Cognitive and Ecological Techniques Compared for Weapons of Mass Destruction Scenarios

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***Abstract*— The attempt to usefully model workflow in a target domain has produced many techniques that vary greatly in their cognitive and ecological assumptions. Cognitive work analysis (CWA) and goal-directed task analysis (GDTA) are two recent and powerful techniques developed for the disassembly of complex human-machine systems into more meaningful, coherent, and actable forms. In this paper, we discuss the use of these two techniques in the domain of responses to weapons of mass destruction (WMD) events, comparing and contrasting them in an attempt to determine what information can be drawn from the methods, whether or not it is redundant, and what overall benefits and costs are associated with these techniques. Their use in automation planning is featured as a key element for distinguishing one technique from the other.**

Index Terms - human-robot interaction (HRI), cognitive work analysis (CWA), goal-directed task analysis (GDTA), weapons of mass destruction, decision support systems, automation planning, situation awareness (SA)

I. Introduction

Today's methods of task analysis were first developed as a means to address a growing information gap - the distance between what information is available and what people actually need to know. As information increases and information overload plays a larger role in our perception of the world, these techniques can only grow to become more useful. Most modern methods, including the two discussed in this paper, share a rich common ancestry of user centered design (UCD) while also acknowledging and incorporating both ecological and cognitive principles, as opposed to older descriptive task analyses.

The formal study of WMD response systems, especially as they relate to automation planning, has intensified since the events of September 11th, 2001. Although related domains, including urban search and rescue (US&R) [1], have been studied intensely, the particular constraints of a WMD environment present additional challenges to the traditional methods of task analysis.

Cognitive work analysis, as developed by Rasmussen and Vicente, was initially created for modelling causal systems such as process control plants [9]. It has since been widely adopted as a tool for mapping various intentional systems as well, including those in military [3], [8] and emergency management [13] domains. Cummings, in her doctoral thesis [3], dealt with modifying CWA to fit the ecological constraints of revolutionary domains. These modifications and their applications to WMD systems will be discussed later in this paper.

Goal-directed task analysis, developed as a means for enhancing situational awareness (SA) by Endsley [5], is a newer technique and at this time has few practical examples, mostly concentrated in the domain of airspacec navigation and negotiation [6], [7]. As a decision support method, however, it seems to yield information and ideas not presented in CWA. It also traces its lineage through the ecological principles first adopted by Ramussen and Vicente. In the weapons of mass destruction domain, it will be shown as a useful tool for the analysis of responsibilities that is key in automation planning.

Sections II and III of this paper present the methods of GDTA and CWA that will be used in this domain. Section IV provides a comparison of the two methods and discusses their specific implications in the domain of WMD, and Section V presents the conclusion as well as outlining further work.

II. Modified cognitive work analysis

Cognitive work analysis is a more flexible system than those that preceeded it, focusing on the development of revolutionary decision support systems. Its principles are inherently more flexible than methods designed for any specific task and its constraint-based approach can provide information even in unanticipated scenarios.

Traditional CWA consists of five seperate stages, which are enumerated and described below. As the environment becomes understood, the stages move from a focus on ecological elements to a cognitive analysis to account for the user's actions. A CWA for a specific domain provides a generic map that can then aid in the creation of a flexible design for an interface.

An initial shortcoming of the method came in its application to revolutionary domains, that is, those fields which do not yet have established users. Cummings [3] dealt with the issue by introducing two new steps, which will also be discussed below.

A. Analysis of global social and organizational factors

The analysis of global social and organizational factors should occur prior to beginning the CWA in order to assure that all ethical and large-scale constraints are met.

B. Work domain analysis

Work domain analysis (WDA) is the first phase of cognitive work analysis and the key phase of ecological interface design [2]. It involves identifying all the goals and purposes of the system being studied. The first step requires reviewing all existing documentation in the particular domain of the system being studied, interviewing subject matter experts (SMEs), observing field exercises and analysis, etc. This information then gives a picture of the workplace that is not worker or task driven but is instead all-inclusive, giving an empirical perspective on the domain being studied. This data can then be combined, collated and visually demonstrated in order to present it in a more usable format to both the researchers and the users who will evaluate the analysis. Two well-established visual representations that are commonly used are the abstraction-decomposition and the abstraction hierarchy.

1) Abstraction-decomposition: An abstraction-decomposition is one method of representing a work domain analysis in a two dimensional matrix, answering the question of the nature of the subject domain and its components [11]. The decomposition has five or more steps, forming the rows of the matrix, as well as a part-whole decomposition going from left to right progressing from the most general part of a system to the most specific. The five steps that we will discuss include, at the highest level, goals, followed by priority measures, general functions, processes, and objects, in that order.

Goals are broad, abstract, encompassing components of a system that must be met in order to achieve system success. They are more cognitively demanding than any of the other components in the abstraction-decomposition. On a lower level, a priority measure gives a metric for evaluating the completion of a goal, rather than a specific description of a task. General functions are doers - breaking down goals into doable objects and giving some sort of sequence to tasks, while processes are elements of action that occur without the consideration of motivation. Objects are non-cognitive items required for processes, such as maps, books, or electronic information.

For any given subject, several abstraction-decompositions may be required in order to model the sequence of events occurring along with their associated goals.

2) Abstraction hierarchy: An abstraction hierarchy presents much of the same information as the abstraction-decomposition, but in a different form, answering the "why" and "how" questions associated with a WDA. It consists of a connected diagram, with the same number of steps as the abstraction-decomposition. It illustrates shared elements, interactions, and orderings between steps with connecting arrows, representing the means-ends relationships involved and showing how these steps come together to support decision-making.

Again, as with the abstraction-decomposition, many abstraction hierarchies may be required to fully represent the target domain. It should be noted that preserving the wording between this description technique and the abstraction-decomposition can be useful in maintaining coherence within the CWA. All data from the abstraction hierarchy should also be represented in the abstraction-decomposition, but the converse is not necessarily true, as it would not yield additional insight into the work domain.

C. Constraint-based task analysis

In a CWA, the WDA yields information about environmental constraints and gives an overall view of the system, while a constraint-based task analysis (CbTA) delves deeper and focuses on the actionable items that are considered in the decision-making process. It answers the question of what information and relationships are relevant for any given situation and the constraints that exist in the pursuit of goals [12]. The main method of visually representing a CbTA is the decision ladder.

1) Decision ladder: The decision ladder is commonly used to show the information processing activities and states of knowledge that are seen when command activities are performed. It is a valuable decision support tool, mapping the structure of the decision-making process [9], independently of how tasks are accomplished or who will do them.

The ladder is drawn with connected boxes and circles, where the boxes represent data-processing activities and the circles represent states of knowledge. A decision-making loop can also be used to represent reassessment in the decision-making process. The flow of the ladder generally will proceed from chronological start to end, but will leave some room for variability.

In addition to its decision support role, the decision ladder can be used as an automation planning tool by calling out the various stages that can be simplified by automation, drawing connecting arrows in between. This clearly shows exactly where decision support systems can come into play, as well as giving a better overall perspective on the cognitive nature of the decision-making process. Automation planning is a key point of comparison between GDTA and CWA that will be discussed in a later part of this paper.

D. Analysis of effective strategies

While a control task analysis describes the actual actions that need to be completed in order to achieve target goals in a particular domain, a proper analysis of strategies will show how these actions can be accomplished. However, this does not mean it should concentrate on accomplishing detailed procedures, but should instead focus on a higher level of strategic methods [12]. This can be difficult to perform in a revolutionary domain, like weapons of mass destruction, but educated guesses or prototype testing can aid in the process [3]. An information flow map is the primary method for visualizing an analysis of effective strategies [12].

1) Information flow map: The information flow map details the connections between possible strategies that an operator could use to effect success in the target domain. It also yields information on the considerations that go into the decision-making process.

Visually, the map illustrates (on the left) the decision to be made, (in the center) the options that are available, and (on the right) the likely outcome that could result. Since these considerations are inevitably connected, they are also connected in the information flow map. Action items studied in the CbTA and represented in the decision ladder are broken down to yield an information flow map, and thus it may take many information flow maps to represent a particular domain. Since some of the options in the map may depend on each other or may be linked in other ways, they are also connected.

E. Simulated domain

Developing a simulated domain as a testbed is an essential component of analysis for those fields for which there are no existing users. Without it, there can be no prototyping or other empirical testing in a revolutionary domain.

F. Analysis of local social and organizational factors

This fourth stage of CWA is the first that is not actor-independent: in fact, it actually describes the roles, responsibilities, and communications of each participant in the system. Within the context of traditional CWA, it is primarily cognitive in nature, focused on the individual worker rather than the organization as a whole. The social and organizational step is traditionally split into two parts: individual role allocation and analysis of organizational communication. In revolutionary domains, this analysis is hard to perform because of the lack of existing structure, along with the variability of scenarios in non-causal domains [3]. The main methods of analyzing the social and organizational factors in a domain is a listing of relevant social groups and the development of a communication flow map.

1) Relevant social groups: Identifying relevant social groups is a key component of organizational analysis. The routes of communication can be determined (through connections) and the relative structure of the organization can be discovered. Only groups immediately involved in the communication structure should be included, and they are boxed in position relative to their order in the chain of command. This information should generally be obtained from SMEs or observations, as documentation in this regard can be out-of-date or reality may differ from protocol, especially in intentional domains.

2) Communication flow map: A communication flow map illustrates the order and hierarchy through which information is conveyed. It demonstrates the flow of communication from source to those with a need to know. Types and/or methods of communication can be indicated by changing the type of link connecting the two groups involved in the discussion and then explained in a key.

G. Identify demands on worker competencies

Identifying demands on work competencies is a vital cognitive component of CWA. Done correctly, it can yield an understanding of worker capacities and capabilities, which becomes vital as the constraints and requirements of the work domain are understood (through the ecological methods already discussed). The two methods discussed here for breaking down worker competencies are the activity analysis and the skills, rules, and knowledge (SRK) taxonomy, which are primarily non-visual.

1) Activity analysis: Activity analysis is one method of assigning tasks based upon worker limitations [8]. It involves developing a two dimensional matrix that encompasses, as rows, the work problems and, as columns, the status of the worker. Alternate team designs can then be boxed out and given feasibility scores, based on the determination of their capabilities.

2) SRK taxonomy: The SRK taxonomy illustrates three levels of cognitive behavior, sometimes known as divisions of human performance [12]. Developed by Rasmussen [10], it differentiates worker actions into three levels by increasing cognitive demand: skill-based behavior (SBB), rule-based behavior (RBB), and knowledge-based behavior (KBB). An SBB occurs without planning or conscious thought and is generally reactive. A RBB is an action or set of actions that has been learned or integrated consciously but is now almost entirely rule-based. A KBB, the most cognitively demanding of the behaviors, is a behavior that requires complex cognitive processing, possibly developing the procedure for a new RBB for a new situation. The KBB phase of cognitive processing is the one that concerns worker competencies and should be developed as far as necessary.

H. Summary

Cognitive work analysis is a useful tool in the analysis of ecological and cognitive constraints in a work environment. Its elements combine to form a broader and more complete picture of the target domain than would be suggested by the sum of its components. Describing the workplace from a multitude of perspectives, CWA provides an insightful look at the decision-making process it supports.

III. Goal-directed task analysis

Goal-directed task analysis is a method developed in order to support decision making, specifically by supporting situational awareness (SA). SA is a concept that has had many definitions, but the widely accepted formal definition is '*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status into the near future*' [4]. It thus has three levels:

1) Perception of elements in the environment
2) Comprehension of the current situation
3) Projection of future status

In its attempt to support SA, GDTA breaks down a specific work domain into various goals and subgoals that have specific SA requirements which can then be enumerated. To formalize this description a bit, goals are defined as '*higher-order objects essential to successful job performance*' [5]. From an ecological and user-centered perspective, the four steps described below are designed to yield a complete picture of the SA needs in a particular domain, aiding in the eventual creation of any particular interface or automation that may be needed or desired.

A. Goal hierarchy

A goal hierarchy (GH) is a preliminary visual structure that defines and gives an ordering to the primary and secondary goals of a system. It is generally created through an exhaustive review of documentation within the domain, personal contact and free-flowing interviews with potential users, and observation of the current system in action.

The hierarchy consists of a layered flowchart, with each subsequent level representing lower-level goals. At this preliminary stage, the GH should not extend beyond representing a total of 3 levels: the primary goal of a system, its associated subgoals, and their associated subgoals. Within each level, some sort of ordering should be given to each goal (e.g. chronological, by importance, etc.), aiding further revision.

As well, numbering the goals and subgoals and giving a definition to each term used will help comprehension when secondary interviews are performed. Ensuring that the goals described are not information requirements (e.g. status, conditions, etc.) or tasks of a cognitively simple nature at this step will lessen confusion and the need for revision later in the analysis.

B. Secondary interviews

The second round of interviews with subject matter experts is done in order to confirm the initial results of the goal hierarchy, as well as expanding it or modifying it in any way necessary. All efforts should be made by the researcher(s) to not bias interviews with preconceptions based on the initial structure(s) developed, including introducing the structure of the goal hierarchy or other documentation in stages.

Confirming each level of goals should be the primary objective of these interviews, as well as ensuring that the terminology used in the GDTA is approporiate for the domain in question. These concerns ensure that the results of the GDTA will be usable by persons working in the subject area and other researchers in the field.

Recording the interview through microphones, cameras, or other recording equipment may assist in later revisions of the GDTA structure, but caution should be taken that answers will not be biased by the presence of this equipment. Questions should be prepared ahead of time and limited to the amount of time available for each interview, but, if time permits, spontaneous questions should be voiced.

C. Expanded goal-decision-SA structure

Once the results of the secondary interviews have been incorporated into the structure of the preliminary GDTA, expanded goal structures should be created, with additional levels as necessary. These new goals should fall naturally under the mantle of existing higher-level goals.

The next step is thus to incorporate decision questions for each goal that, if answered correctly, would compactly, efficiently, and completely achieve the goal. These should not be phrased as yes or no questions but instead should be answered using higher cognitive processing. Several questions may be needed to appropriately address each goal and in that case each question may have its own SA requirements. The wording used in these questions should remain consistent with the wording that has been used throughout the GDTA.

Finally, the SA requirements needed to answer these questions should be positioned underneath these questions and should detail all the information the user needs to make that particular decision, without acknowledgment to the means by which the data is gathered [5], found by reviewing the literature already examined as well as the notes taken from SMEs and observations. Caution should be taken when reviewing literature that gives procedures for the subject domain, as a GDTA is inherently goal-oriented in nature. If specific SA requirements are used in multiple decisions, they should be "called out" and moved outside both of their SA structures.

D. Feedback

Feedback on the GDTA at this stage should be conducted similarly to the secondary interviews already completed. Discussion should focus on specific issues encountered, deficiencies noted, and limited understanding discovered within the context of information incorporated into the expanded structure of the GDTA. At this point, the amount of information present in the GDTA is often too large to present in complete form to the SMEs. For that reason, the interview should be concentrated on the areas already noted above and the information formatted in such a way as to support that goal. The feedback received should be iteratively fed back into the structure of the GDTA and the process repeated if necessary until a high level of consistency, coherence, and completeness has been achieved.

E. Summary

Goal-directed task analysis is a powerful technique specifically designed to support situational awareness in a given domain. It uses information that directly relates to user ideas and concepts and can thus be easily checked by SMEs or compared to documentation at any point. Although not as wide-ranging in its perspective as CWA, GDTA gives very specific SA requirements that can directly assist in the conceptualization and development of interfaces or necessary tools. Used properly, it yields a broad but yet specific and meaningful sketch of the target domain.

IV. Comparison of two WMD response models

Figure X illustrates proposed relationships between elements of the GDTA and the CWA, using standard logic and functional notation. These were discovered and developed by application of the modeling techniques in the domain of WMD and subsequent review, interviews, observations, and discussions. By making these connections, however, we do not intentionally imply that every item in a given GDTA will be represented in the CWA in such a fashion, but merely that there is a possible correspondance between those particular elements. For example, some of the priority measures in the WDA can be higher-level questions in the GDTA and vice versa but they do not all have to be mapped in this manner. There is some repetition of elements in the CWA that is noted in figure X and will be discussed below.

A. Mappings

Goals, as used in the work domain analysis portion of CWA, can be mapped one by one to the goals of GDTA, due to their nearly-identical definitions and usage. Within the CWA itself, individual priority measures in the WDA can be combined to form the basis for creating a decision ladder in constraint-based task analysis. Outside of CWA, priority measures can be converted without much alteration into appropriate higher-level decision questions from GDTA, as they share similar purposes. General functions and processes are sometimes themselves subsumed into the information processing portion of individual decision ladders, depending on the priority measures being employed. If their state is considered, some processes and objects can be mapped onto the situational awareness requirements of GDTA.

In fact, some of the states of knowledge in the decision ladder, the relevant social groups, and information from the communication flow map can *also* be mapped onto SA requirements within GDTA. This mapping can be achieved since the SA requirements in a given domain are multitudinous and cover a wide range of information that is more clearly partitioned in CWA. The information flow map can correlate to one or several lower-level questions in GDTA (i.e. those underneath the upper 2 levels) by breaking down major goal decisions into their components. This correlation is not necessarily exact, as the information flow map seems to focus more on the decision-making process, while the lower-level questions attempt to elucidate the nature of the decision itself in order to support SA. As GDTA is mostly actor-independent, there does not seem to be a corresponding representation for the activity analysis procedure of CWA.

B. Findings

Automation planning, as incorporated into the decision ladder of CWA, is not explicitly represented in GDTA. A goal hierarchy can be augmented with additional information about levels of automation or other general ideas of possible decision support tools, but as it stands the goal hierarchy does not clearly delineate the areas of the decision-making process affected by the possible introduction of automation nor does it discuss how they might be changed. This seems to be an important distinction between CWA and GDTA.

Another key point in favor of CWA is the inclusion of timing elements into the structure of the analysis. The decision ladder and the information flow maps do, by definition, incorporate timing as a means of organizing their elements, and other parts of CWA can be similarly adapted. Although some time order can be given to the goal hierarchy of GDTA, it cannot account for overlapping goals or variable situations (in an intentional domain), whereas the lower-level elements of CWA can. Difficulties can arise when interviews are being conducted in communicating the nature of each element in sequence. For example, the goal of investigating to assign responsibility for a WMD attack, taking place after an event, was confused with the goal of investigating to prevent WMD attacks, which takes place before an event, because no time sequence was given. Eventually, a chart giving a time sequence for the events of WMD response was developed and this issue was somewhat obviated.

In GDTA's favor, however, its methods and elements are easier for potential users in intentional domains to comprehend, give feedback on, and eventually use. The elaborate and varied visual schemes of CWA do not seem to map as cleanly to the existing documentation in the WMD response community as do the ideas of goals, tasks, and situational awareness, which are all familiar terms in that community. Thanks to this distinction, GDTA is more relevant to intentional domains, using the proper terminology to support the decision-making process clearly and succinctly. A GDTA for a given domain is also simpler to construct than the corresponding CWA, due to its narrower focus on supporting SA. On the other hand, the variety of labels CWA places on the environmental elements it considers can make for a more organized, efficient, and productive discussion than an interview focusing on a multitude of SA requirements distinguished only by the goals that partition them. GDTA's SA requirements seem to be "catch alls" for many categorically different pieces of information, whereas CWA has many methods that intersect SA, as discussed in the mappings section, but show it in a richer and more organized manner.

By applying both methods simultaneously, however, the directness of the GDTA with its focus on SA and the broad and detailed sweep of CWA provide a much more specific and thorough analysis than either one on its own. A mix of the methods used to put each technique to work can then go into the later evaluation of automation, interfaces, and other HRI concerns. Greater than the sum of their parts, both techniques have been useful as intense WMD response study has shown.

V. Conclusion

Although both CWA and GDTA offer comprehensive data on the decisions that need to be made in a WMD response situation, the situational awareness focused approach of GDTA lends itself to the quick decision-making process needed in a WMD event. It is also faster to construct and easier to understand. However, CWA is a more established procedure and has been seen to lend itself to automation planning, timing issue resolution, and a clear categorization of information. Both will be pursued as this work continues.

Future work in this area includes finalizing a detailed CWA of a WMD scenario, as well as completing the GDTA that has been created. Observation of WMD response exercises, increased interviewing of response personnel, and continued review of WMD and cognitive literature will also be done to enhance our overall perspective on WMD response events.

This work will be done in an attempt to eventually analyze, design, and evaluate automation and interfaces for a WMD situation.

ACKNOWLEDGMENT

The authors would like to thank Officers Chip Hooper, Mike Schilling, and Todd Mask of the Nashville Metro Police and Tim Henderson of the Nashville Fire Department for their feedback on the research presented within.

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