Towards Dominant Battlespace Comprehension in Network Centric Warfare

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Abstract

Wars in the XXIst century will place unprecedented demands on the commander's ability to make critical decisions under volatile conditions and extreme time pressure. Advances in information technology and cognitive science have made possible new types of decision aids that can help commanders to meet those demands. Design of commander decision aids for Network Centric Warfare is in the focus of this paper. The first section treats command and control in terms of dynamic asset allocation and considers the cognitive complexity of allocation decisions under shifting constraints and priorities. The next section compares two decision strategies: a) template-matching and b) creative utilization of past experiences under conditions that are rapidly changing and have no exact precedents. We argue that creative and efficient application of rules and past experiences requires battle space comprehension and suggest that current decision technologies do not recognize the role of comprehension and thus overlook a fundamental prerequisite for efficient command and control. The third section outlines a model of expert commander decision processes, and defines a new approach to the design of decision aids that facilitate commander's comprehension of the battle space and help to increase the speed of control and self-synchronization in highly mobile and geographically dispersed forces.

1. Comprehension for speed and coordination.

The objective of battle command is to assure favorable outcomes throughout the battle space, that is, to maximize the destruction of enemy assets and capabilities while minimizing the friendly losses. In the Force XXI, advanced sensors will be combined with precision fire power and improved maneuver capabilities. Since the enemy will have weapons comparable to those in the possession of friendly forces, fast and coordinated command and control will become the primary means for denying the enemy the use of those weapons and/or minimizing their consequences. Asymmetric warfare places even higher demands on speed and coordination, as compared to conventional warfare.

In the commander's decision process, coordination assumes the form of balancing between following the orders and relying on one's own judgment and initiative. Military history is replete with examples of high costs paid for upsetting the balance.

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Consider the battle of Waterloo in 1815 where Napoleon, facing British forces under Wellington, dispatched a large contingent under General Grouchy to pursue the Prussians under General Bluecher and prevent them from joining Wellington (Figure 1). Due to weather changes and other unforeseen developments, artillery exchange started earlier than planned, with Napoleon expecting Grouchy to abandon pursuit of the Prussians at the sound of cannon fire and hurry to the main battlefield. Instead, Grouchy stuck to his orders: He caught up with and engaged a Prussian detachment. Bluecher sacrificed his rearguard and rushed to join Wellington who by that time was barely holding his ground. The unexpected appearance of the Prussians decided the outcome of the battle.

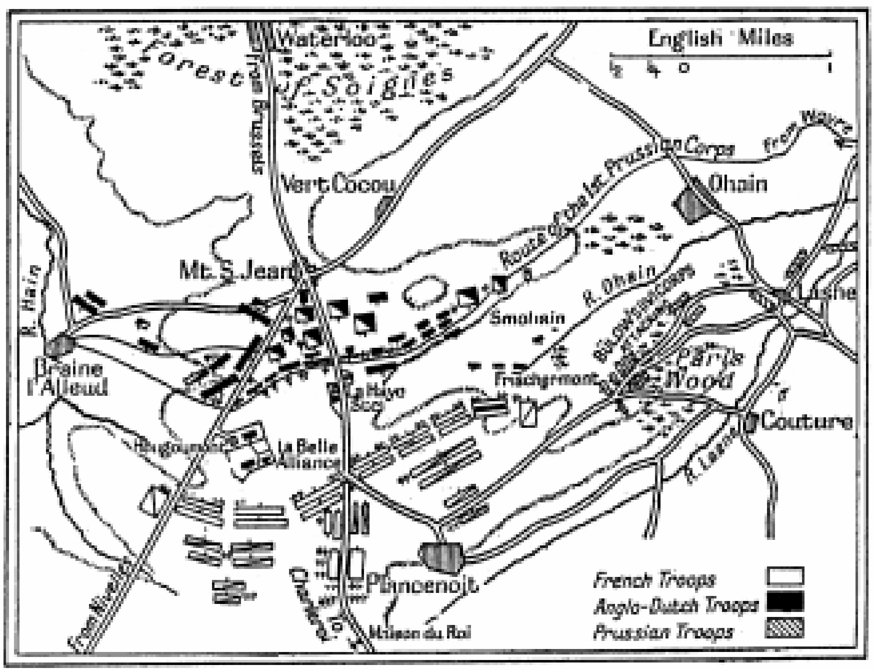


Figure 1. The unexpected appearance of the Prussians on Napoleon's right flank was decisive: The British attacked on the French left while the Prussians stormed on the right, causing disorganization of the French forces and their headlong flight

Consider another episode in the same battle. Cavalry under General Ney was commanded to seize a village held by the British. Ney quickly succeeded, and believing that he found an opening in Wellington's defenses, pushed forward on his own initiative, provoking a heavy counterattack. Napoleon could not allow his elite cavalry to perish and sent cuirassiers from the center, at the expense of leaving the center unprotected.

There are three points to be made here.

First, in the course of the battle, initiative is mixed and shifts between the center and subordinate units. Mixed and shifting initiative thwarts preconceived battle scenarios and makes the outcome inherently uncertain.

Second, commander's decisions cannot be fabricated in advance but must respond flexibly to the changing circumstances which can never be fully anticipated. As stated by Napoleon "To every circumstance its own law" or, more elaborately:

> "There are no precise, determinate rules: everything depends on the character that nature has bestowed on the general, on his qualities and defects, on the nature of the troops, on the range of the weapons, on the season of the year, and on a thousand circumstances that are never twice the same" (Napoleon, cf. Herold, 1955, p.223).

Third, success is determined by the speed of command and maneuver and the degree of coordination across the force, rather than the size of the force:

> "The art of war consists, with a numerically inferior army, in always having larger forces than the enemy at the point which is to be attacked or defended" (Napoleon, cf. Herold, 1955, p. 221).

The remainder of this section looks closer at the task of coordination and the cognitive abilities it demands. Units in the battle space form an organization. Coordinating the units is contingent upon the commander's ability to grasp the main features of this organization and its propensities to change. We define such ability as battle space comprehension.

Battle organization results from interaction between the units. Minimal interaction exists between units executing orders of the central command independently from each other. Interaction increases when units cooperate, that is, share targets, supplies, intelligence, and maneuver in a concerted fashion. Dynamic interplay of different initiatives in the battle space produces temporary cooperative unit groupings, or coalitions that emerge, change and dissolve as the battle progresses. For example, cuirassiers formed a temporary coalition with Ney's cavalry; the coalition dissolved when the cuirassiers retreated.

Coalitions are re-constituted via transferring personnel and equipment, re-directing supplies, re-nominating and re-distributing targets, etc. Opportunities and pressures for such re-constitution depend on many factors (enemy actions and capabilities, terrain, weather, intelligence, transportation, conditions of the personnel, other) that vary throughout the battle space. As a result, coalitions have different propensities to change. Efficient coordination requires commander to identify such propensities and either facilitate or suppress their consequences. In this way, battle trajectory can be steered in the desired direction, without adhering to any preconceived plan. More precisely, starting with a plan, the commander must be open to changing any step in it at any time.

The degree of coordination is high if local objectives pursued by the individual coalitions are aligned with the global objective posed for the entire force. Coordination is low if meeting local objectives contributes little to or undermines the global goal. For example, detachment under General Grouche, although succeeding locally, remained uncoordinated with the main force, bringing about collapse of the entire French army.

Collapse involves break down of coordination and fragmentation of the force, with all individuals acting independently from each other and from the central command.

From a computational standpoint, the problem of coordination reduces to dynamic combinatorial optimization under changing constraints and priorities. Computational and cognitive complexity of such problems is rooted in combinatorial explosion: The size of the problem grows faster than the square number of entities subject to coordination (Alberts et al, 1999). Figure 2 illustrates the mechanism of combinatorial explosion.

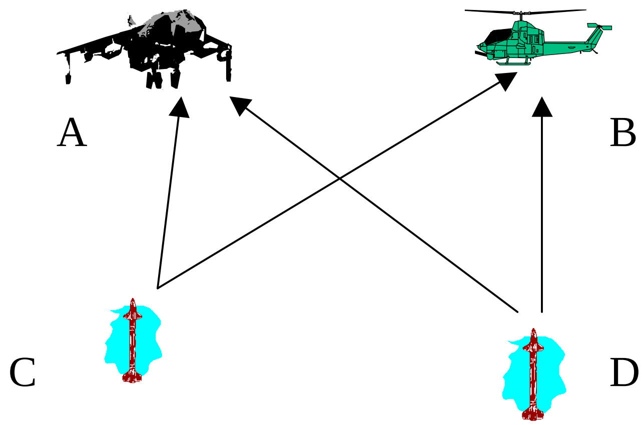


Figure 2. Allocation of two weapons to two targets produces nine weapon-to-target combinations: 1. No action. 2. Both C and D are allocated to A. 3. Both C and D to B. 4.C to A and D to B. 5. D to A and C to B. 6. Only C to A. 7. Only C to B. 8. Only D to A. 9. Only D to B. Expanding the number of weapons and/or targets accelerates production of new combinations.

To appreciate the role of coordination, assume that 1) target A has higher priority (value) than target B, and 2) weapon C can act against both targets while weapon D is effective only against the target A. Commander C acting independently from commander D will direct his weapon against A, which yields the highest pay-off for C but allows B to get through. A coordinated decision could direct weapon C to target B and weapon D to target A, thus reducing the pay-off for C but obtaining a better global result.

The complexity of command and control is due, to a large extent, to a staggering number of combinations hiding a few good choices in the mass of the worthless ones ("the friction of war" (Alberts et al, 1999). Note that uncertainty and bad information ("the fog of war") contribute to the complexity but are not its only source. Having good information does not necessarily prevent bad decisions. For example, Bluecher and Grouchy received the same information (the sound of cannons), but decided differently.

The question is: What strategies can be employed by successful decision makers allowing them to contain combinatorial explosion? In view of an astronomical number of combinations produced by even small coordination tasks, the strategy must be centered on suppressing spurious combinations so that no time and effort are wasted in evaluating and rejecting them. For example, it has been observed that spurious moves do not come to the mind of expert chess players, no more than illegal moves would come to the mind of a novice familiar with the rules of the game (DeGroot,1978). By the same token, a competent commander is unlikely to spend much time considering maneuvers that are physically and/or logistically impossible. Chess machines lacking human cognitive mechanisms for containing combinatorial explosion end up searching through millions of worthless moves before discovering a few good ones that a competent human player can obtain without much search. The mechanisms are astonishingly efficient, how do they it work? Stated differently, what cognitive processes underlie comprehension?

2. In the mind of the commander.

Comprehension is not based on recognition and template-matching. A flow of kaleidoscopic changes in the battle space cannot be captured by templates and, consequently, can be neither comprehended nor controlled with their help. Whether fighting a battle or killing a fly, conditions are never twice the same. As has been often observed by great generals throughout history, knowledge of the past battles provides a necessary but insufficient basis for winning the future ones:

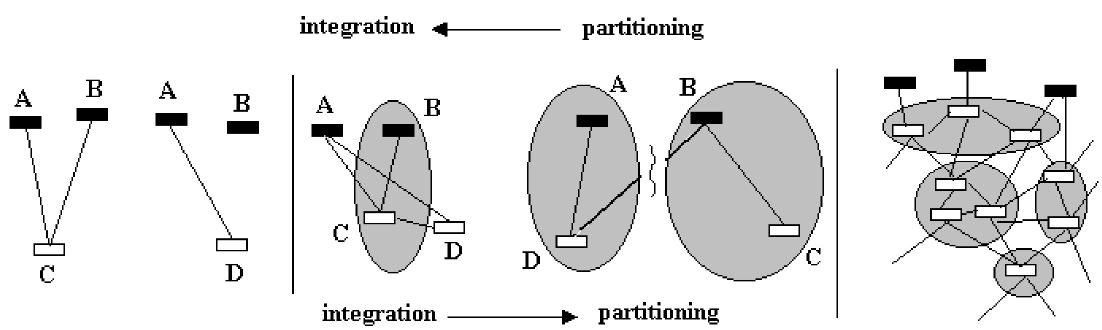
> "In almost all other arts and occupations of life the active agent can make use of truths … which he extracts from dusty books. But it never so in War…The moral reaction, the ever-changeful form of things, makes it necessary for the chief actor to carry in himself the whole mental apparatus of his knowledge, that anywhere and at every pulse beat he may be capable of giving the requisite decision from himself. Knowledge must, by this complete assimilation with his own mind and life, be converted into real power " (Von Clausewitz, 1968 (1832), p. 200).

Comprehension converts knowledge into power. Without comprehension, decisions are made by identifying the present situation with one of the past precedents (templates). By contrast, comprehension allows one to make creative use of all the past precedents, without replicating any of them. A model called Virtual Associative Network (VAN) hypothesizes a "mental apparatus" that can be responsible for assimilating experiences and applying them efficiently under changing and novel circumstances (Yufik, 1998; Yufik & Sheridan, 1997). Briefly, the hypothesis is as follows.

In the commander's memory, information about the battle space undergoes many stages of processing until it is stripped of the sensory detail and registered in the form of a network representing battle space entities and their interrelations, not unlike the map in Figure 1 represents a battle space stripped of the colors, smells, and sounds of the battle. Similarly, diagrams of chess positions tell nothing of the size and color of the pieces. In the network, all pertinent information is condensed into two parameters: Relative worth of the entities (node weights) and relative strength of the interrelations (link weights). The network is not formed momentarily but over a time period while the battle space is examined and attention is shifted between the entities in no particular order. Emergence of a connected and weighted network gives rise to the sensation of situational awareness, and completes the initial, exploratory phase in the comprehension process.

The next phase is the crucial one: The network is self-partitioned into non-overlapping subnets, or clusters. Such clusters are internally cohesive and externally weakly coupled, that is, the cumulative strength of internal links inside the clusters exceeds the cumulative strength of the external ones connecting the clusters to each other. Such clustering occurs automatically in the Long Term Memory, entirely outside the scope of one's conscious awareness. However, one becomes aware of the cluster contents as they are processed in the Short Term Memory, one at a time. During such processing the stages are reversed so that the sensory data removed on the way into the memory is put on back on the way out, until in the sensory periphery at the output is matched attentively against the new sensory input. Node weights determine the order of such matching. Attentive processing is confined to a small memory buffer where the input and output meet. In this way, one is aware of the contents of the currently processed cluster but not of the core memory mechanism responsible for creating it and bringing to the surface of conscious awareness.

Clusters having high internal strength are experienced as more cohesive and stable than the weaker ones. This difference in cluster's stability underlies commander's perception of opportunities and vulnerabilities in the battle space, and his "intuition" of the likely developments. Comparison of one's expectations with the actual events creates the feeling of comprehension if successful, and that of confusion if otherwise.



(a) (b) (c)

Figure 3. (a) Prior to integration, problem in Figure 2 is perceived as two unrelated problems. Considered independently, both weapons will be allocated to A. (b) Linking C and D creates a unified network and reveals the opportunity of allocating C to B. Emergence of two clusters makes combinations "D to A" and "C to B" inside the clusters "obvious," while suppressing combinations across the cluster boundaries. (c) The larger the problem, the larger the relative number of such suppressed combinations.

Comprehension iterates between unifying battle space representation in a connected network, and partitioning it into clusters. As the circumstances change, the network is updated, entailing new partitions and different clusters. In this way, the mental process is synchronized with the pace of the battle, allowing commander to influence the developments as they unfold. Figure 3 uses example in Figure 2 to illustrate the process.

Experience enters the process in the form of weights associated with the network elements: The current input is mapped onto the memory structure formed and weighted by the history of past experiences. This function is crucial: Proper weights reflect salient features of the battle space and produce clusters commensurate with the force coalitions.

"Knowledge is assimilated with one's mind" in the form of clustered network which is not available to introspection but is manifest in the way information is memorized and retrieved. For example, chess players, after viewing briefly a position, retrieve and describe it in clusters of several pieces, with distinct time intervals between the retrieval of each cluster. Expert players do much better than novices in memorizing realistic positions, and equally badly in random positions (Gobet & Simon, 1998; 1996).

Besides the experience, cognitive abilities play a role, in keeping the network connected and updated. As long as the network stays connected, adjustments in any cluster propagate to all the other ones, ensuring coordination and consistency in the decision making. Stress and fatigue undermine integrity of the process, making one incapable of seeing how changes in one part of the battle space influence conditions in the other parts. Ultimately, the propagation can be arrested, making one fixated on a course of actions disregarding both the remote and immediate consequences (e.g., Friedman et al, 1991).

3. Decision technology for network-centric warfare.

The salient features of battlespace organization in the 21st century include the following:

> "1) increased linkages among battlespace
> entities existing in the 21st century;
> 2) integration of various Common Operational Pictures (COPs),
> resulting in fewer COPs, each with the ability to provide an
> increased number of tailored views; and
> 3) introduction of battlespace agents which perform selected tasks
> as delegated by decision and actor entities."
> (Alberts et al, 1999, p. 125).

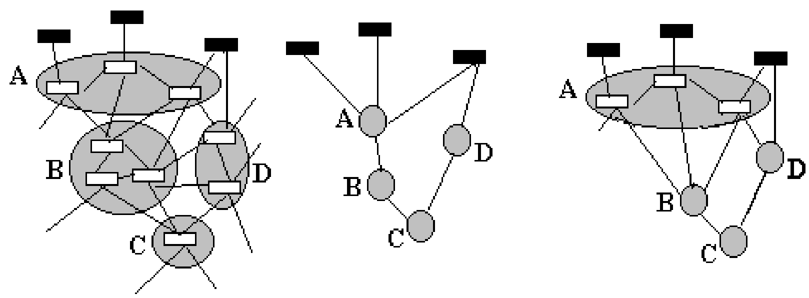
The next subsection suggests novel approaches to decision aiding and COP design.

3.1. Battlespace comprehension and visualization.

The VAN model claims that 1) command and control consist in dynamic resource allocation under changing constraints and shifting priorities, 2) fast near-optimal allocations can be obtained by partitioning large allocation problems into a sequence of smaller ones, 3) adequate partitions are derived from the network representing relative resource values and interrelations between the resources in the battlespace, and 4) dynamic partitions in the resource network underlie ”intuitive” decision making by competent commanders. Consequently, decision support is needed in:

A) creating a connected weighted resource network;
B) updating the network;
C) partitioning the network into clusters (resource coalitions);
D) predicting directions in which the coalitions are likely to evolve.

Figure 3.3. suggests a Common Operational Picture comprising four coalitions. Figure 4.2. displays interrelations between the coalitions, hiding the details of their internal organization. Figure 4.3. places one of the coalitions into the foreground (by showing the details) while keeping the rest in the background of the display.



(a) (b) (c)

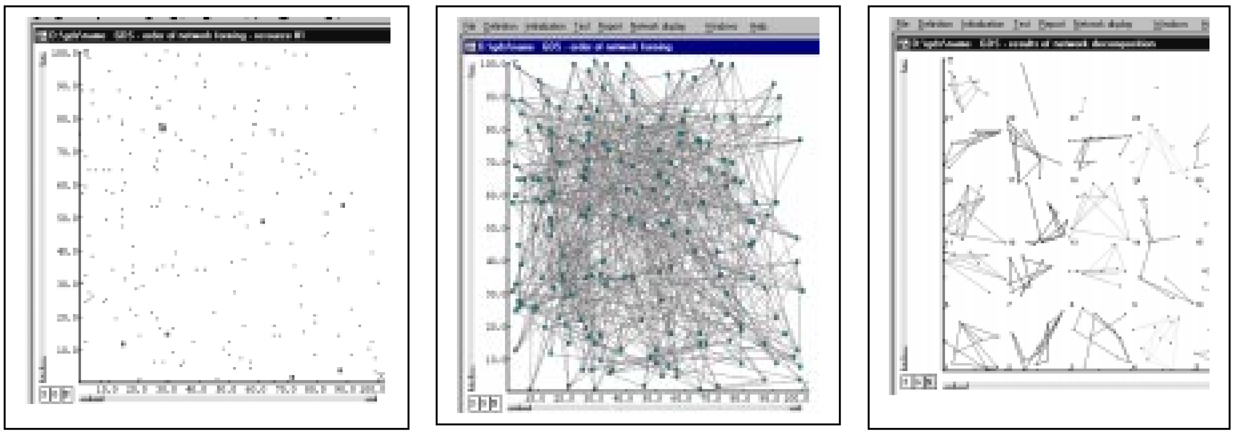
Figure 4. VAN proposal for the Common Operational Picture. (a) Resource network is partitioned into coalitions. (b) Top (superior commander’s) view of the battlespace. (c) Commander A’s default view of the battlespace.

A comprehensive COP allows commander to alternate between the different views, facilitating common understanding of the battlespace and its dynamics. Alternations between the views 4.a, 4.b and 4.c correspond to the phases of comprehension. For example, reviewing a chess position starts with its quick partitioning (e.g., “strong center, weak left flank,” as in 4.a and 4.b), followed by examining piece clusters, as in 4.c.

Observations of chess players have indicated that their skill level correlates with the cluster size: The higher the level, the larger the average size of the piece cluster in the player’s memory (Gobet & Simon, 1998; 1996). Computational experiments this section examine the cluster size- performance relationship in weapons allocation.
The experimental system includes weapon data base, target data base, Task Generation Module (TGM), Weapon Allocation Module (WAM), proprietary Resource Clusterization Module (RCM), and graphical user interface. Weapon data base holds a list of weapons and their kill probabilities respective the targets listed in the target data base. Experiments proceeded through two phases: training and testing. Training included a series of episodes, with each episode consisting of the following four steps:

1. Targets are randomly selected and quasi-randomly prioritized by the TGM module.
2. The WAM module computes a near-optimal weapons allocation. for the target set.
3. The RCM module links weapons allocated to the same target, increments the weights of the links, and verifies whether a connected network has been formed linking all the weapons. If the network is unconnected, control returns to 1.
4. The RCM module partitions the network into cohesive weakly coupled clusters.

Figures 5 depicts the steps in the training process.



(a) (b) (c)

Figure 5. (a) Weapons are distributed over a geographic area. (b) In a series of allocation tasks, cooperating weapons (allocated jointly to targets) are connected by weighted links, until a connected network is formed. (c) Network is partitioned into weapon clusters. Note that the display reflects only compositions of the clusters. Clusters can include weapons from different locations, and are superposed across the entire area.

Testing includes the following two steps:

1. A new target set is generated different from any set participating in the training.
2. The WAM module computes near-optimal weapon allocations, in two modes:
   - A) using the clusters, and
   - B) ignoring clusters.

Results in mode a) and mode b) are compared based on the overall utility values they yield, and computation time. Experiments varied the cluster size (limits on the minimal and maximal number of nodes in the cluster) and problem size (maximal number of weapons and targets). Figure 6 illustrates the findings.

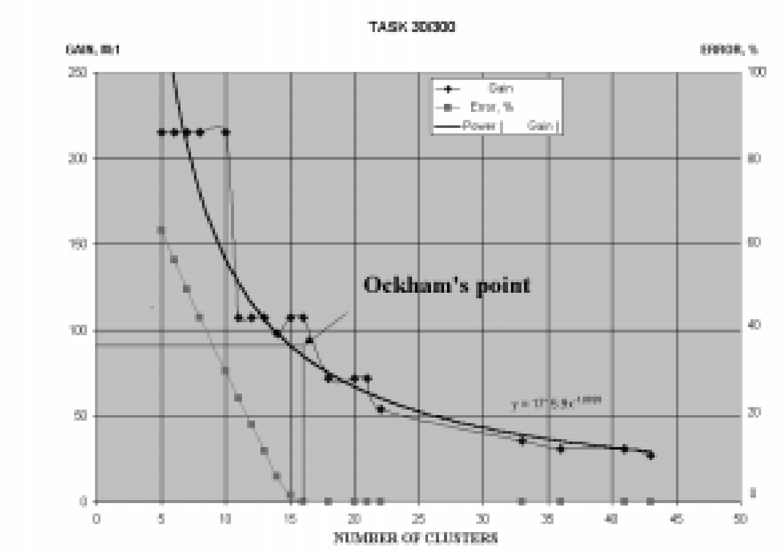


Figure 6. Allocation episodes used sets of 300 weapons and 30 targets. Parameter "Gain" (i.e., speed gain) is computed as the ratio of computation time in the mode B and mode A. Fore example, Gain of 100 indicates that using the clusters accelerated computation by a factor of 100:1. Parameter "Error" is computed as the ratio of the global utility values obtained with and without the clusters.

Figure 6 shows that as the cluster size grows (the number of clusters decreases), the value of the Gain increases. Since the hardware and the allocation algorithm remain always the same, the time it takes to complete allocations is determined exclusively by the number of weapon-target combinations the algorithm is going through. A less intuitive and more significant finding concern the Error function. Figure 6 reveals a large range of cluster size variation where Gain continues to grow without appreciable accuracy losses (error < 0.1%). However, at the lower bound of the range the Error curve experiences a sharp upturn. Variations in the number of targets and resources (between 10 and 100 and 1, 000 and 10, 000, correspondingly) demonstrated that this relationship between Gain, Error and cluster size is independent of the problem size.

The point in the Gain curve corresponding to the upturn in the Error curve is called "Ockham's point" (*O*-point). Clusters of decreasing size located to the right of the *O*-point contain irrelevant details, causing deceleration in the process without improving its accuracy. However, increasing cluster size past the *O*-point entails loss of significant details. Characteristically, the *O*-point was usually found in the vicinity of cluster size (20 nodes per cluster) corresponding roughly to a maximal comfortable number of information elements in a display (exceeding that number creates clutter and confusion).

These findings appear consistent with the claims made at the beginning of section 3.1.

3.2. Architecture for command and control.

Increased linkages among the battlespace entities entails nested coalitions, as shown in Figure 7.

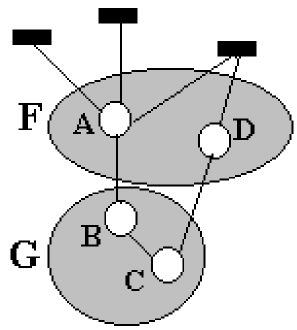


Figure 7. Cooperating coalitions form a nested organization in the battlespace (coalitions of coalitions).

Dynamic properties of such nested organizations can be conceptualized in the following terms: resource, coalition, coalition stability, and interlocking hierarchies.

Resource is the basic functional unit having fixed composition.
Coalition is composed of resources and is the basic functional unit having variable composition.
Stability is a measure of the coalition's propensity to change spontaneously under changing external conditions.
Interlocking hierarchies becomes the control architecture for optimizing performance of nested coalitions. Figure 8 illustrates the concept.

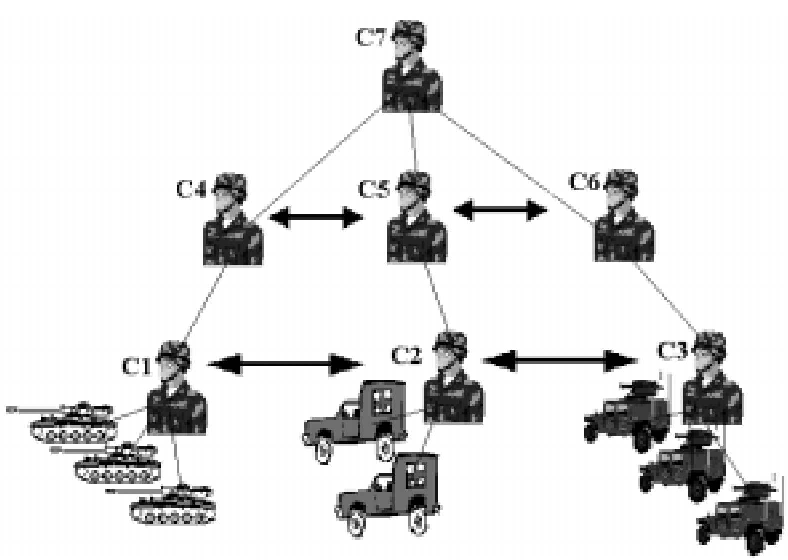


Figure 8. Interlocking hierarchies allow lateral interactions and coalition forming between entities residing in different subordination lines.

Commanders C1, C2 and C3 control different resources and have different superiors. In a conventional hierarchy, decisions concerning cooperative relations between the commanders will have to propagate upward through the levels, to the commander C7. By contrast, in the interlocking hierarchies cooperation can be established via lateral interactions inside the levels. As a result, informational burden through the upper nodes is reduced, limited to issuing objectives and priorities, monitoring execution, and interfering when results in the subordinate units start deviating from those expected.

Lateral collaboration requires decision aids of a new kind. Figure 9 provides an example.

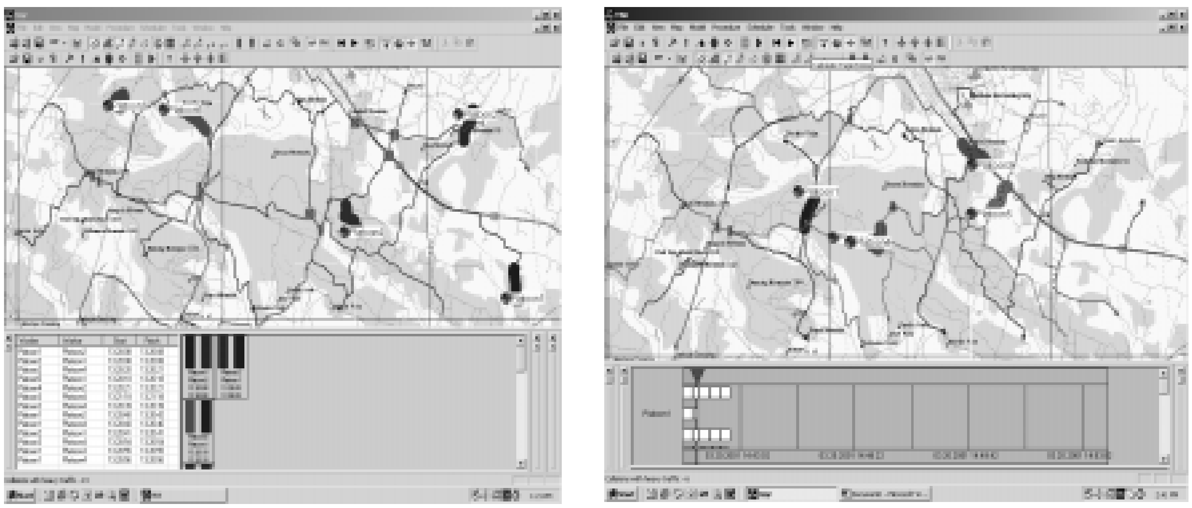


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Figure 9. 1. Collaborative maneuver planning for several units identifies optimal routes to their respective destinations while minimizing delays caused by road sharing and meetings at the intersections. Unavoidable intersections are identified, allowing commanders to negotiate the order of their crossing. Decision aid follows progress and provides re-routing advice if conditions change. 2. Superior commander can monitor and coordinate execution. Coordination is supported by displaying progress of all the units characterized by the expected schedule, their current position, and the adjusted schedules responding to the changing trafficability.

Modeling and supporting command and control in network-centric warfare challenges conventional views, calling for new approaches in understanding both computational and psychological problems involved.

Conclusions.

A variety of mathematical methods have been applied in combat modeling (Dockery & Woodcock, 1987). However, we are far from understanding how combat is modeled in the mind of the commander.

The conventional framework for understanding human decision making is that of Template Matching (TM). The idea is rooted in the studies of animal conditioning at the first half of the past century, and in the later models of animal behavior. The TM concept took hold in psychology and cognitive sciences which have been stretching the idea in all directions in applying it to human behavior. Arguably, frames, schemas, scripts, cases, scenarios, recognition primed decision making, discrimination nets, expert systems, neural nets, and variations of these models are incarnations of the TM concept, all sharing the basic premise that the organism interacts with the environment by fabricating and storing templates, and then recovering and exercising those templates which the present conditions happened to unlock. Parallel distributed processes and holographic memory models share the same premise, with an emphasis on template retention in degraded memory and template recovery by incomplete and noisy inputs.

This paper advances a different modeling approach intended to explain human ability to solve hard combinatorial problems and use past experiences without repeating them. Much work remains to be done in reducing this approach to practical applications.

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