Representing Military Units Using Nested Convex Hulls – Coping with Complexity in Command and Control

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Abstract
Computer supported geographical systems are common in military command and control. Traditional unit symbols are often used to present positions and movements on digital computerized maps. This report discusses weaknesses in the approach and proposes a complementary representation design. In short the proposed representation uses position data from lowest level units and aggregates a presentation using a convex hull approach.

Introduction
Maps are essential in military command and control (C2). Their use covers most C2 situations and phases as important elements of numerous tasks. When moving from traditional paper maps and plastic sheets to computer supported tools, many new possibilities emerge. Considering the complex nature of command and control it is important that these tools are efficient. A central part of the tools is their use of representations of real world properties in the computer medium. We must know what to represent and how to represent it. The most obvious property to present on a map would be unit positions, and traditionally this is conducted using standard military unit symbols positioned on the map to represent one or more real world objects.

The next section briefly introduces command and control and describes sources of its complexity and what is needed to cope with it. After those preliminaries we touch upon the area of representation design to give a theoretic ground for further analysis. Then follows a short review of implications on needs and problems concerning maps and unit positions. The main result is then presented, covering design of a unit representation that confronts identified problems. A discussion and our conclusions complete the paper.

Command and Control
Command and control is a central and vast part of all military activity. It is a large system of humans and artifacts, cooperating in a hierarchy to reach their common goals or as Pigeau and McCann (2000) put it: “The establishment of common intent to achieve coordinated action” (p. 165). The artifacts range from simple paper maps with plastic sheets and marker pens for drawing, to advanced technical devices for communication and computerized information systems. Artifacts also include the military organization and doctrine. The humans on one specific level in the structured hierarchical organization use the artifacts to command and control their sub-ordinate units, to report to and receive orders from the unit above, and to cooperate with the side-ordered units. Systems involving humans and artifacts in this fashion can be described as joint cognitive systems (Hollnagel & Woods, 1983). Crucial for command and control is the nested structure where each node will be a part of other joint cognitive systems formed by the units’ before mentioned structure. This means that all units are involved (to a very varying degree) in each unit’s command and control – upwards to the root and downwards to the leaves (Figure 1).
Figure 1. The nested nature of command and control joint cognitive systems. Each unit, including staff and artifacts, is (to a varying degree) involved in the other’s command and control. The main relations are shown in three different bold lines – upwards, to the sides, and downwards.

Complexity

The concept of complexity can be interpreted in many ways. One way to characterize the complexity for C2 is by using Woods’ (1988) four dimensions:

1. **Dynamism of the system:** To what extent can the system change states without intervention from the user? To what extent can the nature of the problem change over time? To what extent can multiple on-going tasks have different time spans?

2. **Parts, variables and their interconnections:** The number of parts and the extensiveness of interconnections between the parts of variables. To what extent can a given problem be due to multiple potential causes and to what extent can it have multiple potential consequences?

3. **Uncertainty:** To what extent can the data about the system be erroneous, incomplete, or ambiguous – how predictable are future states?

4. **Risk:** What is at stake? How serious are consequences of users’ decisions?

Beginning from the top and the dynamism (1); because of the recursive structure of command and control, humans will always be a central part and it is clear that the system must certainly will – to a great extent – change states without the current user’s intervention. Furthermore, since conditions can vary dramatically during the course of actions in military warfare, for example weather, terrain, enemy activity and personnel conditions, it is natural that the nature of problems also changes over time. There are several examples when it comes to multiple on-going tasks: a user handles both activities with very short time span such as reporting enemy activity to a friendly unit in that area, and those with longer time span such as monitoring resources to be able to carry out future orders.

It is hard to model C2 in some “true”, discrete, unique parts (2) but it is agreed that there are numerous interacting processes involved (e.g. Worm, 2000). To give one example, imagine this scenario:

A user identifies a unit, aided by some artifact. With results indicating that it is an enemy unit, the user reports to higher unit using another artifact. Let us say that it was not an enemy unit. The cause of this problem could be that the user misinterpreted his artifact result – but – the cause could also come from enemies’ use of information warfare. A consequence of such a problem could be unnecessary rerouting of planned movements or it could result in friendly fire.

This leads us into next dimension, the one of uncertainty (3). Enemy (re)actions are naturally a great source of uncertainty – they cannot afford to be predictable. The tough physical circumstances in the military domain are another source of uncertainty considering extreme heat, cold, noise, etc.

The last dimension is about risks (4). Even if the consequences of actions can be costly in exercises and in peacetime, it is during real operations catastrophic ones can occur – lives are at stake.

In Leplat’s (1988) definition of complexity aspects such as: time pressure, interruptions and feedback lag are dealt with. In C2 time pressure varies considerably during different parts and phases of the chain of command. On the extreme level is time pressure for fighter pilot activity (Amalberti & Deblon, 1992), but many other situations in command and control are time critical as well. Interruptions of tasks are frequent and demanding, as the earlier examples suggest and feedback in the system is often delayed or missing (e.g. radio communication problems). What we are trying to say here is that we are dealing with a highly complex system – nothing more.

Staying in Control

Dealing with such complex systems, gaining and maintaining control get harder and more crucial for successful use. Complexity cannot be removed, only hidden and to hide complexity is risky. An alternative approach is to design for complexity and provide the users with aids for coping with the complexity (e.g. Hollnagel, 1995; Hollnagel, 1992). Designing for complexity is not a trivial task though. To gain and maintain control of systems we need:

- **Observability:** By providing means for knowing what has happened, and what happens right now in the system, the users get verification of their actions as well as what state or mode the system is in at the moment.
- **Predictability:** By providing good predictions of future events users know what will happen/can
Experience/knowledge: Users have to know what to do, when to do it, and how to do it. This knowledge could be achieved from experience (training with the system) or more formal education.

Sufficient time/right task load: If the rate of input or amount of simultaneous data is too high to gain enough information (data overload), users are forced to handle this in some way. Users could be forced to filter data, queue tasks or, if worst comes to worst, abandon the tasks. On the other hand, if the task load is too low, other problems can occur like oversimplification or users slipping into zombie state (data underload).

Ability to carry out actions: Even if the systems are observable and predictable, the users’ knowledge considerable, and there is sufficient time and the task load is good, all that is of limited use if the actions to complete the tasks cannot be carried out. Extensive degree of automation (or clumsy such) is an example where systems can cripple the users’ ability to carry out certain actions (e.g. Dekker & Hollnagel, 1999).

Looking at how staff is coping in C2 today, we see several strategies that can be related to these needs. Strong organization and structure are omnipresent in military activity. Doctrines, rules, regulations, procedures and organization and structure are omnipresent in military activity when new computer support artifacts are introduced into C2 systems, these needs have to be considered on lower levels for successful joint actions of military staff and the new artifacts.

Representation Design
A good research basis for going about fulfilling the needs of system control is representation design (Woods, 1995).

Woods describes two challenges for successful representation design: The first considers finding the important real-world properties and real-world relations that are informative given the goals and context of the involved practitioners. The second is the challenge of setting up the mapping between the real-world and the medium for representation, in such a way that observers can extract the intended information. The way a problem is represented directly influences how it can be solved.

Cognitive task analysis (Schraagen et al., 2000) is one method of many others suited for taking on the first challenge. How do we set about in practice to confront the latter problem? Woods and colleagues (Woods, 1995; Woods et al., 1996) present three basic principles:

- Find suitable frames of reference: The first step is to find frames of reference that allow expression of the relevant relations between data. By using different frames of reference, different problems can be found.
- Put data into context: Within the frames of reference the represented data should be put into the context of related values. Provide landmarks in the frames of reference, representing significant real world circumstances.
- Highlight significance: When the real world object/process/etc. changes, the representation of these patterns of behavior should support highlighting of interesting events, changes and contrasting values.

If the design succeeds to follow these principles properties will be emergent – they are more than the sum of the properties of the parts they are built up of.

An important issue in representation design is how the represented elements or signs refer to their real world counterparts; their form of reference (Woods, 1991; Woods, 1995). Signs that do not resemble the object in any way and forcing the relation to be learned are said to have a propositional form of reference. It is arbitrary or purely conventional (e.g. alphabetical letters, numbers). If the structure and behavior of marks in the medium are directly connected to structure and behavior of the referents, the representation is said to have an analogical form of reference. Propositional or digital signs can be very exact, but they require deliberate processing to a higher degree than analogues. Analogical representations can help operators use their experience of work procedures in a more parallel or reactive way.

Military Geographical Needs
Most battle activities have attributes in the spatial domain, such as positions of friendly units, reported positions of enemy units and different geographical elements that inform where tasks are to be carried out. Maps are
common tools in C2, ranging from traditional paper maps and plastic sheets, to modern computer-based versions. They serve as a framework for the spatial domain and are used for planning, tactics and more and more for providing time critical situation overview as well as giving and receiving orders.

What is then needed from the geographical support systems in C2? One way to probe that is by collecting data from military exercises and using a system to replay and analyze the course of events afterwards. We used one such methodology framework called MIND (Morin, 2002) for two field-studies of military exercises concerning mechanized units on battalion level and below. Initial field-study results from visualized system interaction logs indicate that map use is problematic. Long sequences of panning the map back and forth and zooming up and down suggest that the operation is not very efficient. One possible cause is the keyhole effect making the user move around in the map like looking through a keyhole, without getting good overview. In the same time, changing zoom mode often requires mental effort to reassess the spatial situation of the map.

Furthermore, communication analysis from the field-studies shows that spatial information is a very big part of the radio communication in mechanized battalions. It is crucial when companies report continuous progress, when battalion commanders demand position data from companies for coordination with other units such as indirect fire, and when companies collaborate to solve common goals. Often commanders want to know where an outer limit of a company is, (e.g. “Where are your eastmost units?”), “Is the front unit north of road r?”), or want to make sure that units are at a specific place (e.g. “All units should be west of lake l before 1400”). Individual vehicles’ positions are also requested at high detail.

Military Unit Representation
Since geographical support systems are important, and a big part of modern C2, it is crucial that they are effective tools, suited for the commanders’ tasks. To date many of these geographical systems still rely heavily on traditional elements. Well known such elements are unit symbols (Figure 2). The purpose of these symbols is mainly to convey information of unit type, size and unit identification. These symbols are often used on maps to spatially present whereabouts of military units. Different unit sizes are mixed, which means that one unit can be plotted on company level when others on platoon or individual vehicle level. Higher level unit symbols usually represent a certain vehicle or command post, or sometimes the front or centre of the unit.
When the symbols are presented on a map they indicate positions for the units, but is it clear exactly what these positions refer to; the command post of the unit, the front vehicle or something else? And is it always the centre of the symbol, or the corner that is the origin? Of course there are standards for these concerns, but nevertheless, the form of reference is not very analogical when it comes to positions. The structure and behavior of the real world events are not directly connected to the representations in the computer medium.

One C2 support system used during the field-studies has identified this and put more emphasis on call-signs and positions than traditional symbols for its geographical presentations. Instead of the standard symbols the system uses simple cursor like signs for each vehicle and provides its call-sign below (as depicted in Figure 4a). Still, limited screen size and resolution make the keyhole effect problematic. It is hard to both have an overview and still be able to see individual details. When zooming, some units might end up outside the view (or new units might end up inside the view), and the users need to regain the spatial overview, losing some of the momentum.

In sum, both these examples of representing units fail to handle some important issues:

- **Minimize the keyhole problem:** A bunch of symbols scattered on a map is hard to navigate among.
- **Clearly present the units as such:** If the symbol is built up of many graphical elements, clutter may occur.
- **Clearly present the units’ positions:** Symbols may be ambiguous when it comes to positions.
- **Present several units on a small area:** If zoomed out, units may occlude each other making it hard to see anything.
- **Present the relations between units:** If two companies’ vehicles are close it can be hard to hold them apart.
- **Present patterns on different unit levels:** It is hard to easily answer questions like “is the whole company east of the river?”

How can these problems be tackled? We have good grounds to believe that units’ positions on both individual basis and also on organizational level are important real-world properties and real-world relations that are informative given the goals and context of the involved practitioners.

**Alternative**

Going back to the principles of representation design, what are the relevant frames of reference? Clearly the map is one spatial frame of reference. But the important hierarchical structure of military organizations, helping to cope with C2 complexity, is another important frame of reference, which is largely unused in previous examples.

**Nested Convex Hulls**

By using the positions of all involved vehicles in a unit we can produce the unit’s outer limit by calculating the convex hull (e.g. Preparata & Shamos, 1985). Figure 4 depicts a simple example of three vehicles in a platoon. To understand the convex hull concept imagine a board with a set of partially nailed down nails. We then take a large rubber band and stretch it so it surrounds all nails. When we release the rubber band it will contract around the outer nails and thereby represent the convex hull of the set. Using the convex hull technique recursively for the whole company makes it possible to draw a new convex hull around each platoon (Figure 5). For every larger unit size the radius used for rounding the vehicle coordinates are increased (e.g. 100 meters for platoons and 200 meters for a company). The hulls are semi-transparent to avoid occlusion of the map.

![Figure 4](image_url)

**Figure 4.** A screenshot from an implemented prototype showing a platoon represented as (a) individual vehicles and (b) as a convex hull.

![Figure 5](image_url)

**Figure 5.** A complete company, TI, recursively represented as nested convex hulls, with the platoons AT, BT and CT.
Continuing on higher levels will provide an organizational frame of reference that both gives us means for presenting positions, but also the structure of the involved units. The context is then built up of all the individual positions forming the nested structure of the presentation. Call-sign captions tie the shapes to their represented units. This is done by placing the caption in the centre (or a visible non cluttered area) of the shape using a font size related to unit size level. By using two levels of convex hulls, the needed detail can be connected to the actual user. A battalion commander can choose to see his companies as convex hulls which in turn are built up of their platoons (as in Figure 5). Even if the commander does not see individual vehicles explicitly, they are implicitly contributing to the presentation.

Returning to the earlier identified problems, how does this approach handle them? First, clutter can largely be avoided, since two levels of nested hulls limit the amount of graphical elements on screen (Figure 6). If a company is grouped tightly and another more spread out, a common zoom level is possible using convex hulls. Furthermore, there is no ambiguity when it comes to positions. A convex hull is well-defined and all vehicles must be within it. It tells you the outer limits of the units’ collected positions. For individual positions a circle will stand for the exact coordinate for that vehicle. The relations between units are clearly visible thanks to the additional frame of reference. Not only can a user tell which unit belongs where, but also how units are positioned in formations (Figure 7). The edges of the hulls represent relevant properties themselves, namely the unit limits. This helps answering common questions involving statements such as “eastmost units” or “are all north of?”.

Figure 6. Vehicles from three platoons presented as individual units (a) make the view cluttered for the current zoom level. Using convex hulls (b) clears up the clutter and still provides information based on all underlying position data. The platoon AR is selected in this example and is therefore highlighted.

Figure 7. To grasp the relations among units when using individual symbols (a) we need to do some processing to visualize the structure. Convex hulls (b) help providing that information in a more direct way.

The most important benefit of the nested convex hull technique though, is how it tackles the keyhole problem. Fairly small screens, with limited resolution make screen real estate valuable and it has to be made the most of. Earlier techniques presented individual symbols for the units with no explicit relations between them, making it hard to take other units into account beside the ones currently on screen (Figure 8). A convex hull approach however, provides more information for the same underlying data. If we see just a corner of one convex hull in the bottom right part of the screen (Figure 9), that will tell us a lot. By the definition of a convex hull we can quickly conclude that there are no parts of this unit north or west of this corner. The problem of regaining overview when panning or zooming is tackled as well. When interacting with the map system, the few shapes of the units’ convex hulls will probably be easier to recognize and keep track of than the many individual symbols (Figure 10).

**Powers**

The proposed approach tackles many of the inherent problems of geographical computer systems in C2. Looking at the earlier presented needs for controlling complex systems, nested convex hull representation:

- helps maintaining observability among large data sets of unit positions,
- gives hints on unit positions and patterns both within and outside screen area, making predictions easier,
- and lowers workload by aggregating many individual graphical elements into larger chunks, that helps answering important questions in C2.
Discussion

All sub units in a military unit are not equally interesting during different phases in C2. When a commander controls his/her units in time critical battle, the fighting parts of the units will be of main concern and therefore the ones building up the convex hulls. During other phases this might be different. What if the hulls get very large? Single vehicles or units might for different reasons diverge from the other units. Sometimes these units are not interesting to maintain focus on anymore, and should not contribute to the hull. Therefore it should be possible to exclude (and re-include) units to the hull. When units indeed are unusually spread out for special reasons making the hulls inconveniently large things are trickier. Splitting the hulls seems to be one solution, but then the very benefits of convex hulls are tampered with. We would not be able to draw the same conclusions from the presented units’ positions. Simplicity is often a good solution, especially in military concerns, and by providing means for turning on and off convex hull presentation for individual units this problem can be handled.

The proposed approach demands a reliable and continuous update of unit positions to be fruitful. With infrequent or erroneous coordinates the changes of the hull shapes would be problematic. Furthermore, for temporary sub-ordinate units, unknown or unfamiliar units and for enemy units a convex hull approach might be less beneficial, stressing the need of both strategies. However, for military intelligence, work has been done to automatically aggregate enemy units based on time-stamped reports of position, type and more (Cantwell et al., 2001), making a convex hull approach possible.

Conclusion and Future Work

We have identified possible conflicts between commanders’ needs in graphical support systems and the traditional way of representing units as abstract symbols. By taking representation design as a starting point we presented a complementary approach for representation of units. Based on the well-defined concept of convex hulls our approach tackles inherent problems in the area. It makes use of the military organization structure to preserve patterns on different levels, highlights important aspects concerning the extent of the units, and helps spatial navigation by taking advantage of units outside visible limits.

We think this approach would be a good complement to traditional techniques for lower unit command and control. It is important though, to further test and evaluate the usefulness of nested convex hulls.

References


Interface for co-understanding and cooperation, July 17-18, Hieizan, Japan.


Figure 10. The figures (a) and (b) each show two different zoom levels of the same units using different representations. When zooming and panning among several individual unit symbols (a) we might have troubles keeping the visual momentum. Nested convex hulls (b) function as simpler landmarks to navigate among.