

KNOWLEDGE ACQUISITION IN SUPPORT OF ARTIFICIAL INTELLIGENCE: AN EXAMPLE AND SOME LESSONS LEARNED

Martin S. Kleiner

Logicon RDA
113 Kingsway, Suite 102
Hampton, Virginia 22639, U.S.A.

Scott A. Carey

Logicon RDA
317 S. 2nd Street
Leavenworth, Kansas 66048, U.S.A.

ABSTRACT

The Defense Advanced Research Projects Agency (DARPA) Command Forces (CFOR) program has undertaken the development of intelligent agents to perform the function of command and control within advanced warfighting simulations. While service-related tactics and doctrine publications provide a general description of what a commander must do, they do not address the cognitive processes that are applied during command decision making. Furthermore, existing material is not in a format that lends itself to knowledge engineering. DARPA instituted a focused knowledge acquisition (KA) effort as a component of its Synthetic Theater of War (STOW) program to support the development of intelligent command entities (CEs).

This paper presents the methodology and products that have been created to support the development of Army CEs within the STOW CFOR program. Additionally, it provides some insights and lessons learned that may have applicability across a wide field of KA efforts.

1 BACKGROUND

Logicon RDA is currently under contract with DARPA to provide KA services and subject matter expert (SME) support for the STOW Advanced Concept Technology Demonstration (ACTD). This ACTD has been designated STOW-97 and will be conducted in support of U.S. Atlantic Command during exercise Unified Endeavor 98-1. Core simulation technologies that support STOW are under development by DARPA's Information Systems Office (ISO). These core technologies include Modular Semi-Automated Forces (ModSAF), Intelligent Forces (IFOR), and CFOR for the U.S. Navy, U.S. Air Force, U.S. Marine Corps, and U.S. Army components of a Joint Task Force (JTF). ModSAF provides platform-level representations of weapons systems and small units whose behavior is controlled through the use of rule-based tasks

organized in task frames or by an intelligent agent, interacting with the vehicle-level ModSAF simulation through an entity control interface.

CE representations are being developed as part of the CFOR program. CEs exercise command and control over subordinates, which may be manned simulators, virtual simulations such as ModSAF and IFOR, or, in some cases, real manned combat vehicles. The first CEs will be the Army's heavy company team (Co/Tm) commander, and the attack helicopter company commander, as well as a limited battalion command capability.

A detailed description of the Army capabilities planned for STOW may be found in Feldmann (1995). The CFOR concept and technical reference model are described in Dahman, et al. (1994).

2 COMMAND FORCES COMMAND ENTITIES

The goal of the user model is to represent the discrete decision-making processes that a specific functional commander and, where appropriate, his staff use to plan and execute combat operations. In order to be effective over a wide range of applications, the model must be soundly based on doctrinal principles and take into account the following considerations:

- Command decision making involves both innovative and deductive reasoning (commonly referred to as the art and science of warfare).
- Command decision making is always highly contextual. This requires a clear definition of the variables that set the context (e.g., the construct of Mission, Enemy, Terrain/Weather, Troops and Time Available (METT-T)) and a method for weighting these variables.
- The model should incorporate human factors such as levels of aggressiveness and willingness to take risks.
- The model should accept the inputs and produce its outputs in the same form and format as the real-world entity that it is emulating.

The CE must be capable of both planning and executing an operation, in the sense that as the reality of an ongoing operation diverges from the plan the CE must recognize this and adapt its unit's behavior to deal with the situation. To date, several developers have demonstrated effective CEs, at a more than rudimentary level, within varied tactical situations.

3 DOMAIN DESCRIPTION

In order to fully understand the scope and intricacies required of the CFOR CEs it is first important to understand the real-world entities that they must emulate and the environment in which they must operate.

3.1 Organization

The Army is a hierarchical organization whose basic building blocks are individual soldiers assembled and organized into small groups. Each group has specific missions, functions and lines of authority. The most elemental group is the section or squad. In the infantry, the squad is the lowest-level element that can conduct the collective task of fire and maneuver. In units possessing major weapons systems, such as tanks, infantry fighting vehicles, or artillery pieces, the crews of one or more weapons system constitutes a section. Multiples of these elements (usually two to five) are then organized into platoons and then into company-level units (sometimes designated as batteries or troops depending on their branch or mission).

The full authority and responsibility of command and control decision making reside at the company level. This is the first level where the commander has complete responsibility for planning, organizing and executing the full range of tactical missions. The company commander is also responsible for the logistical, administrative and personnel support of the unit and all attached elements. Although the term *commander* is sometimes used at lower levels, such as tank commander, they have a much narrower (although still great) responsibility for fighting their weapons system and directing their crews.

Continuing up the organizational structure, a number of companies are organized into a battalion, with the battalion commander exercising authority over all of the company commanders. This is the first level where the commander is supported by an organized and assigned staff. A number of battalions constitute a brigade, with a brigade commander and staff, and thus up through division, corps, and Army levels.

3.2 Command Authority and Responsibility

While the Army is organized from the bottom up, its missions, command authority and command responsibility are

delegated from the JTF commander and flow down to the company level. The company level is where the majority of actual fighting takes place during wartime.

A unique aspect of ground combat forces is that at each sequential level of command, down to the company, the commander is given a mission, a set of assets and a three-dimensional block of terrain. He is then given full responsibility and authority for this terrain, within which he is to employ his assets and accomplish the mission.

3.3 The Decision-Making Environment

Along with the commander's authority and responsibility comes a degree of autonomy that is unique. In some respects this autonomy is complete, as in the fact that no one, including his higher headquarters, can fire into, enter or otherwise effect change within the block of terrain, without explicit coordination and permission. In other respects, his autonomy is restricted, bounded and influenced by outside factors:

- The commander must plan and execute his actions in accordance with the mission guidance from higher headquarters (i.e., he may not retreat if his mission is to attack).
- The commander is expected to follow the commonly held principles of war, doctrine, tactics, techniques and procedures (he does not rush hastily ahead nor fall behind in an attack, thereby exposing his, or an adjacent unit's, flank).
- The commander is influenced by the enemy's actions (he can not execute a pursuit if the enemy executes an effective defense).
- The assets and terrain assigned to the commander enable or preclude certain actions (e.g., without bridging support he must find and use natural fording points on streams, thus limiting mobility and avenues of approach).

For planning purposes these influences have been collected and ordered into the factors of: Mission, Enemy, Troops, Terrain and Time, referred to as METT-T.

The company commander also possesses a higher-order knowledge that results from his training, experiences, and knowledge of his commanders and subordinates. This knowledge and the factors of METT-T form the basis for the commander's decision making.

As an analogy, the JTF HQ can be viewed as a force-generating element (and, in fact, force generation is a function that is attributed to high-level headquarters). Each of the intervening headquarters can be viewed, again simplistically, as a reduction and distribution gear, applying this force down to and across the battlefield. In the end, the force is applied by the weapons systems, both human and physical, that belong to the companies. To make use of this analogy though, one must realize that force is not

applied evenly nor equally across the battlefield. The principles of war dictate that a commander both "Concentrate combat power at the decisive place and time" (mass) and "Allocate minimum essential combat power to secondary efforts" (economy). It is here that the cognitive capabilities of the intervening commanders, and their staffs, come into being. It is their knowledge of the higher commander's intent, the mission, the situation and the enemy (METT-T) that allows them to alter the "ratios" and paths of the individual gears, thus applying the maximum force at the opportune time and ensuring decisive victory.

Finally, it must be noted that the decision-making process is continuous and iterative. When a company commander receives a mission it is likely that he has already formulated a general concept or plan, based on a warning order or some other prior knowledge. As he receives more information, he considers various courses of action, choosing some and eliminating others. He goes through this process for each phase of his mission. He then formulates his decisions into a plan and issues it as an order to his platoons and attached support elements. As he executes the plan he reviews each decision and the factors that now exist in reality (METT-T). If the actual factors vary significantly from the planning factors that caused him to select a given course of action, he may decide to modify or choose a different course of action. If, during the planning phase, the commander has considered and analyzed the full realm of possibilities, this real-time tactical decision making becomes the substitution of a more appropriate (and previously devised) course of action to meet the circumstances of reality. While seemingly reactive, it is the result of proactive prior planning.

One critical note on command decision making, especially in combat, is that it must be conducted within the elements that Carl von Clausewitz refers to as the "fog and friction of war." Translated into modern problem solving terminology, this means that the commander is always dealing with the following issues:

- An incomplete and changing problem specification
- A constant requirement for situation awareness that is never fully satisfied
- The feedback of effects on both enemy and friendly forces, neither of which is entirely true nor complete
- The issue of a rapid tempo and fleeting opportunities, requiring that decisions must be made before complete decision criteria are available

In summary, the issue is succinctly stated in the following quotation by Helmuth von Moltke:

The problem is to grasp, in innumerable special cases, the actual situation which is covered by the mist of uncertainty, to appraise the facts correctly and to guess the unknown elements, to reach a decision quickly and then to carry it out forcefully and relentlessly.

4 DEVELOPMENT OF A GENERALIZED UNIVERSAL KNOWLEDGE BASE

One of the basic precepts of the CFOR program is that there will be many agencies utilizing various approaches to developing the CEs. In some cases different agencies will develop representations of the same CE, and in other cases they will develop complementary CEs that will be required to interact with each other. Since all of the CEs will be required to work within an interactive environment that includes humans as well as constructive and virtual simulations, this demands that the CEs be based on a universal and doctrinally recognizable knowledge base.

To ensure doctrinal soundness, inherent validity, and a high degree of user acceptance, a decision was made to develop the knowledge base within the construct of the Army Training and Evaluation Program (ARTEP). The ARTEP, by type and echelon of unit, defines the missions, the collective tasks, the conditions and standards that Army tactical units are expected to perform and achieve. At the interface between each echelon the tasks of the lower element, from individual soldier to brigade level, are subsumed into the missions and tasks of the higher unit.

Utilizing the appropriate ARTEP Mission Training Plan (MTP) for the units to be modeled, the critical warfighting tasks are extracted and a discreet decision module is built around each of these collective tasks. This provides a set of clearly defined, doctrinally based, mission-related primary decision elements. Each module is produced in a standardized format and consists of:

- The decisions to be made
- The possible paths or interactions of these decisions
- The variables involved in the decision as defined by a doctrinally based set of factors; i.e., METT-T
- A list of inputs required to make the decision, as well as the sources for those inputs
- The specific outputs required from each decision, including the required form and format (i.e. orders, plans, messages, etc.)

Additionally, each module includes detailed graphics depicting the execution of the task in order to provide the knowledge engineers with a contextual visualization and understanding of the task.

While the individual modules are the fundamental building blocks of the command decision process, alone they fail to address the key elements of the higher-order process that occurs at the company level and above. Key elements of this higher, second-order decision-making process are:

- Decisions for one task are interrelated with and must be made in concert with the other tasks and decisions that constitute a mission, operation or campaign
- Collectively, as well as individually, the tasks must meet

the criteria of:

- Suitability (they accomplish the mission)
- Feasibility (the resources are realistically available)
- Acceptability (the pain is worth the gain)
- Individual task decisions must be part of a cohesive process that is conducted within and defined by the specific factors of METT-T

In order to accommodate the requirement to make these decisions on an interactive, mission-related basis a generic, but representative, tactical mission is developed and amplified from the planning phase through its execution. This higher, second-order decision process describes the interrelationships, interactions and dependencies of the subtasks and decisions within the context of an overall mission. This second-order process normally represents a mission that begins with a planning process and proceeds through preparation, execution (to include adaptation to changes), reconstitution, and transition into a subsequent mission. In keeping with the goal of adhering to a real-world form and function, this integrated event has been designated as a virtual field training exercise (vFTX) and mirrors the field Army's use of an FTX as a capstone training and evaluation tool for each echelon of command.

The first series of task modules and vFTX addressed the attack mission. These products were accompanied by a series of additional papers, designed to provide the computer scientist and software engineer with necessary background and contextual information. The papers provided a broad overview of the U.S. Army and then focused on the decision-making environment of the company team commander. They include information on:

- Task organization
- Threat tactics, doctrine and organization
- Terrain and weather effects
- Operational terms and graphics

These initial deliveries were followed by additional task modules and vFTXs covering defensive operations, company logistics operations, and the missions of delay, screen, and guard. The concept for developing the CEs is that they will initially be able to conduct a full, but very basic, mission from beginning to end. Their capabilities are then expanded in terms of both types of missions and the complexities of the missions.

4.1 Support for the Development Process

From the outset it was known that additional information and levels of detail would be required in order to translate the initial knowledge base into functioning CEs. At the initiation of each development agency's effort they are briefed on the concept and contents of the knowledge base and encouraged to initiate a dialogue with the SMEs. Questions received from the developers generally fall into two categories, either approach specific or general to the domain.

The first are questions that are directly related to or generated by the particular approach that a developer is taking. These often require the creation of products that are tailored to the developer and might be useful to only their approach. In some instances, however, the development of these products points out an area that represents a general information deficit. In cases where the issue of proprietary information arises, the issue is referred to the MITRE program integration office and, if necessary, a generic product is produced and distributed to all of the developers.

The second case involves questions that are common amongst all of the developers and arise out of vagueness or a lack of detail in the general knowledge base. More often than not, these points revolve around the most complex issues that represent the more advanced human behaviors such as course of action (COA) generation and bounding. In this particular case a tutorial was developed and presented to the developers and the program integration office collectively. While there was some concern that this tutorial did not reduce the COA generation process to a series of flowcharts and decision matrices, it did involve the developers in the very human process of developing and bounding COAs in a constrained environment. The end result was that the developers gained a much greater appreciation for the process and were able to implement it with significant success.

As the CEs continue to be developed in both breadth and complexity of mission, a continuous dialogue has developed between the developers and the SMEs. This aspect not only provides the developers with additional information but also expands the technical understanding of the supporting SMEs.

4.2 Testing and Evaluation of Command Entities

Once the development of the CEs was initiated, it was necessary to develop a method for evaluating their tactical behavior and performance in a realistic manner. Again, the real-world method was employed by adapting the evaluation portion of the ARTEP to measure the company teams' performance. Utilizing the real-world training and evaluation paradigm as a guide, it was understood that the virtual CEs would progress from a limited capability to a broader and more complex capability, mirroring their human counterparts. In order to accommodate this growth, a progressive training and evaluation regime was developed. At an early stage, a series of products was developed that laid out to the developers the performance criteria that was expected of their CEs. These products included a matrix, as shown in figure 1, and an ordered task listing:

- The matrix defines the possible universe within which the virtual company team commander would be expected to be tested. The variables consisted of the

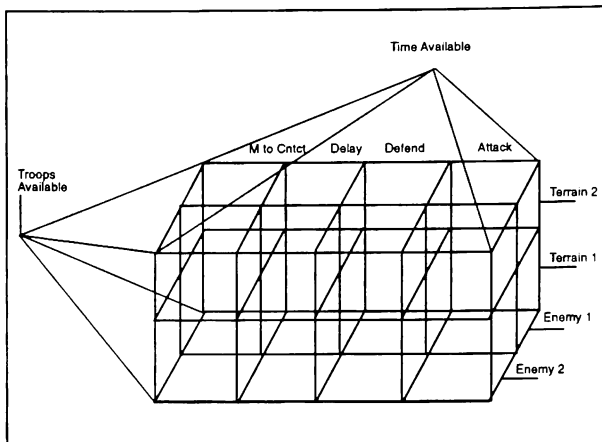


Figure 1: Command Entity Test

standard categories of METT-T, which were then broken down into clearly distinct sets with one to four variations of each factor.

- Mission
 - Attack
 - Defend
 - Delay
 - Movement to contact
- Enemy
 - Type 1 force ratios as expected for the type of operation
 - Type 2 force ratios either greater or lesser than expected
- Troops available
 - A general variable ranging from pure armor or mechanized infantry to a mixture including scouts and mortars. The number of platoons will range from two to six.
- Terrain
- Time available
- A general variable that will fall within the practical range that would be encountered, but that might force a commander to choose between certain options within a mission, such as routes of march or the emplacement of various types or numbers of obstacles.
- A listing of tasks that is designed to accommodate growth from a very primary capability to a more advanced and adaptive level of competence. The tasks were placed in three categories by mission type:
 - Category 1. A discretionary selection of tasks within a mission type that constitutes an elementary vFTX within that mission. The ability to accomplish a vFTX consisting of these tasks within each mission type is necessary in order to constitute a rudimentary virtual Co/Tm commander.
 - Category 2. The complement of tasks within a mission type that, combined with category 1 tasks and

a wider range of the other variables, demonstrates an increased ability to properly react to unplanned for circumstances and constitute an “apprentice” virtual Co/Tm commander.

- Category 3. The full range of tasks within a mission type constitutes a competent virtual Co/Tm commander.

The numbering of these tasks in no way constitutes a rank ordering of their importance to a commander, either virtual or human. This breakdown of tasks is simply a way of accommodating the development, growth and fair testing of candidate software.

4.3 Mission-to-Task Decomposition Methodology

Although the ARTEP prescribes a listing of all applicable tasks by mission, it does not present any distinct methodology for determining which tasks are required to accomplish any specific mission under a set of conditions. To date, the development of mission-related task strings for a given set of METT-T has been accomplished by highly experienced professionals and has fallen primarily within the purview of the “art of war”. When the devolution process to lower units and the integration of supporting BOSS is undertaken, this process becomes very complex but is an absolutely critical component of commanding a unit.

To overcome this deficiency, an effort was launched to develop a clear and concise mission-to-task decomposition methodology. The goal of this effort was to provide the developers with a tool that could apply the variables at hand and consequently extract the specific set of tasks required to accomplish any given mission. While almost any task can occur in any given mission the ones that are actually required are generated by the factors of ETT-T as associated with the assigned mission. Although the tasks often, and sometimes must, occur sequentially, they are not necessarily mutually exclusive and many may occur concurrently as well as in varied sequences.

As work on the methodology progressed, it soon became apparent that there was some element of phasing that lay under and, along with the specific factors of ETT-T, influenced the selection and ordering of the tasks. Initial efforts were made at utilizing a geographically based phasing method. While this method proved to be effective in attack operations, which normally involve movement and an orientation on terrain or an enemy location, it proved unsuitable for application to defensive operations. Subsequently, a temporal-based phasing method was developed, but this too proved unsatisfactory when applied across all mission areas. At this point it became obvious that the phasing should not be coupled with one of the primary variables in the METT-T equation, but should rather be associated with general processes that occur within all missions.

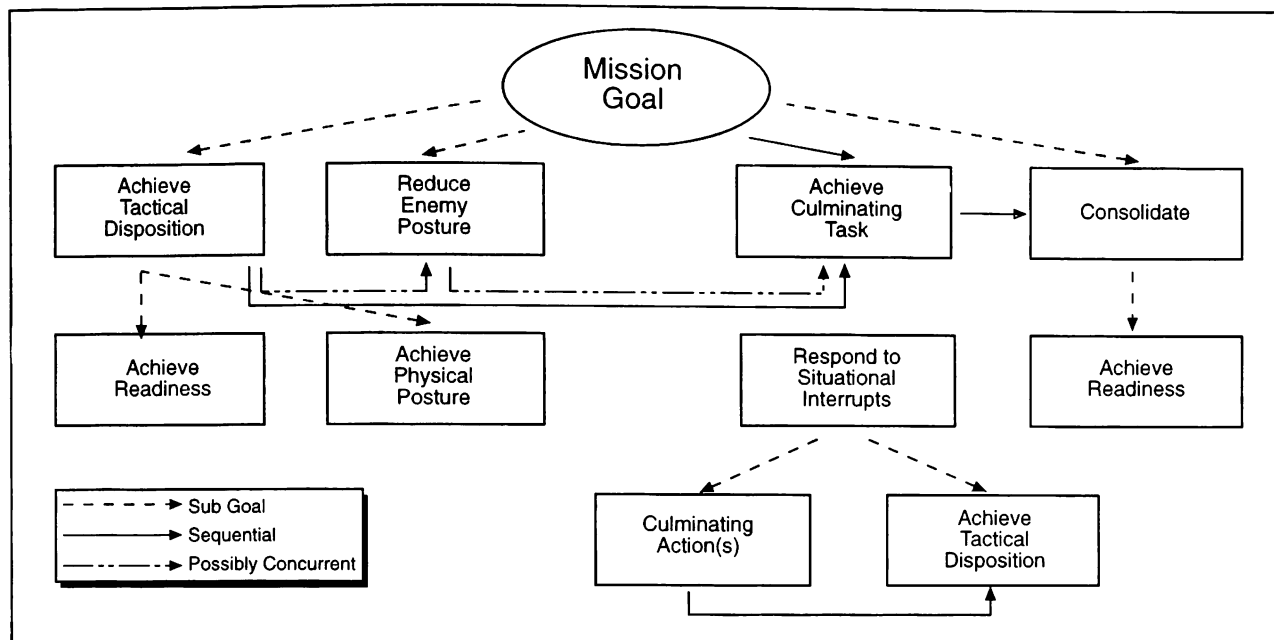


Figure 2: Universal Mission-to-Task Decomposition Model

After careful analysis it was determined that each mission within the ARTEP MTP can be decomposed into logical segments (see figure 2), each with a precondition (or set of preconditions) and a goal. These segments are:

- Achieve tactical disposition
 - Achieve readiness
 - Achieve physical posture
- Reduce enemy posture
- Achieve culminating task
- Consolidate

For any given mission, one culminating task is selected and represents the entry point into the process. Once the culminating task is selected, the reverse planning sequence is utilized in conjunction with the factors/variables of ETT-T to determine the specific string of tasks that will be required under the given conditions.

Situational interrupts may occur when the unit is influenced by unplanned factors, such as an enemy attack or impassable terrain. Situational interrupts may preclude the unit from accomplishing its mission.

An example of the company team attack mission-to-task decomposition is depicted in figure 3, including an assignment of missions to subordinate platoons. In the interest of brevity a listing of the referenced tasks has been omitted, but may be found in ARTEP 71-1 MTP.

This mission-to-task decomposition has been developed for all heavy battalion task force missions, for all heavy company team missions, and for a representative sampling of platoon-level missions. It has been used for the integration of combat support (CS) and combat service support

(CSS) operations and is extensible to virtually all types and echelons of units conducting operations.

5 LESSONS LEARNED

5.1 The Role of Doctrine and Its Adversaries

In creating a knowledge base to support the development of intelligent CEs, doctrine is not merely useful or helpful, but is in fact absolutely critical. Military doctrine represents not only the group's previous experiences but its practitioner's hard won insights and, when formed properly, the innovative thinker's projections for future warfighting. As stated in the Army's capstone manual, "Doctrine touches all aspects of the Army. It facilitates communications between Army personnel no matter where they serve, establishes a shared professional culture and approach to operations, and serves as the basis for the curriculum in the Army school system" (FM-100-5, 1993).

If the knowledge base is not tightly tied to the service's doctrinal base, then it may only represent one individual's knowledge and experiences within a limited set of circumstances. An individual's experiences are more often than not anecdotal, explaining what happened, but not why it happened. They may often represent a very specific solution to a unique problem. Developers unfamiliar with the domain will then integrate these methods as the norm and thus limit the CE's ability to deal with the wide range of situations encountered. When the knowledge base is developed as an expansion of the service's doctrinal

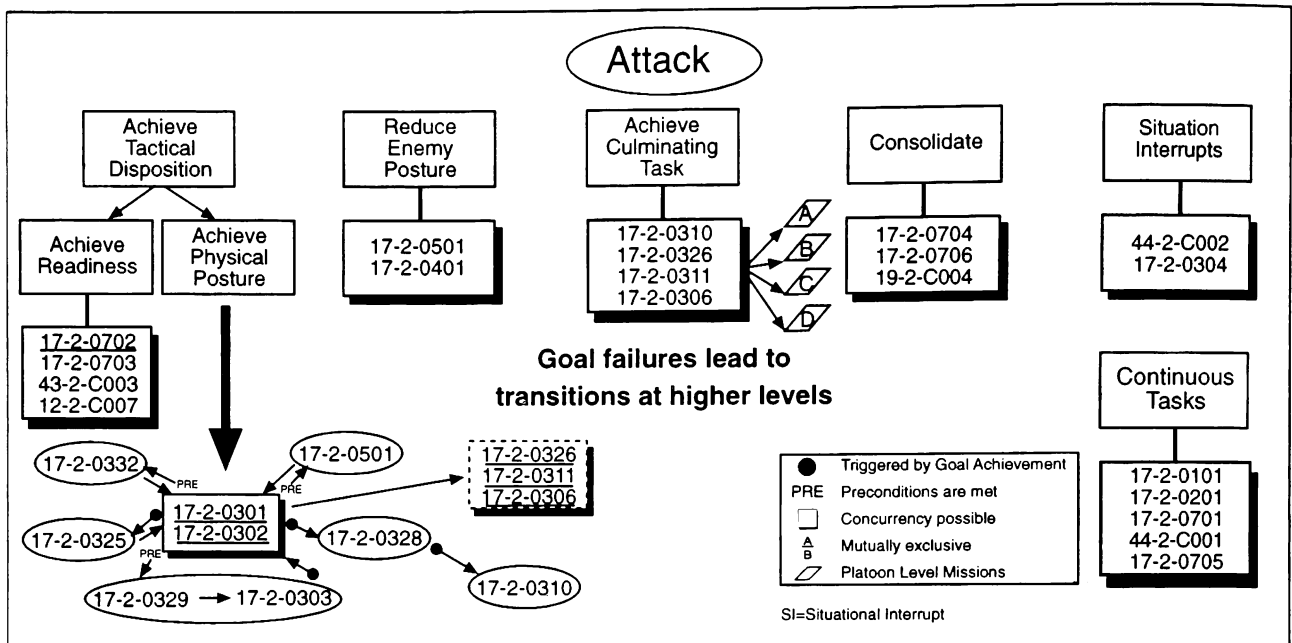


Figure 3: Company Team Attack Mission-to-Task Decomposition

base, the CEs become much more robust in their ability to deal with a host of circumstances.

A second benefit of utilizing the doctrinal base as the foundation for the CEs is that it significantly supports the validation of the end product. When the vast majority of the knowledge base is rooted in doctrine, there is little question as to its acceptability or why it is included. Additionally, when the developers of the CEs have become steeped in the terms, jargon, and processes that are used by the actual practitioners they are emulating, they are much better able to articulate their processes to the target audience and are much more accepted by them.

Unfortunately, doctrine has many adversaries, both within the services and in the development community. These adversaries hold the view that doctrine is simply a rigid set of rules and processes that represents the lowest common denominator for articulating a problem or finding a solution. In their view doctrine is a backward-looking, stifling influence that will inhibit initiative, preclude innovation, and eliminate aggressiveness. This precept is often held by those that have neither studied nor practiced doctrine in its true sense, and the battle to overcome their resistance is constant. As appropriately practiced or integrated into a CE, the use of doctrine meets the following criteria: "Never static, always dynamic, the Army's doctrine is firmly rooted in the realities of current capabilities. At the same time it reaches out with a measure of confidence to the future" (*ibid.*).

5.2 Combined Arms Integration

With the development of various CEs, it became apparent that a specific effort would have to be made to ensure that these elements could perform as an integrated combined arms team on the virtual battlefield. This situation was anticipated because it accurately reflects the circumstances as they exist in reality. Although aware that they must operate in a combined arms environment, the Army's branches concentrate primarily on their specific areas of responsibility. It is the task of the combined arms integration centers and field commanders to ensure that the various processes, procedures and equipment operate in a collective and synergistic manner.

In the CFOR program the combined arms team's complexity came to light when the question was raised as to how the fire support CEs would integrate the maneuver CEs concept of operations. This requires the fire support and maneuver CEs to carry on a dialogue with the resulting fire support plans and products supporting the maneuver CE's plan. This requirement had not been actively anticipated by the majority of the CE developers and it was decided that they should be made aware of such issues sooner rather than later. To this end, supporting materials were developed and a seminar was conducted that detailed the integration and interaction that is required to conduct combined arms operations at the battalion task force level and below. This seminar used the same form and format as the previously developed products (i.e., decision modules, vFTX) and built on them where necessary. In particular, it expanded the mission-to-task methodology

to the point where it is now capable of incorporating the required CS and CSS functionality along with the maneuver CEs requirements. The seminar was very interactive and proved a significant boost to stimulating the combined arms integration development.

5.3 Individual Knowledge, Experience and Personalities

While both domain SMEs and CE developers must possess significant knowledge and experience in their respective fields, it is often the individual personalities and attitudes that contribute to the project's success or difficulties.

While there are many successful military officers, only a small subset are well suited for supporting the development of intelligent CEs. First of all, their military service must have been a vocation, not simply an occupation or a job. This group has both the aptitude and inclination to spend the necessary hours of research required to articulate the decision-making processes that seemingly comes natural to them (e.g., one SME reported that while he could develop the detailed plan for occupying a battalion assembly area (ARTEP Task #7-1-3001) in less than half an hour, it took over a week to develop the decision paths and factors showing how and why this is done in a doctrinal manner.)

Secondly, most military officers are used to working in a hierarchical and authoritarian structure where decisions are made, orders are issued and there is little after-the-fact questioning. Working with development engineers (when it is done correctly) is a very collegial proposition in which almost everything is questioned, both to determine its necessity and validity, and also to understand the process being modeled.

Thirdly, an effective SME must be willing to absorb significant amounts of constructive criticism. Once an SME has completed a product, it receives a two and sometimes three-step review by peers and superiors. This review is detailed to the point that it addresses individual words in order to ensure doctrinal validity, eliminate anecdotal or personalized aspects, and remove ambiguity about the decision process being described. This process results in the highest quality product, but also requires a certain degree of kenosis on the part of the SME. Collectively these are major adjustments that many potential SMEs do not wish to make.

On the other hand, CE developers tend to take either a global or a specific approach to the development process. The first group actively seeks to learn all they can about the domain in which their agent will be operating. The second group, however, takes a tighter view of the domain and is characterized by the approach "don't confuse the issue with extraneous details, just define what I have

to model." While this second group is very good at producing highly detailed representations of very specific behaviors, the first group, in general, seems to be much more successful at developing intelligent, adaptive agents capable of operating in a variety of situations.

ACKNOWLEDGMENTS

The authors wish to thank the Command Forces team at DARPA, MITRE, and NRaD, with special thanks to Dr. Lashon Booker, for their dedication, support and guidance.

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AUTHOR BIOGRAPHIES

MARTIN S. KLEINER is the director of Logicon RDA's Knowledge Acquisition program and has served in this capacity since its inception two years ago. He retired from the U.S. Army with the rank of colonel and has experience in the areas of maneuver warfare, intelligence, campaign planning, operational level targeting, and research and development. He received a baccalaureate degree in organizational behavior and management from the University of Houston and is a graduate of the U.S. Army War College.

SCOTT A. CAREY is the deputy task leader for Logicon RDA's Knowledge Acquisition program in support of the DARPA Command Forces project. He is a retired Army lieutenant colonel with more than twenty years experience as an armor officer. His last assignment before retirement in 1994 was as the senior command and control battlefield operating system subject matter expert and observer/controller for the Battle Command Training Program at Fort Leavenworth, Kansas. He has been in his current position for the past two years. Mr. Carey has a bachelor of science degree in education from the University of Maine and a master of science degree in business administration from Boston University.