct error correction.*

7.4.2 Analyzing the Cognitive and Perceptual Components

Once the hierarchies of goals and objectives are identified and assigned, a detailed analysis of the cognitive/information processing aspects of the activity can be completed. Table 7.2 is a draft template for describing goal-directed human activities, based on the structure of the perceptual control loop of Figure 7.1. It contains fields for describing the input sensory processes, the output/behavioral processes and the perceptual/cognitive processes that characterize central rather than peripheral processing. Recognizing that the transformations that map sensation into perception and error into behavior draw on

Table 7.2: A Template for Analyzing the Cognitive and Perceptual Aspects of a PCT Loop

ASSIGNED OPERATOR						WORLD	
		Required knowledge states	**Perceptual/ cognitive processes (pick list)**	**Ending conditions**	**Output/behavior (pick list)**	**Output interface**	
Goal	**Output**	Declarative: •	•	•	•	•	
	Σ	Situation: •		**Influenced Variable(s) (Internal)**	IVI:	**Influenced Variable(s) (External)**	EV1: EV2: EV3:
				Initiating conditions	**Input/sensation (pick list)**	**Input interface**	
	Input			•	•	•	

knowledge structures held in memory, there are fields for both the long-term declarative and procedural knowledge, and the transient situation specific knowledge (situation awareness), required to achieve the goal.

Influenced variables, both internal and external, are tracked. Initiating and ending conditions are those that cause the attentional mechanism to shift control from one loop to another. The contents of the output and input interface fields must reflect the sensory and behavioral mechanisms that have been assumed. Initially these fields may contain generic statements such as a *hand controller or a visual display*. As design proceeds, these descriptions can be refined in light of constraints imposed by the environment and the capabilities and limitations of the human. Note that the interface between the operator and the world must bridge the gap between human sensory and effector processes, and the variable that is being influenced. Both world and operator constraints will determine the specification of this interface.

The information gathered in Table 7.2 directly feeds tools such as IPME for operator workload and performance prediction (e.g., see Hendy & Farrell, 1997). Hence the analysis and validation/verification stages are tightly linked. For example:

- The initiating and ending conditions, along with the required knowledge states provide the logic for running and terminating the task in a task network or equivalent simulation. Some of the strategic aspects of the task are contained in these logical statements, and while most

tools currently support crisp logic only, fuzzy reasoning (McNeill & Freiberger, 1993) could be incorporated in the future
- Table 7.2 is arranged so that the *Input/Sensation, Perceptual/Cognitive* and *Output/Behavior* processes fields directly feed the IP/PCT human operator information-processing module in IPME. Therefore Table 7.2 reflects the current information requirements of IPME and could be considered a minimum data set for the purposes of discussion. A useful addition to Table 7.2 would be, at least, a field containing a narrative description of the activity
- The Internal Variables (IVs) are the specific knowledge state(s) influenced ("controlled") by the loop in question
- The declarative and procedural knowledge that one brings to the job is that knowledge required to form perceptions and appropriate outputs/behaviors for *this* loop. Accumulating this knowledge across the task inventory defines the experience/training requirements for each operator and so feeds a training analysis. One could represent levels of expertise in terms of missing declarative and procedural knowledge that can be used to control the functioning of a task network simulation
- The situation specific knowledge is that which must exist, together with the declarative and procedural knowledge, to form appropriate perceptions and outputs/behaviors for *this* loop. It will include the pre-existing status of the initiating condition. Tracking the situation specific knowledge allows a task model to modify performance in terms of the level of situation awareness. By explicitly tracking the influenced variables, it should be possible to track emerging situation knowledge. Note that the knowledge required (both situation and declarative/procedural) is that which is required to do the job, rather than that gained (internal influenced variable) as a result of doing the task. That is, the knowledge required is a precursor (must exist before the goal can be actioned). Knowledge gained while the goal is being actioned is tracked by the state of the internal influenced variable
- The exit state of the ending condition (that is the state of the variable(s) when the task is completed and attention switches to another task) would be known to the operator (and manifested in an internal influenced variable).

To ease data entry requirements between the PCT analysis and IPME, Table 7.2 indicates that pick lists would be used for several of the fields rather than relying on free text entry. Obviously these data are tied to the requirements of the IP/PCT model in IPME and might be augmented or replaced by other data if a different theoretical framework were being pursued. The IP/PCT implementation within IPME models multi-task interference in the visual, auditory, psychomotor/kinesthetic, and cognitive domains (Hendy &

Table 7.3: Pick Lists for Cognitive/Perceptual Categories Describing Goal-Directed Human Activites

INPUT/SENSATION (FROM THE ANALYST)	COGNITIVE/PERCEPTUAL PROCESS CATEGORIES FROM TABLE 4 OF DCIEM 97-R-71 (DEFAULT VALUES)
VISION 1. Central 1.1 Text, dial reading 1.2 Pattern, spatial relationship, tracking, graphic displays 2. Peripheral	Verbal encoding Spatial encoding, visual pattern recognition Automatised, highly learned perception
AUDITION 1. Tone or simple auditory signal 2. Speech input (incidental to the primary task) 3. Auditory pattern ? Auditory localization 4. Speech input (attended to, salient to the primary task)	Automatised, highly learned perception Passive (pre-attentive) monitoring of auditory signals Semantic (use verbal) decoding Spatial decoding Verbal decoding, speech recognition
KINESTHETIC 1. Tactile 1.1 Simple stimulus 1.2 Complex stimulus	Automatised, highly learned perception Spatial encoding
MEMORY 1. Recall from memory 1.1 Accessible, familiar 1.2 Verbally coded 1.3 Spatially coded 1.4 Semantically coded (potentially new category) 1.5 Complex operation	Automatised Verbal decoding Spatial decoding Semantic (use verbal) decoding Recall
OUTPUT/BEHAVIOR (FROM THE ANALYST)	
VOICE 1. Voice output	Speech production
PSYCHOMOTOR 1. Manual output 1.1 Simple 1.2 Difficult but familiar 1.3 Complex and/or unfamiliar	Automatised, highly learned response Spatial encoding Memorization/recall, calculation, estimation, deduction, reasoning
MEMORY 1. Commit to memory (LTM and STM)	Memorization

Farrell, 1997). The linkage with IPME is shown formally in Table 7.3. The left-hand column shows a simple taxonomy for the input and output processes, which include activities, that are entirely internal to the human (drawing from memory structures and putting down new memory traces) as well as those that interact with the external world. These are matched to the set of perceptual/cognitive categories implemented in the IP/PCT version of IPME.

Table 7.4 is a simplified form of the Table 7.2 template for objectives that are assigned to machine agents rather than humans. For machines one might not need to track internal variables, although one would always track the set point and external influenced variables. A machine might have internal states that would be of interest from a designer's point of view, but the humans can only know about the variables that are given form in the external world. In human systems modeling, tracking the internal variables of the humans in the system allows one to explore the concept of the team mental model. Similarly, one could track the machine internal states to see if the humans and machines diverge as

Table 7.4: Template for Analyzing Non-Intelligent (Machine) System Components

ASSIGNED SYSTEM					**WORLD**	
			Operations	**Output**	**Output interface**	
Objective or set point		**Output**	• • •	•	•	**Influenced Variable(s) (External)**
	Σ		**Influenced Variable(s) (Internal)**	IVI: IV2:		EV1: EV2: EV3:
			Operations	**Sensor Data**	**Input interface**	
		Input	• • •	•	•	

to a common understanding of the world. The transformation operations might be tracked too as an aid to the equipment design. These transformations will also determine the states of the internal and external influenced variables.

Tables 7.5 and 7.6 illustrate how these templates might be completed using the categorization schema shown in Table 7.3. In the first case the activity involves both internal and external variables; in the second case only internal variables are involved.

7.5 ANALYSES EMERGING FROM THE PCT APPROACH

Two forms of analysis emerge from the PCT approach to systems decomposition. These analyses do not appear to be explicit in any other form of work analysis. They are:

- An analysis to investigate the potential for instabilities caused by multiple control of common variables, and
- An analysis to investigate how information from low-level goals flows up to high-level goals.

Table 7.5: Illustration of a Completed Template for an Activity Involving Both Internal and External Variables

CO PILOT						WORLD	
		Required knowledge states	**Perceptual/ cognitive processes (pick list)**	**Ending conditions**	**Output/behavior**	**Output interface**	
	Output	Declarative: • radio op procedure • comm procedure	1 Automatised 3 Verbal encoding 5 Memory recall and memorisation	• clearance obtained and understood (e = 0)	**Voice Output** • establish radio link (voice, keyboard etc.) • transmit clearance request **Memory** • add contents of clearance to memory	• Radio head • PTT • display controller • audio pickup and/or • keyboard	
Goal 1.2.1.1 ...the TO clearance has been received and understood	Σ	Situation: • radio ON/OFF • position in checklist • aircraft status • flight plan/ intentions		**Influenced Variable(s) (Internal)**	IVI: Clearance belief (1) IV2: Clearance status (1)	**Influenced Variable(s) (External)**	EV1:ATC clearance (1) EV2: Clearance request (1) EV3: VHF 1 Freq.
				Initiating conditions	**Input/sensation (pick list)**	**Input interface**	
	Input	• clearance status		• clearance not obtained and understood ($e \neq 0$) • if $e \neq 0$ obtain clearance else do nothing	**Memory** (1.2 recall verbally encoded) **Vision** (1.1 Central, text) **Audition** (4 Attended speech) **Kinaesthetic** (1.1 Simple tactile input)	• audio transducer and/or visual display • published charts/ frequencies	

7.5.1 Stability Analysis

In any system both humans and machines are exerting an influence over many variables in the environment. Depending on the division of control at any point in time (shared or segregated), the commonality of goals/references, and the compatibility of the transformation functions that shape input and output signals, the system might be either stable or unstable. The potential for instability is obvious when two agents are simultaneously trying to drive a variable in different directions according to incompatible set-points or internal transformations (this is what sometimes happens when two people, approaching head-on, attempt to pass one another in a corridor). This analysis investigates the existence of potential instabilities between human-human and human-machine control. In this analysis human and machine control are placed side by side.

Table 7.6: Illustration of a Completed Template for an Activity Involving Internal Only

AIRCRAFT COMMANDER						WORLD	
		Required knowledge states	**Perceptual/ cognitive processes (pick list)**	**Ending conditions**	**Output/behavior (pick list)**	**Output interface**	
Goal	**Output**	Declarative: • ATC procedures • aircraft performance	3 Verbal decoding 4 Spatial decoding 5 Memory recall and memorization	• plan made (e = 0)	**Memory** • add contents of plan to memory	•	
1.2.1.3 ...the departure has been planned	Σ	Situation: • ATC clearance (1) • flight plan • NOTAMs • plan status		**Influenced Variable(s) (Internal)**	IV1: Plan (1) IV2: Plan status (1)	**Influenced Variable(s) (External)**	EV1: EV2: EV3:
				Initiating conditions	**Input/sensation (pick list)**	**Input interface**	
	Input			• plan not made ($e \neq 0$) • if $e \neq 0$ make plan	**Memory** (1.5 Complex operation)	•	

The first three columns of Table 7.7 can be generated by parsing the database produced by the decomposition of system goals/objectives. Entries are sorted by external variable. The potential for simultaneous control can be determined by examining the goal/objective assignments by agent (which operator or machine). This information is entered in Column 4. If a network simulation or other time based tool has been run, this could be a time-based analysis. Training should prevent instabilities occurring due to systemic differences in procedural or declarative knowledge; however, there is the potential for differences in transient or situation specific knowledge states. Loss of synchronization in situation awareness is likely to vary over the mission time.

As the systems designer develops strategies to resolve these conflicts, new goals/objectives will be added to the master list (shown in the last column of Table 7.7). Note that this is a potentially recursive process. Generally one might exercise this process once or at most twice. Strategies for attaining stable multiagent control include:

- Separation of control
- Ensuring compatible set points and transformation functions, or
- Allowing one controller to dominate through high-loop gain.

Most resolution strategies will involve informing each of the players as to who or what is controlling. If control is not separated (including allowing one

Table 7.7: Stability Analysis

Influenced Variable (external)	Operator or System Assignment	Goal/Objective/ Reference	Potential for Simultaneous Control (pick list)	For stable control
	• Operator 1 • Operator 1 • Operator 2 • FMS	• ...the aircraft rotated for TO • ...the glideslope intersected • ...the altitude maintained • ...the altitude at x feet	• Operator 1 and FMS • Operator 1 and Operator 2 • Operator 1 and 2 and FMS	• push/pull disconnects AP with voice and visual warnings • hand over procedures, voice and visual warning if multiple inputs are detected • as above

loop to dominate), it must be blended smoothly by ensuring that all agents have compatible goals and internal transformation functions.

7.5.2 Support to Higher-Level Goals

This analysis should start at the lowest level and work up. This is the reverse process to the function/task decomposition. Traditional top-down decomposition by function and task traces the downward flow of information in a system. This matches the downward flow of action exerted on the system that is inherent in the means-end hierarchy. However, to exercise control (error correction) at any level, the state of the influenced variable(s) at that level must be fed back. In traditional MFTA there is no explicit mechanism for tracing the upward flow of information in the system which is required to achieve error correction at all levels. In Table 7.8, the database generated by the decomposition of system goals/objectives is parsed by goal/objective. Generally this would be started one level up from the lowest level goal (the example in Table 7.8 was arbitrarily completed at the top two levels of this analysis). A level N goal and its assignment are listed in the first two columns of Table 7.8. For each goal/objective at level N, the subgoals/ sub-objectives at level N–1 are now listed, along with their assignments, in the next two columns of Table 7.8. The data in the first four columns of Table 7.8 comes directly from the database.

This process yields two new pieces of information:

- The highest-level goal is controlled by each machine in the system. This is particularly salient in considering decision support systems. Few machine implementations share top-level goals with the human (e.g., in modes other than full auto, an aircraft Flight Management System ([FMS]) has no top level objective to complete a flight to a given location, even though it supports all the lower level goals of

Table 7.8: Analysis of the Upward Flow of Information in the System (Support to Higher-Level Goals)

Goal/objective	Assignment	Subgoals/subobjectives	Assignment	To support higher level goal/objective
		1.1 ...aircraft being pre-flighted	AC	AC to brief MC
		1.2 ...aircraft taking-off and departing	PF	PF to brief MC
		1.3 ...aircraft ingressing to the mission area	Mission Computer	TD to display current aircraft position
		1.4 ...aircraft conducting mission segment	Mission Computer	As above with mission status indicated
		1.5 ...abnormal handled	AC	AC to brief MC
		1.6 ...retasking completed	All crew	All stations to brief MC
		1.7 ...etc.		

maintaining a heading, altitude, etc.). Obviously if the machine/automation doesn't support all the lower-level goals, it doesn't completely support the level above

- Even if all lower-level goals are supported, this information has to be combined in some way to provide feedback at the level above. This will apply to both human and machine controllers. Interface design should facilitate this process, and the fourth column in Table 7.8 provides the additional goals that the interface must support to achieve this end. The analyst must provide the resolution shown in the last column of Table 7.8. This analysis will make the designer consider *how the information is passed up* to support higher-level functions and activities. One should not rely excessively on human memory in performing this upward synthesis of information. There are various mechanisms for fusing/storing/manipulating lower-level data to support higher-level goals/objectives and their assignments. This is a potential application for various levels of machine "intelligence" and decision aids.

Note that if the higher-level goal, and the supporting subgoals one level down, are all assigned to the same agent, then there may be no need to flow the information up. It could be assumed that as all goals are assigned to the same agent, that agent would have access to all information. However, the existence of the higher-level goal involves two processes:

- The upwards flow of information, and
- The synthesis of that information to form a perception that can be compared to the goal state.

Design should accommodate both requirements. The intent of data fusion systems is to roll up low-level data to support a higher-level perception ("big picture"). Decision support systems have similar requirements.

7.6 APPLICATION OF PCT SYSTEMS ANALYSIS

In this section, the application of PCT-based analyses to systems requirements specification is discussed. First, the use of a PCT analysis of a future land forces command and control system is described, specifically as it compares to the more traditional MFTA approach. It will be seen that the PCT analysis provides additional insight into the requirements for interface design. Second, the potential benefits of the PCT approach in analyzing adaptive intelligent interfaces are considered. Developing processes for capturing the requirements of these types of interfaces is perhaps the next grand challenge for human factors specialists. Because a PCT based analysis develops a hierarchical goal structure for the system, it appears to fit well with the requirements for goal-plan tracking structures that often drive such systems (Edwards, 1997) and with the overall notion of explicit user models (Edwards & Sinclair, 2000).

7.6.1 Land Forces Command System

An MFTA of the Canadian Land Forces Tactical Battlefield Command System (TBCS) was completed in preparation for writing detailed requirements specifications and future procurement action. A single segment of the TBCS analysis was selected for a proof-of-concept application of the PCT based systems analysis and comparison with the traditional approach (Dahn & Lowdon, 2000). This work was performed under contract to BAE Systems—Canada, and Micro Analysis and Design (MA&D) of Boulder, Colorado, USA. Both contractors were highly skilled and practiced in the use of traditional MFTA, but had minimum exposure to the PCT approach.

Specific objectives of the study included:

- Assessment of the applicability of the PCT protocol, relative to traditional analyses
- Qualitative assessment of PCT implementation issues, and
- Identification of lessons learned.

The following extracts from the contractor's report summarize the outcome of this exercise:

The comparison of PCT and non-PCT results suggests that the PCT approach is highly appropriate to conceptual phase-analyses, and offers benefits over the traditional MIL–HDBK–46855 approach used previously. The analysis of "support to higher-level goals" increases the likelihood that workload associated with monitoring/supervising/controlling the performance of others is captured and correctly represented in the model. This was evidenced by the 37 additional goals identified during this analysis which had been missed during the original TBCS analysis. Admittedly, some of the lower-level tasks should have been identified during the previous analysis, but there is still currently no logical process for identifying workload associated with the performance of functions above the task level. Similarly, the stability analysis provides a structured process for identifying situations when a particular variable could potentially experience multiple controls—i.e., either human-human or human-machine. This process also supports the identification of solutions to ensure the potential instabilities are effectively managed—e.g., through system design, procedures, etc. The traditional approach provides no process for ensuring that instability issues are adequately addressed during the conceptual-phase analysis.

There is another aspect of PCT that warrants consideration. Although the analysts at BAE Systems admit to limited exposure to the process, the general perception is that PCT is not as intuitive as the traditional methods, and probably requires a greater degree of training/experience to become truly proficient. This is particularly significant for those not previously exposed to control theory. There is also the consideration that the end-user/customer/ Subject Matter Experts (SMEs) will have similar difficulty in grasping/comprehending the significant aspects of the process. This concern should certainly not be a show stopper, particularly since the limited experience of the analysts renders it premature to pass judgment in this area. However, the utility of the process is clearly an issue that warrants consideration.

The success of the PCT analysis in identifying 37 additional goals, missed in the traditional MFTA, is heartening. These goals were all associated with support to higher-level intent. For the TBCS, it would seem that established command and control procedures had largely addressed the issue of stability, as the potential for simultaneous control was not a factor in the analysis of this segment of operation.

The contractors identified ease of use as a potential problem in the application of this new process. While the validity of a process is always of primary purpose, ease of use influences the acceptance of the method by a design team.

Ease of use is also a major factor in the timeliness of the deliverables. Ultimately ease of use will be a contributing factor in whether the process is used in design. While MFTA is familiar to anyone with basic project management or systems engineering skills, PCT systems analysis varies sufficiently from this model that a learning curve is to be expected (the level of specialist knowledge required of CWA has already been identified as an issue by Chin, Sanderson, and Watson ([1999]) for a similar domain of application).

PCT systems analysis was implemented using IPME for this proof-of-concept study. IPME currently makes no particular concessions to the PCT method, although it is compatible with the process. The ease of applying the PCT method is likely to be improved when an interface is developed that directly supports PCT (Dahn & Lowdon, 2000). Intelligent tutoring and help can also lead the analyst through the process (e.g., see Edwards, Hendy, & Scott, 2000).

7.6.2 Intelligent Adaptive Interfaces

The concepts that make up perceptual control theory, taken individually, are not unique. They appear in many theories, some which have been around for a very long time. What makes the contribution unique is the combination of those concepts into an approach that promises to add important insights into the analysis, design, and implementation of intelligent, adaptive systems.

It is difficult to say how long the notion of purposeful behavior has been with us but it is discussed early in the life of psychology by William James, among others, later in elaborated theories of learning, and still later in cognitive psychology and information processing theories. More recently, various subfields in artificial intelligence (e.g., the subfield of planning) deal with purposeful behavior.

Many of the concepts used in the description, explanation, and prediction of purposeful behavior overlap these disciplines, concepts like goals, plans, states, feedback, hierarchies, closed loops, conflict, cooperation, and so on. The different ways these concepts are defined, elaborated, and used can provide useful cross-disciplinary insights.

In the interest of building intelligent, adaptive systems, it is worthwhile to take some time to examine how some of those concepts are treated and what other disciplines have to say to PCT about how they might be used. In particular, this section will look at PCT from the perspective of some of the concepts used in AI for building intelligent, adaptive systems. Aspects of its purpose include clarifying differences in the use of same or similar terms, providing a basis for transforming usage between the two fields, identifying apparent discrepancies, highlighting areas where questions remain, and laying a foundation for future refinement and elaboration of ideas necessary to building those systems.

7.6.3 Two Views

PCT's basic unit of purposeful behavior is the reference signal, taken from control theory. Unlike control theory, the reference signal is not given from the outside by some observer or user of the control system but emerges from within. For humans, reference signals are inferred and cannot be observed directly.

Reference signals exist at many different levels of abstraction and are linked together in ways that can help define all complex systems. At any given level of abstraction, a reference signal is compared to a perceptual signal (at that same level) and if a difference is detected, the system produces responses intended to change the perceptual signal in ways that will reduce that difference. The results of those changes provide feedback in the form of an altered perceptual signal that moves through the same process again. All of this happens in a closed loop system not easily described in terms of traditional notions of cause and effect.

In AI, in the area of planning, for example, the notion of goal is a key concept. In general, a goal is a state and there are two states of particular importance in plan generation work: the current state of the world and a desired state held by some entity (person or machine). In a similar way to the negative feedback system in PCT, the object of planning is to reduce the difference between the current state and the desired state and, in the case of AI, this is done through the application of operators. Early work in this area conducted by Newell and Simon (1963, 1972) made use of a means-ends analysis in the application of operators to reduce that difference.

During this process, it is important to understand the preconditions, or conditions for applying an operator, and to make sure they are met before attempting to apply the operator. A second aspect of the process is understanding the effects that will be produced in the world when the operator is applied. Effects add and subtract facts from the system's current model of the world. Examining preconditions and effects leads to another aspect of AI planning systems: the detection and avoidance of conflicts among goals and subgoals. For example, satisfying one goal may produce an effect that prevents the pursuit of an important, related goal or may actually reverse the effects produced by the successful pursuit of earlier goals.

Similar to PCT, there are different levels at which goals occur, both higher and lower relative to the goal currently in focus. Subgoals support the achievement of goals above them and supergoals are the goals that motivate the goals below. In other words, subgoals are the means by which supergoals (ends) are achieved.

From these two descriptions, it is clear that there are a number of points on which PCT and AI seem to agree. They both support the notion of goals, the concept of differences between goal states and current world states, and the need to reduce those differences to bring the (perception of the) world in line with the desired goals. Further, they support the notion of an organized hierarchy of goals. The treatment of preconditions and effects in AI is accommodated in PCT through perceptual signals that reflect the nature of the current state of the world and effects that operate on it. An inner PCT loop, referred to in earlier sections, would seem to allow for rehearsals of reference, perceptual and error signals, and this is consistent with a reasoning component in AI systems that examines optional subgoal structures that might lead to a successful plan. Further elaboration of these inner loops and their relationships within and across levels would be instructive.

7.6.4 The Notion of Plans

A corresponding and complementary concept to goals in AI is the notion of plans. Plans are sets of subgoals (possibly only one) that support the achievement of some higher-level goal. The goal is specified at some level and subgoals are identified that will help achieve that goal. The goal of course is a supergoal relative to all the subgoals in the plan but we refer to it simply as a goal and its meaning will be understood in context.

In PCT, there seems to be some reluctance to embrace the notion of plans either because it seems to imply knowing what may not be knowable (Powers, 1993) or that plans somehow reflect brittle, repeated actions that cannot accommodate changes in the real world:

> There can be no plan of action precise enough to carry out this process that the driver accomplishes every day. What we really see is not a series of repeated actions that have repeated consequences, but a series of variable actions that have repeated consequences. (Forssell, 1997, p. 9).

Subgoals seem to be implied; however, PCT's hierarchical control model points to a need for such a hierarchy based on perceptual dependencies.

> The rationale for hierarchical classes of perceptual control is based on the observation that certain types of perception depend on the existence of others. Higher level perceptions depend on (and, thus, are a function of) lower level perceptions. (Forsell, 1997, p. 4)

Since a reference signal is identified in PCT as synonymous with goal, it stands to reason that a hierarchy of such reference signals is a hierarchy of goals. Reference signals at lower levels support those higher up and are required to reduce the error signals at higher levels. Thus, those lower-level signals would seem to constitute ways (plans) for achieving the higher-level signal (goal).

Passing over PCT objections to the use of the word "plan," what seems problematic is how the various reference signals operate in concert with each other to produce intelligent, adaptive behavior. That is, how is a set of low-level reference signals chosen from many possible alternate sets in a way that permits the successful achievement of a higher-level reference signal?

Assuming all these relationships to be hardwired flies in the face of a concept like adaptation and even the claims by PCT theorists themselves. Appealing again to some internal operations (inner loops) provides a way of linking PCT concepts with adaptation to changing circumstances in the world.

In many circumstances, goal achievement requires only the application of previously learned behavior in the presence of familiar circumstances (some world state), monitoring the environment for changes, and using other learned methods to adjust behavior so as to accommodate those changes (as in PCT's familiar example of driving a car to some desired destination).

In contrast, planning an action or activity that is new or that may require substantial variation from past behavior demands some kind of (inner loop) rehearsal for the behavior to be effective. Some form of rehearsal and even practice may be necessary to establish the new behavior required to achieve the desired goal. Participating low-level behaviors, or at least aspects of those behaviors, may not need to be learned.

To help bridge the gap between PCT and AI approaches on the issue of plans, PCT might be more explicit about the relationships among reference signals in its hierarchically organized systems. Specific examples of adaptive systems created using the PCT approach would be helpful, along with the more general principles and methods used to define relationships within a PCT hierarchy.

7.6.5 The Nature of Hierarchies

A key difficulty in constructing hierarchies is establishing clear criteria for defining their levels. Lower layers seem more easily identifiable and the criteria for differentiating them easier to specify. Likely, this is due to the fact that "behaviors" at those levels are far more limited, simpler and easier to identify, detect, and measure than those at higher levels. The PCT hierarchy illustrates these points nicely.

Powers (1973a, 1990) proposed a hierarchy of eleven levels with the lowest level systems controlling perceptions that represent intensity from the environment. The next level is sensations, which includes things like sounds and colors and which are functions of intensities at the lowest level. A third level supports the control of configurations, which are combinations of sensations and, so it goes, on up the hierarchy.

Descriptions of these low-level control systems seem quite reasonable; it seems clear how they support one another and how a system might be constructed based on such a hierarchy. As you ascend the hierarchy, however, things become increasingly tentative and questionable. Incidentally, this point can be made about many non-PCT hierarchies as well.

At the upper end of Powers' hierarchy are levels called categories and programs. Categories capture the notion of class membership and programs specify "if-then" contingencies. At these levels, Powers has moved into areas that involve symbolic systems and it is not at all clear why that shift occurs and how criteria used to establish those levels relate to criteria used to differentiate lower levels of the hierarchy. Powers' highest levels of principles and system concepts refer to very broad notions, namely, generalizable rules and disciplines such as science, mathematics, and art.

Two of these higher levels are worth noting relative to the concepts of goals and plans in AI. The first is the next level up from categories, called sequences. Sequences represent unique orderings of lower-order perceptions and provide a first hint at how PCT might be seen to accommodate the notion of plans. The next level up from that one is programs, as defined in the previous paragraph. The notion of a program captures much of what might be considered a goal and the plan for achieving it, including the specification of contingencies that contribute to the adaptiveness of the plan or to the use of a different plan altogether.

Returning to the nature of hierarchies, a little reflection on the levels in this proposed PCT hierarchy will show that it is not at all clear how the higher levels are related in any coherently logical, smoothly transitioning way to the lower levels, nor is it clear whether the criteria used to differentiate any two levels bear any resemblance to those used to distinguish any other pairs. More theoretical work is needed of course, along with implementations and demonstrations of systems that attempt to use those higher levels.

7.6.6 Hierarchies and Plans

To further elaborate the notion of hierarchies and plans, the following example from Hendy et al. (2000) is instructive.

> Human behavior is commonly described with action verbs, rather than perceptual states. For instance, going from the first floor of a building to the top floor, one might walk to the elevator, press the door button, enter the elevator, press the numbered button, wait for the doors to close then open, and exit the elevator. This sequence of events might lead the reader to believe that the human is directly controlling their actions, perhaps in response to some stimulus. However, implicit in this elevator scenario is the goal of reaching the top floor, the initial

> perception of being on the first floor, and a series of actions that move the current perception closer to the goal state (p. 7).

Although the example is meant to show that a characterization using action verbs can be represented as changes in perceptual states, it also provides a convenient way to illustrate how AI might represent those perceptual states in a hierarchy of goals and subgoals (plans). One of many useful rule sets for understanding such examples, developed by Abelson some years ago (see Schank & Abelson, 1977), is formulated as follows:

Actions Cause States; States Enable Actions

Applying this rule set to the above example, along with the concepts of goal and subgoal (states) and actions (operators), we have:

State 1	(Subgoal5):	Being on first floor
Action 1	(Opt1):	Walk to elevator
State 2	(Subgoal4):	Being at elevator
Action 2	(Opt2):	Press button for elevator
State 3	(Subgoal3):	Elevator at first floor (and) doors open
Action 3	(Opt1):	Walk into (Enter) elevator
State 4	(Subgoal2):	Being in elevator
Action 4	(Opt2):	Press button for desired floor
State 5	(Subgoal1):	Elevator at desired floor (and) doors open
Action 5	(Opt1):	Walk out of (Exit) elevator
State 6	(Goal):	Being on the top floor

If the states above adequately reflect conditions in the real world, then the actions that follow are consistent not only with output functions invoked by the error signals of PCT but also with cognitive theories which require the evaluation of testable conditions to trigger consequent behavior and even behavioral notions of chained responses to (antecedent controlling) discriminative stimuli.

In AI, the entire sequence can be thought of as a plan for achieving the final goal (State 6: *Being on the top floor*), but actions at any level can be understood to achieve the goal represented in the following state. Each state is a subgoal in the service of the final goal (state) and the actions and subgoals together constitute a plan for reaching that final goal, at whatever level that may be defined.

Comparing this to PCT, subgoals are equivalent to controlled real-world variables and thus to perceptual states that occur as consequences of an entity's acting on the world, and from the actions (and properties [states]) of other entities (e.g., the actions and states of the elevator).

As actions achieve each of the subgoals, the final goal (reference signal): *being on the top floor* is compared against the current world state and an error signal generated which shows that the difference is less than before. That process is repeated as each of the subgoals is achieved until the error signal is effectively zero.

If the plan is a clear one and the currently satisfied condition is a recognizable condition within the plan, the next action to reduce that difference with the final goal should be clear also. If the next "logical" condition is not satisfied, however, replanning may need to take place.

What happens for example if the elevator is out of order? Cognitive theories permit replanning by allowing the person to use alternative routes such as taking the stairs or asking an attendant for help in getting the elevator working. Conditions in this scenario that could influence whether and when such replanning takes place might include a light above the elevator door that provides information about where the elevator is and whether it appears to be working.

How might PCT handle the problem of replanning? Will the person determine that the stairs are a best alternative under the circumstances or are they left standing at the elevator repeatedly pushing the button? That is, does the behavior continue to repeat since the error signal remains the same or does the control system have a way to effectively replan? An intriguing question, and one that the reader, in finding an answer, should also uncover other areas of correspondence between AI and PCT.

7.6.7 Hierarchies Revisited

As indicated, there are fuzzy aspects to hierarchies, deciding what criteria to use in differentiating the different levels, how many there are, and so on. In the example above, the action-state sequence can be thought of as a kind of hierarchy leading to a final goal.

That particular concept of hierarchy is based primarily on identifying an appropriate sequence of actions and states rather than identifying different levels of abstraction or granularity in those actions and states. In a sense, the whole sequence, as described, could be thought of as existing at one level in an abstraction hierarchy. Within the PCT hierarchy, that might be the program's level.

To illustrate, contrast the action-sequence hierarchy with that involved when performing any given action in that sequence, for example, pressing the elevator button. To accomplish that, one has to move the hand, extend a finger and perhaps tilt the body slightly forward as the finger comes into contact with the elevator button. Those acts involve bringing muscles into play, altering muscle cells and, at an even more fundamental level, firing neural impulses. The goal of pushing the button then is achieved by a set of lower-level actions in a different kind of hierarchy than the action-sequence one above, by body movement and position, the flexing of muscles, changes in muscle cells, and activation of neural impulses.

Table 7.9: Classification of Goal Relationships

	Negative Interactions	**Positive Interactions**
Internal	Conflict: Mutually opposing goals held by a single entity (person or machine)	Overlap: Goals achieved more easily together than apart
External	Competition: Mutually opposing goals held by different entities (people or machines)	Concord: Mutually beneficial goal possessed by several entities

Powers admits that he doesn't know how many levels there are and that he doesn't know what determines the reference signal for the highest level. He points out that there are perhaps thousands or even more control systems, for example, one or more for each of the 800 muscles in the body. He also recognizes that some of those systems may operate independently and simultaneously, or even dependently.

Much of our understanding about hierarchical representations for the design and implementation of adaptive systems is yet to come. Other forms of representation are also possible and should be considered for what they have to say to hierarchical systems such as those in the PCT and AI fields.

7.6.8 Final Thoughts on Shared Concepts for Intelligent Adaptive Interfaces

This section has explored only a few of the concepts from PCT and AI that continue to be important in the analysis, design, and implementation of intelligent adaptive interfaces. It is not meant to be a thorough review and comparison of the two areas, only a primer on some of the relations among their concepts.

Many other aspects of PCT and AI could have been discussed such as how each might handle conflict and cooperation, within and among sets of control systems (people and machines), or how they might account for the modeling of one set of control structures by another in the service of understanding what goals (reference signals) are appropriate in interpersonal situations (see for example Edwards & Sinclair, 2000).

Since some time has been spent on stability analysis in this paper, classification of goal relationships from AI might motivate an exploration of how PCT can accommodate these in its approach to building adaptive control systems. The following is a modification from Wilensky (1983), and shows one way to classify goal relationships.

Competition, cooperation, and coordination of these different relationships among goals, within and across entities, needs to be accommodated within PCT and it will be instructive to explore just how PCT deals with each.

Finally, the questions raised here and elsewhere in this section are not meant to argue for PCT or AI in the analysis, design, and implementation of intelligent adaptive interfaces, but rather to encourage the elaboration of ideas within both so that correspondences and differences can be understood more clearly. Achieving that goal will provide real opportunities for mutually beneficial discussion and effective refinement and extension in adaptive system building.

7.7 DISCUSSION

This paper proposes a hierarchical goal analysis, based on the theoretical underpinnings of PCT, as an alternative to the traditional MFTA approach to human systems analysis. It is argued that a PCT-based HGA addresses many of the deficiencies associated with traditional MFTA. The overall structure of PCT-based HGA is similar to hierarchical task analysis (Annett & Cunningham, 2000) which also assumes that humans behave as goal-driven, closed-loop controllers. PCT, however, brings a more formal application of control theory into play and along with this comes the need for error correction at all levels within the hierarchy. The formal representation of closed-loop control theory within PCT spawned the two emerging analyses related to the detection of instabilities in the system and support for higher-level goals.

Vicente (1999) describes a comprehensive design and analysis process he calls *Cognitive Work Analysis* (CWA), based on Ramussen's approach (Rasmussen, Pejtersen, & Goodstein, 1994) to cognitive systems engineering. He argues (p. 48) that "…work analysis should begin with, and give primary importance to, the constraints that the environment imposes on worker's actions." The desired objective of this approach is said to be to "…ensure that workers will acquire a veridical mental model of the environment, so their understanding corresponds as closely as possible, to the actual behavior of the context with which they interact." CWA also attempts to avoid the pitfalls of traditional MFTA, but does so by taking a more revolutionary approach. Vicente (1999, Chap 3) has been a most vocal critic of what he calls the traditional methods of task analysis and points to what he believes are fatal flaws, particularly for the design of complex open systems, with any method that is mission or scenario based. Such approaches are seen to be normative and instructional as missions, and scenarios are thought to result in designs that impose a prescribed sequence of actions upon workers. By implication this would include PCT-based HGA because of its association with MFTA.

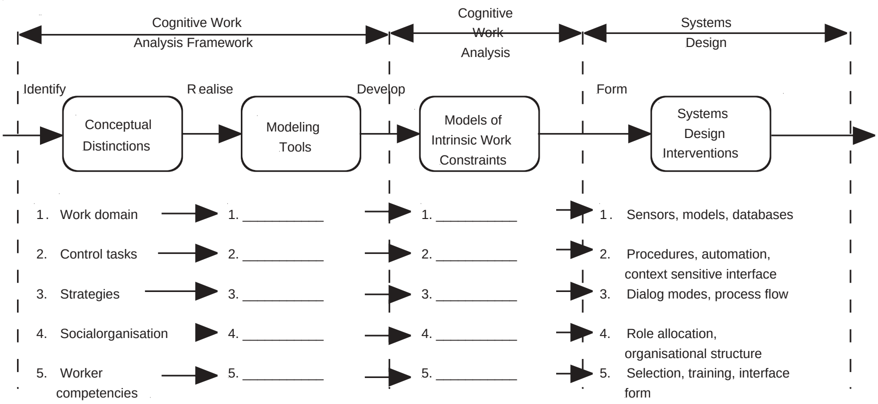

Figure 7.4: A framework for cognitive work analysis. (From Vicente, 1999, p. 136.).

Because of this uncompromising position, it is worthwhile making some comparisons between the methods.

CWA consists of a process and an evolving series of tools for conducting this process. The framework of CWA is shown in Figure 7.4 (the modeling tools and models that bridge the gap between the five conceptual distinctions and the corresponding five design interventions have been omitted from the diagram). Figure 7.4 outlines a structured process that has much in common with procedures that have evolved for human systems analysis as described earlier in this paper. CWA differs from the approach to human systems analysis described previously, not so much by the overall form of the process but by the specific methods used to implement it. While the necessary link between CWA and the rest of the engineering process has not been formally elaborated, there is sufficient commonality with other methods that one could imagine CWA partially mapping onto the structure of Figure 7.1. The one area that doesn't appear to be covered in CWA is a mechanism for verifying the design decisions, the final step in the iterative design process shown in Figure 7.1.

On the other hand, the overall framework of the PCT systems analysis method largely parallels that of traditional MFTA, and therefore fits within the systems engineering process, described in Figure 7.1. The differences between MFTA and PCT stem from the combination of the function and task analysis phases in PCT into a single process of hierarchical goal analysis, and in the two emerging analyses (stability analysis and support to higher level functions) that come from this method. At the heart of these differences is the realization that all goals, from the highest to the lowest, are candidates for assignment to a system agent. While the data requirements for the two methods are a little different, there is not a huge conceptual gap between the HGA and MFTA. The basic flaw in traditional MFTA is a result of an analysis method that explicitly traces the downward flow of information in a system but only captures upward flow fortuitously.

Fundamental to PCT is the notion that goal-directed human activity is driven by a process of closed-loop negative feedback control. Vicente (1999) makes repeated references to a closed-loop negative feedback model of the human information processor throughout his book, and uses this model to support several of his assertions. Yet he doubts the appropriateness of this form of representation for human action in complex systems (p. 73). His position appears to stem from the difficulty in giving explicit form to the transformation functions that map sensation into perception and error into action according to Powers' model. This difficulty is clearly acknowledged, but it doesn't in any way invalidate the model. The are many complex physical systems operating strictly according to a closed-loop feedback process that would possibly defeat any analyst to derive transformation functions from first principle calculations. That is one of the reasons that systems identification is used, to build empirical models of complex processes from which stable controllers can be built (DiStefano, Stubberud, & Williams, 1967; Phillips & Harbor, 1991, p. 57, p. 355). Fuzzy controllers have extended this capability from purely deterministic control to rule-based controllers. Just as is the case with a human controller, it is difficult to predict the output of a fuzzy controller under all conditions. However, this doesn't change the fact that the system is under set-point-driven, closed-loop, negative feedback control.

The extensive preoccupation with timelines and sequence that some authors see reflected in traditional methods of analysis appears to be taken out of context in many cases. For example, Vicente (1999) is most concerned with the inability to predict sequence or timing of activities in the presence of disturbances. He uses the example of vehicle guidance in the presence of wind gusts to underscore his point. He argues (p. 76) that because one cannot necessarily predict the pattern of wind disturbances, one cannot determine the timeline of human actions that are intended to counter the effects of the disturbance (note that Bourbon, 1996, uses precisely the same example to argue that it is actually the presence of closed-loop control that allows an operator to cope with these unpredictable disturbances). The message seems to be that you can't design an interface between the operator and the vehicle in the light of this uncertainty. Yet one doesn't need to know the timeline of steering actions to propose that a manual control in the form of a steering wheel be provided for vehicular control. The requirement for such an interface would come from a detailed MFTA, which is relatively neutral with respect to timeline or sequence. Further, knowing the statistical properties of the wind disturbance (mean, variance, max), the dynamic response of the vehicle and the transfer function of the operator, one could determine all design parameters for the interface (size of steering wheel, steering ratio, power steering requirements, augmented visual displays, the need for control quickening, etc.).

Time or sequence is not a parameter in traditional function or task analysis. Top-down decomposition of functions into lower level functions and tasks can be made entirely without reference to time or sequence. Decomposition proceeds in terms of an action means-end hierarchy (c.f., Vicente, 1999, p. 162). Even Functional Flow Diagrams (e.g., Beevis et al., 1999, p. 53) are only weakly time related. They capture sequence when sequence is important to system function (you can't fight the mission until you get airborne, etc.) but accommodate both serial and parallel branching. Sequence becomes an issue only when one needs to chart inter-dependencies between communicating entities (humans and machines), capture a logical progression with time, or establish safety interlocks between systems. Task sequence information might be used in tools for timeline analysis and performance/workload prediction, but many modern tools are not restricted to cases with prescribed task sequences (Hendy & Farrell, 1997). It is also important to understand the role of timeline and performance prediction in the total framework of front-end human engineering analyses. These methods are used to verify that the emerging design is likely to meet specified performance criteria, at least for normal operation. It is not necessary to predict system performance under all possible sequences of operation to answer this question (Hendy & Farrell, 1997).

While recognizing the different tools involved (an action means-end hierarchical function decomposition versus a structural means-end abstraction hierarchy) it would seem that work domain analysis in CWA equates to some extent to function analysis in MFTA (Vicente, 1999, p. 212). Similarly there are equivalencies between control task analysis in CWA and task analysis in MFTA. However, while function and task analysis are inexorably linked through a hierarchical decomposition in MFTA, or through the HGA in a PCT-based analysis, the link between work domain analysis and control task analysis is less well defined. Some loose equivalencies between MFTA, CWA, and PCT are shown in Table 7.10 (it is realized that these equivalencies are open to interpretation, as there are extensive differences in the overall implementation and order of the processes that go beyond similarities in individual steps). It is assumed that MFTA and PCT analyses would be performed in a systems engineering context as shown in Figure 7.3 and therefore would include a detailed analysis of technological and environmental constraints.

It is stated that (Vicente, 1999, p. 182) "…control task analysis should identify what needs to be done, independently of how or by whom…." The notion that control tasks act on the work domain (Vicente, 1999, Fig. 8.1) should be very familiar to PCT proponents as it is a form of analysis that represents human and machine activities by a common format and describes their interaction through a vector of variables in the external world (p. 190). Yet Vicente (1999) is less clear about how one generates the database of what has to be done in the system, without driving this process bottom up from an assumed display concept or physical description of the plant, or top down

Table 7.10: Some Loose Equivalencies Between Procedures Used in MFTA, CWA, and PCT Systems Analysis

MATA	CWA	PCT
Mission Analysis	Not specified	Mission Analysis
Scenario Generation	Not specified	Scenario Generation
Function Analysis	Work Domain Analysis	
Function Allocation	Social Organization and Cooperation Analysis	Hierarchical Goal Analysis
Task Analysis	Control Task Analysis	
Critical Task Analysis	Strategies	
Training Analysis	Worker Competencies	Tracking declarative and procedural knowledge by operator
Performance Prediction	Not specified	Integrated Performance Modeling Environment (IPME)

from some form of function, task, or hierarchical goal analysis (c.f., Vicente, 1999, p. 201). His example for the DURESS task (pp. 181–214) implies a top-down hierarchical decomposition of the functional purpose of the system (by goal and subgoal), with the decision ladder providing structure to this process (Fig. 8.9). The HGA of PCT allows for the decomposition of goals from the highest to the lowest to be independent of *who* but has an implicit *how* associated with the way goals are broken down into subgoals in accordance with a means-end hierarchy. It could be argued that control task analysis in CWA also implies the *how* by the pathways traced in the decision ladder.

What is apparent is that CWA doesn't easily accommodate manpower and personnel trade-off studies. Manning is really an exercise in accountability and workload management. Both aspects are of concern for CWA, but there isn't a clear method within the process for the implementation of trade-off studies to examine these issues. The introduction of automation into a system combines accountability and workload aspects with direct system performance factors such as the latencies involved in meeting goals/objectives and the precision with which these goals can be achieved. There are also human-in-the-loop concerns related to the development and maintenance of situation awareness that one should address during the design phase. PCT combined with the IPME tool can quantitatively address these issues in both a static and dynamic representation. With CWA the assessment is, at best, subjective.

In CWA it appears that the intention of the Abstraction Hierarchy (AH) is to define all the objects (variables) in the work domain that might be acted on, and store information about them in a data base (Vicente, 1999, Fig. 8.6) for display at the operator interface. PCT identifies both a vector of environmental variables that must be influenced (*controlled*) if the hierarchy of goals identified in the HGA is to be achieved, and the knowledge that needs to exist to service these goals. HGA therefore identifies the variables or objects in the work domain that are to be acted on, including those variables associated with high-level goals. Arguably PCT identifies, at the very least, a subset of the variables described by the AH. This subset is bounded at one end by the highest-level functional purpose of the system and at the other by the lowest level at which control is to be exercised and therefore spans much of the AH space. It would seem that the AH and the HGA capture similar information and, if this is the case, the main distinguishing features of CWA and PCT are the tighter coupling between PCT's HGA and the concept of control, through the perceptual control loop, than occurs in CWA's AH and Control Task Analysis (CTA). Further, PCT is clear about the upper bound of the analysis, unlike CWA.

In Tables 7.5 and 7.6, examples are given of knowledge requirements and perceptual and cognitive processes involved in satisfying specific goals within a HGA. As they are described here they are minimal representations of these attributes, largely at the descriptive level, driven by the specific requirements of the IPME modeling environment. This does not exclude the use of more detailed knowledge elicitation tools in combination with the PCT-based HGA. Indeed something like Rasmussen's Decision Ladder (e.g., see Vicente, 1999, Fig. 8.4) or Klein's taxonomy (Klein, 2000) could be used to further decompose the hierarchy. A tool for conducting a PCT-based HGA would include, at the very least, fields for detailed narrative descriptions of the plans, knowledge, decision processes, and subgoals at each level as appropriate.

The amount of work required to perform a CWA seems to expand exponentially as the complexity of the system grows (a PCT-based HGA would be expected to increase more linearly). One would expect that there would be AHs for each of the functional areas identified in an earlier section of this paper, namely: (1) primary mission, (2) training (the need to design for embedded or on-the-job-training), (3) abnormals, (4) maintenance, and (5) sustain or replenish. Similarly there may be different AHs for the time-based behavior of the system, from startup to shutdown. Then what of multiple actors with different levels of responsibilities in a large system (say a ship's command center that is a system of systems)? The work domain of a sensor operator is quite different from the work domain of the commander in a ship's operations room. The notion of nested AHs is already presented in Chin et al. (1999). One would have to iterate this process through every possible manning concept. Yet the starting point of the CWA analysis, which is the generation of an abstraction hierarchy, is supposed to precede the allocation of responsibilities in the system.

MFTA is a relatively mature process that has much in common with accepted systems engineering and project management methods. This is not a case for whether it is a good method or not, just an argument that it is a reasonably well-understood paradigm. CWA and PCT have not had the same opportunity to demonstrate their successes and failures. CWA is a complex process that is still evolving. While Vicente's (1999) book is an excellent starting place for those with an interest in the area, it is hardly a primer on implementing CWA. There are still many unknowns related to the link between the AH and CTA and in the number of AHs that should be developed in complex multicrew and multifunction systems. Tools for the application of CWA are still in the development stage.

PCT based systems analysis is even less well known, but due to the parallels between MFTA and PCT systems analysis, many existing tools can be adapted with relatively little effort, and the overall process can be recognized by those skilled in the traditional method. The similarities and differences between CWA and PCT systems analysis are not yet fully understood and will become more apparent as both methods are applied to systems development and lessons are learned. What can be said of PCT in general, and of the PCT based systems analysis in particular, is that:

- Goal decomposition in the PCT's HGA is based on a means-end hierarchy—because of the 1:1 coupling between goal (internal state) and influenced variable (objects in the work domain) this is basically the same as CWA's structural means-end decomposition
- PCT systems analysis is based on a theoretical framework that describes goal-directed human behavior, machine activity, and communication between actors in the system. PCT brings all the rigor of control theory to the problem
- PCT explicitly generates behaviors that are shaped by both the actor and the environment—learned mental models reflect environmental dynamics for stability…in essence learning is a system identification issue
- All perception and action are shaped by internal knowledge structures whether they be right or wrong, good or bad…feedback and adaptation make this work in many cases…feedback allows less than perfect mental models to null the error (better mental models result in more rapid goal achievement)…an adaptive loop learns new and better mental models as actors interact with the system
- Perceptions and actions will be subject to constraints due to the capability and limitations of the actor (this is the realm of human engi-

neering)…the physical interface will constrain the possibilities for action…the external variables will be constrained by the environment (both their range and cross coupling—this is the realm of the systems engineer)…constraints at the interface may make goals unachievable

- PCT clearly identifies the top and bottom levels of analysis
- PCT is scalable and therefore can be extended upward or downward, as circumstances require, at any time
- PCT links display with action through goals
- Information is not displayed at the interface unless it contributes to the knowledge required to support the achievement of some goal/objective that has been designed into the system.

MIL–HDBK–46855 provides a process model that can be used to establish an HFE process compatible with an HSI program. Any new developments, such as PCT or CWA have to be compatible with the overall HSI process. We are confident PCT is, although it is clear that it will require training or experience to use. From that perspective it is no different from other HFE techniques, because university courses in HF typically do not teach HFE techniques except at the most rudimentary level.

7.8 SUMMARY

Structured analysis methods have been shown to contribute to the systems design process. Such methods have characterized front-end human engineering analysis for several decades. Typical of these structured approaches is Mission, Function, Task, Analysis (MFTA). Yet as systems have become more cognitive, some argue that the traditional methods fail to capture important aspects of the system specification, particularly with respect to the characteristics of the human-machine interface. This paper presents an alternative approach, PCT systems analysis, which claims to overcome many of the problems associated with traditional MFTA. Some comparisons are made with another method for human systems analysis, cognitive work analysis.

This paper presents a method of front-end human engineering analysis, based on the perceptual control theory model for goal-directed human behavior, with contributions from a time-based information processing model of the human operator. While this method might trace its origins to traditional MFTA, there are fundamental points of departure that distinguish the new method from the old. Central to these differences is:

- The replacement of separate function and task analyses with a unified hierarchical goal analysis
- The requirement to consider all goals, from the highest level to the

lowest, as candidates for assignment to an agent(s) (either human, machine) in the system

- The analyses that emerge from this process that trace both the stability of a system with multiple sources of control, and the upward flow of information from each level to support the level above.

PCT analysis and systems analysis can proceed in lockstep with design, shaped both by the constraints of the work domain and the constraints of human actors that are to populate the system as operators and maintainers. It supports the specification of goal and plan tracking databases for intelligent adaptive interface design, and has been used in one proof-of-concept application with encouraging results and tangible contributions to analysis. PCT systems analysis can make use of existing tools although the development of dedicated interfaces, to support this form of analysis, is needed. This will contribute to usability.

In contrast, CWA takes a more revolutionary path by arguing that design must start at the work domain and proceed through several processes before human capabilities and limitations start to shape the evolving system. Arguably it is a more complex process to implement, and the toolset is still in development. It has yet to be formally integrated into the engineering design process and is weak on methods for validating and verifying the design from a human perspective. However if, as some would claim, mission and scenario based analyses will inevitably fail in guiding successful designs of complex open systems, and PCT-based HGA cannot shake itself free of these criticisms, then the method proposed in this paper has a limited future. It is the view of the current authors that this issue is not yet settled.

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