Simulation-Based Decision Support for
Command and Control in Joint Operations

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ABSTRACT: Predicting and evaluating the consequences of tentative plans are essential parts of the decision-making in joint operations. Decision support based on simulation aims to facilitate these two activities. This paper first analyzes the decision-making and the generic planning process in joint operations. Based on this analysis, the paper describes both multi-agent simulation used to predict the consequences of tentative plans and multi-attribute evaluation to evaluate and compare the multi-attribute consequences based on the goals or objectives for the operation. It also clarifies the relationships between plans and agent models as well as consequences and utilities. In order to realize embedded simulation support, an architecture is suggested for network based Command and Control (C2) systems. As a result, this simulation based decision support will enhance the situation awareness by the ability to, not only present and explain the situation, but also to predict it. By iteratively using multi-agent simulation and multi-attribute evaluation in the different planning phases, the commanders will be able to verify and evaluate possible plans in different aspects such as opportunity versus risk, feasibility versus difficulty, task versus consequence, etc. Finally the iterative process leads to a deliberate plan. Therefore, the simulation-based decision support will become an essential part in future C2 systems.

1. Introduction

The use of computer-based simulation to support commanders in the decision-making process has been considered for a long time. Efforts such as DIS (Distributed Interactive Simulation) and HLA (High Level Architecture) have been the means to perform large scale and highly complex simulations to illustrate and learn from processes that strives to resemble the reality [1]. Other efforts aim to reduce complexity in the simulation models in favor of capturing intangible entities such as cohesion and morale, and to better understand the non-linearity of the consequences of the decisions [2]. The concept of agent-based modeling has been suggested to support this latter approach [3, 4]. However, these efforts tend to result in tools that are separated from computer-based support provided to the commanders.
A Command and Control (C2) system is a means used by a commander to synchronize activities in time, space and purpose to achieve unity of a common effort. In decision-making, the commander always pursues to achieve information superiority, create opportunity or risk foresight and then realize command superiority. This requires that a C2 system should support the commander to enhance his or her situation awareness by presenting a situation picture, explain the meaning of it and also to support situation assessment including prediction and evaluation of the future situation as shown in Figure 1. Furthermore, the C2 system supports the commander in describing and explaining their intents and decisions, both in terms of brief concepts of how to perform an operation and in terms of fully developed and very detailed operation plans.

The commander’s estimation and judgment may be no longer enough to get an accurate and quick situation prediction. By full integration of simulation in the C2 system it would be possible to predict the development of the situation and hence facilitate the higher levels of situation awareness. Also by offering the opportunity to simulate plans and concepts, as they are designed by use of planning tools in the C2 system, the consequences of potential decisions or tentative plans could immediately be tested during any phase of the planning process. Thus the simulation needs to be an essential part in the future C2 system to meet the demands as depicted in Figure 1.

To facilitate this integration, it is the purpose of this paper to discuss how to predict consequences from the tentative decision alternatives and then to evaluate and compare them. It attempts to clarify the following issues:

1) Multi-agent simulation that can be used to generate the consequences from a tentative alternative plan.

2) Multi-attribute evaluation that can be used to evaluate and compare the consequences based on the plan objectives, which is also used to direct the planners in the planning process.

Consequently the goals for the paper are to:

1) Design a multi-agent simulation component for a C2 system in order to support the commander and staffs to predict the possible consequences from a plan.

2) Design a multi-attribute evaluating component that rates or judges the generated plan.

Both of these components will be embedded in the C2 system to support decision-making in joint operations. By this integration we argue that the efficiency of the commander and the staff could be greatly increased in terms of enhanced situation awareness by the use of “what-if-simulations”, and increased opportunities by the iterative process as well as increased safety by the possibility to test for deficiencies of the plan before it is executed.

2. The Generic Planning Process

A plan can be thought of as a practical scheme for dealing with the joint operations, which falls into three phases [5]:

1) Initial operations, which include the deployment of forces and establishing a lodgment in a joint operational area.

2) Decisive operations to achieve operational objectives quickly at minimal cost, e.g., reducing the opponent’s defensive capability or joint counteroffensive.

3) Post stability operations, e.g., controlling any remaining oppositions.

The joint operation planning has two distinct processes [6]:

1) Deliberate-planning, which is conducted in peacetime to prepare for conflicts and crises. The planning process cycle is accomplished in five phases: initiations, concept development, plan development, plan review and supporting plans.

2) Crisis-action planning process, which has a limited time to be accomplished. As a result, it provides for a quick transition from peace to crisis or war and is accomplished within six phases: situation development, crisis assessment, COA (Course of Action) development, COA selection, execution planning and execution.
The joint commander and staffs usually generate several possible or tentative plans at the planning initiative [7]. To reduce uncertainties, the staffs will use the planning directive to estimate the situation from different perspectives including personnel, intelligence, operations, logistics, transportation and C2. The commander will then summarize the staff estimations as the basis to select one of the tentative plans. However, the estimating process may be a time-consuming task, and the possible plan may be roughly generated and there are many tradeoffs that should be considered.

Military organizations have instructions on how to perform this planning. The Strategic Commanders Guidelines for Operational Planning (GOC) [8] is one example of such prescriptive doctrines. The purpose of these models is to:
1) Act as checklists to capture earlier experiences.
2) Help coordinating the planning work.
3) Improve the quality of the decisions.

Typically they encourage analytical comparison between several alternative courses of action developed in close detail [9].

These prescriptive models have however been criticized for not taking into account how people do perform decision-making in practice. For instance there is often no time to develop and to evaluate several decision alternatives as prescribed in the planning doctrines. Also it has been shown that decisions are made very early in the process, based on the decision-maker recognizing the situation from previous experiences [10].

Nevertheless it should be possible to represent and simulate the whole continuum from a brief idea to a fully developed and detailed plan on how to execute the operation. Also there should, from a technical point of view, be no limitations in how many potential decision alternatives that could be represented in the C2 system.

Hence a generic model in Figure 2 has been suggested to capture these different aspects of the decision-making process [11]. In the suggested model it is assumed that the decision-making is performed as a collaborative process performed by commanders on different levels in support by their staffs. In turn, these different participants in the decision-making process have been generalized into two actors: the Planner and the Decision-Maker, who use the functions supplied by the C2 system.

According to this model, decision-making involves defining the goals of a task as well as developing one or several solutions to this task. The development of solutions includes iteration between on the one hand suggesting improved solutions, and on the other hand assessing these solutions. The assessment is performed by predicting the outcome and by comparing this assumed outcome to the goals. The actual decisions are made when the task or one of the solutions is either approved or disapproved (the latter calling for further development).

Figure 3 further emphasizes the iterative search for a suitable solution in this process. The terminology has been formalized, letting preferences represent the goals of the task or operation, and tentative plans represent any suggested solution to achieve the task or operation according to the preferences. Figure 3 also emphasizes that the input to the process is the current situation awareness and the output is an approved plan.
Actually, this process has been taken to represent all forms of planning and decision-making performed by the commander and staffs. Although it depicts decision-making primarily performed without any forms of computer based support, development of technical solutions could be considered to support this process:

1) Plans could be generated by use of techniques that recognize the situation and find the most suitable plan from a set of plan templates. Besides, search techniques such as genetic algorithms could be used to successively improve a set of plans according to the preferences [12]. Further discussion of these ideas is however out of the scope of this paper.

2) The prediction of consequences is naturally performed by mental simulation, i.e. within the minds of the decision-makers. War gaming, performed by one individual or by a group of individuals, is one kind of simulation that is externalized by the support of technical artifacts [13]. In section 3 we will however propose other simulation techniques to perform computer-based prediction of consequences.

3) The goals of the tasks may be represented by a utility function by which the predicted consequences may be evaluated. This method will be further discussed in section 4.

3. Simulation to Predict Consequences of Tentative Plans

3.1 The Plan

A plan is a potential solution to a task describing how to deal with available resources to accomplish the goals or objectives. In turn the plan gives rise to new tasks with goals on a lower level of abstraction. From the simulation perspective the plan constitutes a model of the actions of the involved resources.

Figure 4 shows the relations between the different concepts defined by a plan [11]. A task is the representation of something to be accomplished by actions of a resource. A role represents the membership of (or a subordination to) a superior resource, e.g., a battalion or a battleship could be subordinated to the national forces in some aspects and, at the same time, be subordinated to a UN mission organization in other aspects. Hence the concept of roles facilitates dynamic and multiple organizations.

3.2 Multi-Agent Simulation

A multi-agent simulation will be used to predict the consequences of a given plan to be executed. The consequences will be described against the objectives and constraints of the task to which the plan is a solution.

![Figure 4: Relationships between plans, resources, roles and tasks.](image-url)
As discussed before, a plan has defined a number of tasks, resources and roles. There are two levels of resources. At the low level an entity is an object that can independently perform defined actions. The effect by an action is measured by the capabilities of the entity, e.g., a combat entity may have the following capabilities [14]:

1) Movement range
2) Durability
3) Communication range
4) Sensing range
5) Lethality
6) Probability of hit
7) Weapon range

The capability may be represented by values or effects varied within a range.

A unit at the high level is aggregated from several entities. The unit can perform a combined action that is not possible to be performed only by an entity. As a result, the unit capabilities are a combination of all subordinated entity capabilities. It is more difficult for a commander to mentally estimate the aggregated behavior of unit than of a single entity. The use of multi-agent simulation will be of great help to perform assessment of combination consequences.

In multi-agent simulation, an agent represents, or substitutes a resource. An agent is an autonomous system that has the capability to perform tasks. Figure 5 shows the model for agent generation based on the tentative plan. In Figure 5(a), a plan defines a set of agents, called an agent assembly, but an agent in the agent assembly can have only one role. According to a given plan, a corresponding agent is thus generated and assigned with resource, role and task.

As a result, a plan in the planning domain will match an agent assembly in the simulation domain. Thus the consequence prediction of a plan in a given environment is actually transferred to predict the consequences of a corresponding agent assembly in the same environment.

Several interacting agents with different affiliations may be generated, facilitating the possibility to simulate plans of two or more interacting opponents. The preferences or interests of the agent assemblies for the consequences will be different from each other. This implies that a negative consequence for one of the opponents may be a positive consequence for the other.

A task is given by goals and restrictions. All goals given in the task will be achieved when the resource has performed the assigned actions. The actions can be carried out in parallel or sequentially. An action can be grouped into three types:

1) Internal action between different agents within the same agent assembly, e.g., an entity agent at low level supports a unit agent at high level.
2) External action on other agent assemblies, e.g., against the opponents’ agents including offensive, defensive, drawback or holding position, etc.
3) Own action that is performed by the agent itself, e.g., deployment to an operational position.

![Figure 5: Relationship between agent assembly, agent, task and plan.](image-url)
An agent may be represented at entity (low) level or at unit (high) level, depending on the assigned resource. Each resource for an agent has its capabilities to solve the assigned tasks. The capabilities will be dependent of the given resources and combined entities. Figure 5(b) depicts the aggregation of the agent from several agents at low level. There exist different connections between agents expressing e.g. communication or resource sharing. All agents perform their actions in the same environment, which includes geographic area or surroundings.

The multi-agent simulation consists of the agent assemblies, the simulation environment, and an information manager. The simulation environment has different operational areas, in which all related agent assemblies interact to each other. The information manager is used to deal with information flowing into or out from the agents.

An agent can be activated or driven by a given time in the plan or by an event executed by another agent. In the operational area, the simulation starts from a start point and ends with end point. Between these points there are several objective points at which assigned actions take place, which results in different consequences and changes of the agent states.

4. Evaluation of Alternatives

It is maybe enough for the commander and staffs to judge which alternative of the tentative plans is more suitable when the consequences from the simulation have one criterion or an attribute to compare with a few alternatives. For example, one probably chooses the alternative that minimizes the time cost when a deployment is planned. However, a joint operation usually has a number of alternatives with multi-attributes such as cost, time, distance, etc., to be considered. It will be difficult for the commander and staffs to choose an alternative among the different tentative plans. In order to facilitate the selection of an optimal alternative, an attribute dimension using traditional utility theory and probability theory is thus introduced [15, 16].

According to the pure utility theory [17, 18], every possible world that may occur has, for every plan, a degree of utility for the decision maker, who prefers the plan that maximizes the utility. Introducing an attribute dimension enables a more specific comparison between different plans to find an optimal alternative for a specific situation.

When using an attribute dimension, every plan is given a set of attributes upon which the decision depends. Possible plans for a specific task must contain the same attributes to be comparable. Attributes reflect something measurable that can, for each plan, be predicted through agent simulation. These predictions are called consequence values that may be subjective predictions, but they may also be obtained automatically through agent simulation. Using agent simulation to predict consequences results in a consequence matrix as depicted in the left part of Figure 6.

We use the following definitions according to multi-attribute decision-making [19]:

\[
S = \{s_1, \ldots, s_m\} \quad \text{Set of assigned plans to be performed by agents.}
\]

\[
A = \{a_1, \ldots, a_n\} \quad \text{Set of measurable attributes or criteria.}
\]

\[
C = \{c_{11}, \ldots, c_{mn}\} \quad \text{Set of consequences defined by the consequence function } h: S \times A \rightarrow C \text{ which associates each pair } (s_i, a_j) \text{ with a consequence value } c_{ij}, \text{ which, in turn, is obtained in simulation.}
\]

\[
U = \{U_1, \ldots, U_n\} \quad \text{Set of utility functions to transfer consequence value } c_{ij} \text{ of plan } s_i \text{ and attribute } a_j \text{ to utility value } u_{ij}. \text{ } U_j: C \rightarrow R \text{ which defines preferences so that } U_j(c_{ij}) \geq U_j(c_{kl}) \text{ if and only if the decision maker prefer the consequence } c_{ij} \text{ before } c_{kl}.
\]

The consequence matrix represents measured or simulated values regarding the decision situation at hand. The utility matrix in the right part of Figure 6, on the other hand, contains utility values that are of interest solely because they can be compared versus...
each other. They do not directly reflect an actual measurement.

In practice, each attribute weights different for selecting plans, e.g., to save a life may be more significant than to save cost. Thus it is important to find a method for forming a utility function as discussed in [15, 16]. The utility function $U_j$ in Figure 6 transforms the consequence matrix to the utility matrix.

By creating utility functions that act for example like a step function we can model the situation that a commander faces where he wants to grade an attribute into different levels, such as “catastrophe”, “requirement met”, etc. One such model with three levels is depicted in Figure 7. We need to define one utility function, $U_j$, for each attribute, which reflects our belief in that all attributes behaves in a unique way.

![Figure 7: Utility levels and utility values for each attribute.](image)

According to the preferences, a value at each utility level is used as a criterion to transfer a simulated consequence value to the corresponding utility value. Obviously, each utility level is of different significance for the commander.

Using utility theory with attributes requires, as mentioned, one utility function for each attribute. These utility functions then define one utility matrix for every possible consequence matrix. Normally, the possible actions from other agent assemblies can affect the commander’s plan. This gives rise to uncertainty in the model, e.g., an opponent may be assumed to take three possible plans with respective probabilities to meet the commanders’ plan. Therefore, one consequence matrix in Figure 6 will be needed for every possible opponent plan. Summarizing the matrices, weighting with their probability to occur, then finally results in a total utility matrix representing the consequences for all possible worlds. It is this total utility matrix that should be used for evaluating and comparing the tentative plans. It should be noted that uncertainty in the model is now represented as uncertainty regarding what utility matrix is the right one. This is different from the easier situation when you only consider future possible worlds. With this new approach we are able to model his plans regarding my plans and so forth.

By simulation and evaluation, the commander and staffs can design and change the plans anytime. The results of evaluation on the plans can be quickly presented. It thus avoids the time-consuming estimation process and concludes a more deliberate plan.
5. Embedded Simulation Support

Figure 8 shows the architecture of a simulation support component embedded in a C2 system. This embedded simulation support will provide the commander and staffs with abilities to predict the consequences of a plan and to evaluate the plan. It is designed to be a network resource connected to other functional units for the joint operations. In this way, the simulation support provides not only the decision support in the planning process but also the decision-making services for training or mission rehearsal at the joint operation level.

6. Conclusions

The embedded simulation support is used to predict the consequences of generated plans and to evaluate these plans. By simulation and evaluation, the commander and staffs can design and change the plans anytime in a decision-making process. The results of the evaluation of the plans can be quickly presented, which thus avoids the time-consuming estimation process and concludes a plan that better fulfills the tasks and goals.

Multi-agent simulation is used for prediction and multi-attribute utility analysis for evaluation. The multi-agent simulation consists of an information manager, a simulation environment and agent assemblies, while the multi-attribute evaluations consist of decision support presentation and utility matrices. Both multi-agent simulation and multi-attribute evaluation compose the embedded simulation-based decision support, which will become an essential part in the C2 system.

7. References


Author Biographies

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