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A Generalized Command and Control Probability Model

Network-centric Metrics
C2 Modeling and Simulation

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Abstract

This paper presents results of a Johns Hopkins University Applied Physics Laboratory (JHU/APL) effort on the fundamental theory of C2. Probability models have been used successfully in C2 applications where the objective was to destroy as many targets as possible. A "kill chain model," such as Find, Fix, Track, Target, Engage, Assess (F2T2EA), can be useful in evaluating military systems. Recently, Find, Fix, Finish (F3) has been used as a more general C2 probability model. This F3 model still assumes there is a target. This paper presents a generalized probability model based on the concept that C2 is a resource optimization problem, where a set of "opportunities" are identified and then a schedule of resources is applied towards those opportunities. This more general C2 model can be applied to a wider range of military situations, such as those dealing with asymmetric threats.

Introduction

Many military activities have an underlying theoretic body of knowledge. Search Theory, for example, provides a basis for algorithms and situations involving searching such as locating an enemy sub or trying to find a downed pilot. A theoretical foundation serves many useful purposes by enabling analysts to discuss and analyze the problem in a mathematical way. Competing methods can be evaluated based on the theory to identify the relative merits of each. Command and Control (C2) is a critical military activity that has to date not been adequately described by an underlying computational theory. One of the more successful models for C2 is the Find, Fix, Track, Target, Engage, Assess (F2T2EA) model. The limitation of this model is that it is not general enough; it assumes that there is a target to be engaged. This paper presents a more generalized probability model for C2 which can be employed when the action to be taken may not be to engage a target.

The quest for such a theory does not suggest that commanders will soon be replaced by computers; rather, analysis will show that many tasks are accomplished more efficiently by humans than by current algorithms. Truly complex problems do not lend themselves to reduction to simple formulae, but having the foundations of C2 described mathematically would enhance the search for better support systems for tomorrow's commander. The establishment of a direct relationship between the activities of C2 and areas of research facilitates the introduction of new and current techniques into C2 while providing important feedback for the research community.

If we can describe the fundamental goals and functions of C2, then we can better understand, describe, simulate and support real world C2 processes. A theoretical framework provides a solid foundation on which to develop models which help to understand and predict this highly complex system. Such a theory should be universal.

One of the difficulties with C2 models is that they tend to describe **a** C2 system or process but not **all** C2 systems or processes. The more detailed C2 process models tend to become a laundry list of good ideas for commanders to do, not all of which are either necessary or sufficient. The C2 model presented in this paper is a universal model applicable to all C2 situations.

Background

Military models of C2 take on many forms, each with particular strengths and weaknesses. With the revolution in communications fueled by the internet, new C2 paradigms have been proposed (e.g. net-centric) which propose a significantly different perspective on the organization and function of facilities. At this point it is unclear where each C2 paradigm and model is most effective. Therefore, it is in the best interest of all who are invested in a C2 system to analyze the effectiveness of each paradigm in a quantitative manner, weighing the associated costs and benefits carefully.

Numerous conceptual models of C2 exist, such as John Boyd's OODA Loop (Observe, Orient, Decide, Act). This model was developed to explain fighter aircraft engagements but has been applied to a wide range of situations. Similar models include MAPE (Monitor, Access, Plan, Execute), SDA (Sense, Decide, Act) and MAAPPER (Monitor, Access, Analyze, Predict, Plan, Execute, Report). There is also the Lawson C2 model as well as the Enterprise Theory of C2. [3]

A representation of the OODA Loop is shown in Figure 1.

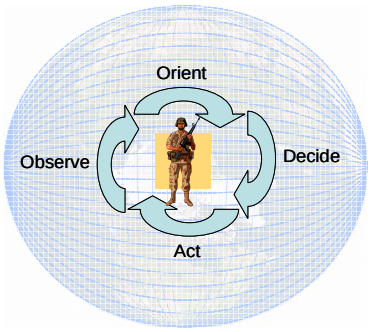

Figure 1. Representation of the OODA Loop

Other approaches such as Builder's Command Concepts focus on the art of command, suggesting that the essential communications up and down the chain of command can (and should) be limited to disseminating, verifying, or modifying command concepts. The ideal command concept is one that is so prescient, sound, and fully conveyed to subordinates that it would allow the commander to leave the battlefield before the battle commences, with no adverse effect upon the outcome. [3]

The C2 Problem

The Department of Defense defines Command and Control (C2) as: "The exercise of authority and direction by a properly designated commander over assigned and attached forces in the accomplishment of the mission. Command and control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of the mission." [1] For the purposes of this paper we will adopt a slightly broader definition of C2 which encompasses both military and civil applications. We shall define C2 as an allocation of resources by a leader over a set of opportunities. The C2 problem, then, addresses:

1) how to define the set of opportunities,
2) how to best allocate resources among the opportunities, and
3) how best to carry out those decisions.

In order to analyze how a leader allocates resources over a set of opportunities, we must consider a plethora of different factors. There have been several models which describe the C2 process, many of which include concepts which are common across them. In this work we choose to use a very general set of concepts in order to decouple the description from any specific model. The problem can be reduced to three general components: Sense, Decide, and Execute (SDE). In this model the tasks associated with each of these components are performed sequentially. For example, commanders and their staffs may first sense the conditions of an environment, then make some decision regarding the opportunities, and finally execute a course of action to deal with the opportunities. Also, the process as a whole may be performed iteratively and recursively. The Sense, Decide, and Execute components are typically performed continuously in a loop, and performing a task associated with a component may involve the SDE loop at a lower level. For example, orders given to a brigade are reviewed, evaluated, expanded and then passed down to the battalions that comprise the brigade. The battalions do the same before they pass orders down to the companies under their control.

The SDE formulation of the C2 problem is a top-down approach which aims to identify the most basic concepts required of a C2 system, abstracted of any specific military or civil needs. This formulation attempts to define the components which are necessary and sufficient to constitute a C2 system. Implementations may certainly include additional features in order to facilitate the operation of the system. Command and control is carried out in many different environments, however, we believe that the foundation described in this paper is common to all C2 systems.

Figure 2 illustrates the key functions of the C2 process. In this figure we define the boundary of the C2 process as the information interface with the rest of the world. Information flows in and the C2 system evaluates the information, selects opportunities to pursue, assigns and schedules resources against those opportunities and then generates orders and other communications to execute the plan.

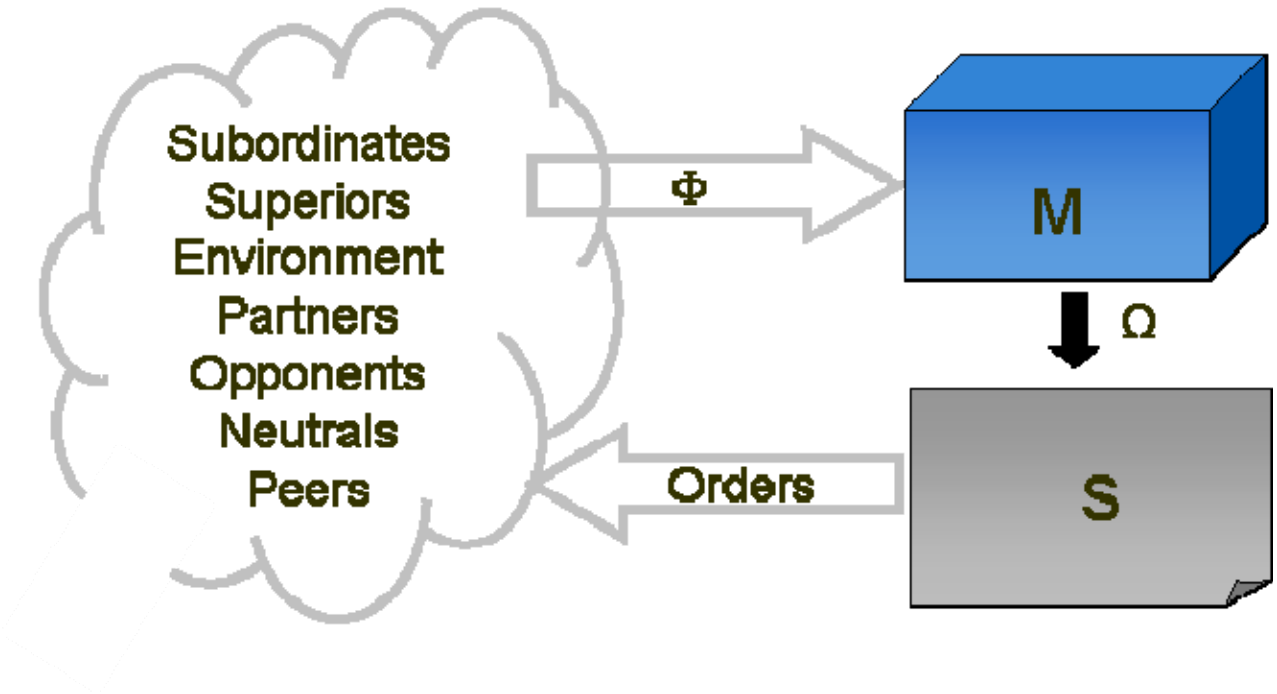

Figure 2. The C2 Problem

- The cloud represents those things outside the C2 system
- Φ, The set of information received by the commander (and staff)
- M, "Machine" that takes Φ as an input and produces Ω.
- Ω, Set of Opportunities that resources may be assigned against.
- S, "Machine" that takes Ω as input and produces orders.
- Orders, Set of communication that indicates the Course of Action (COA) selected.

Uncertainty and Probability

The C2 problem involves a high degree of uncertainty in almost every aspect. All information gathered about the real world has some amount of uncertainty associated with it, and more uncertainties are introduced as this information is transmitted and interpreted. Each source of information and each agent that manipulates the information generally introduce a factor of uncertainty regarding the accuracy of the information. Uncertainty is a natural part of dealing with information in the real world and comes from many different sources. Sensory information has a certain level of uncertainty due to

error in making measurements and possible failure situations. Humans are naturally fallible in many different respects, adding additional uncertainty to the information. Information may also be deliberately modified, so we must judge our confidence that the information is dependable.

In addition, a high degree of fundamental uncertainty exists when trying to predict unknowns, such as an opponent's future decisions or the movements of a weather pattern. Theoretical modeling and practical trials can help to ensure that the decision makers have the best possible estimates of these unknowns; however, accurate estimate of the uncertainty is critical as well. This type of information is critical to making good decisions, so it must be represented as fully as possible. Uncertainty complicates many of the activities of C2 and turns them into difficult and complex problems.

Typically this uncertainty can be quantified using a probability function. In order for a probability function to accurately represent the uncertainty one must take into account all possible outcomes. Each outcome must bear a weight representing the likeliness that the outcome will occur with respect to all of the other outcomes. When the outcome is independent of all previous outcomes, then the probability is *a priori*. In some cases the outcome of a particular event is dependent on the outcome of a previous event, introducing a conditional probability. A *posterior probability* may be calculated for an event with conditional probability if the outcomes of the dependent events are given.

Determining the probability that a C2 system will produce an optimal solution is an important problem to consider when evaluating the system. Given that the three components of a C2 system process a one-way stream of information, the probability that a component performs optimally is dependent only on previous components and not future components. This produces a chain of conditional probability factors. The formation of the probability chain depends on the optimality criteria for a system. In some cases optimality might require only that the optimal course of action be present in the schedule, while in another case optimality might have the criterion that no sub-optimal opportunities be present at all in the schedule. In general the probability model for an optimal solution is:

$$\Pr(OS) = \Pr(\varphi' \subseteq \Phi) \times \Pr(\omega' \subseteq \Omega \mid \varphi' \subseteq \Phi) \times \Pr(\pi' \subseteq \Pi \mid \omega' \subseteq \Omega)$$

Where *OS* is the event that the optimal solution is executed, φ' is the information required to discover an optimal opportunity, ω' is the optimal opportunity and π' is a schedule containing the optimal course of action with the optimal resources assigned.

Notice that *OS* is not equivalent to success; but rather, the execution of the best choice. Decision quality is not equivalent to the quality of the outcome, but rather to the expected utility of all possible outcomes combined. A bad decision might be associated with unnecessary risk and if the risk fails to realize upon resolution of the decision, the original bad decision does not suddenly become a good decision.

Analysis of C2 Failures

Analysis of the failure modes of C2 may be helpful in understanding the generalized C2 model. If a poor decision has been made, why was it made? What do we mean when we say that a poor decision was made? We mean that there exists an optimal solution and that $\pi' \not\subset \Pi$.

Since ω' is the optimal opportunity, either ω' was chosen or it wasn't. If ω' was chosen, then π', the orders given, did not assign the optimal resources to the optimal opportunity. That is to say, the C2 system failed because the wrong or insufficient resources were applied or the scheduling of the resources was sufficiently wrong to reduce the likely outcome. If ω' was not chosen, then the C2 failure occurred earlier in the C2 process and the scheduler function is not to blame.

Given that ω' was not chosen, then if $\varphi' \subseteq \Phi$, then the machine M failed to choose the optimal opportunity when provided the required information. If $\varphi' \not\subset \Phi$, then information provided was insufficient to indicate that the optimal solution was, in fact, the correct choice.

One could also replace "optimal solution" with "good solution." The definition of "good solution" would then need to be defined and each solution generated evaluated vs. a good solution. A C2 system might be measured against "good" solutions because optimal solutions may be impossible to define or identify, and in some circumstances, avoiding bad solutions may be good enough.

Risk vs. Chance of Success

One of the reasons military decision-making is so challenging is that there is always a tradeoff between risk and achieving the mission objectives. It is clearly the commander's prerogative to make this risk vs. reward tradeoff in choosing the best course of action (COA). When the commander doesn't specify the explicit tradeoff then the C2 problem becomes a multiple objective optimization problem.

In situations where there are multiple criteria to optimize, there isn't one optimal solution, there is an efficient frontier of solutions. These solutions maximize the chance of success for a given amount of risk. Other solutions, which do not lie on the efficient frontier, are said to be dominated solutions as they are strictly inferior to one or more other solutions.

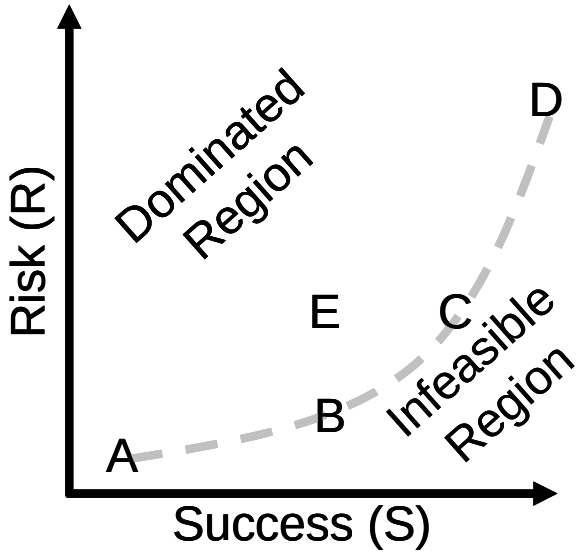

Figure 3. The Efficient Frontier

In Figure 3, A, B, C, and D represent solutions on the efficient frontier. Each represents the maximum chance of success for a given level of risk. Solution E is dominated by solutions B and C. For the same level of success, B offers lower risk than E, while C offers greater rewards for the same level of risk as E.

The general probability model can be applied to multiple criteria C2 problems. The same formulation is used but instead of asking if the optimal solution is found, the question is: does the solution belong to the set of non-dominated solutions? Or, in other words, does the solution lie along the efficient frontier?

How does one measure risk and reward? For each of these measures a utility (or value) function is created, that assigns each solution a value based on the probability of bad (risk) or good (success) things happening. Casualties and loss of assets are clearly key elements of risk, while good things are the accomplishment of various mission objectives.

Results: Risks and Opportunities

Because this model reduces to the standard kill chain model under situations where the C2 problem is a targeting problem, there is only the standard modeling risks when applied to such situations. The advantage of this model is that there are many opportunities to apply this model in which F2T2EA would not be helpful. The model can be applied in unusual situations such as nation building activities or peace keeping activities where many of the activities are not specifically target related. One of the challenges of this new approach is that performance data may not exist. Asking a military planner, "What is the probability that you won't think of the best solution?" may get interesting responses, but it is unclear how accurate the answer will be. Without

empirical evidence of the current and future performance of planning staffs and commanders, finding the correct parameters of the model may be problematic.

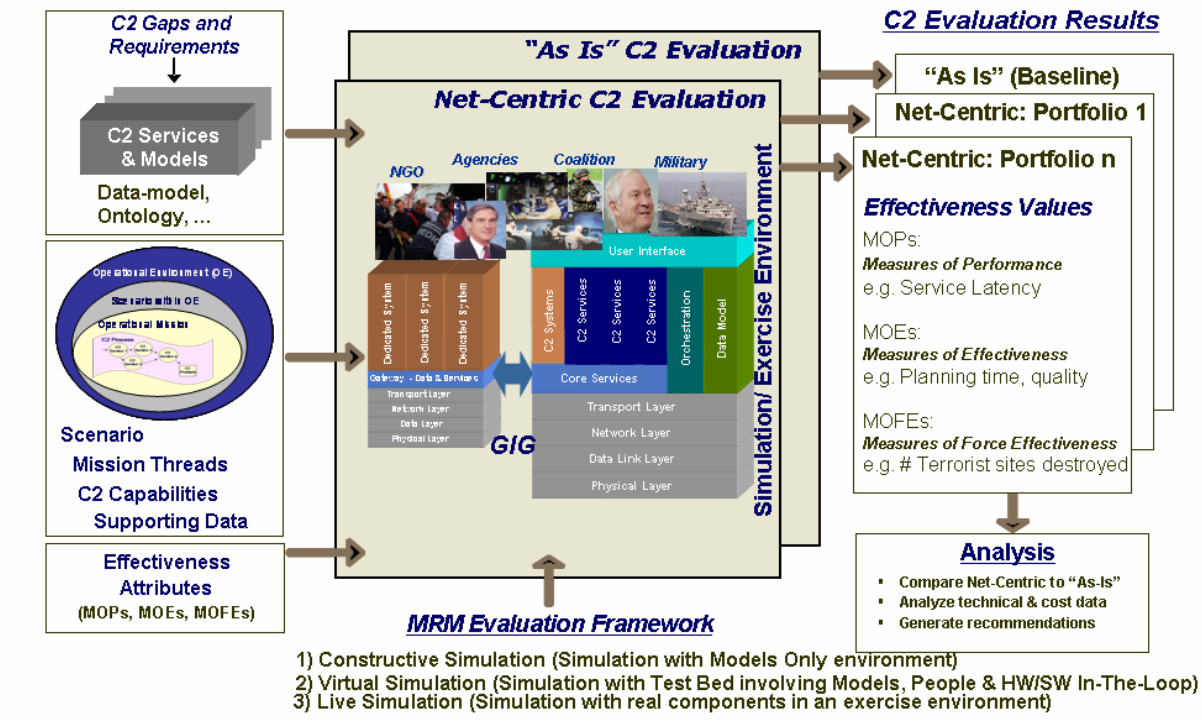

Figure 4. Multi-Resolution Modeling Evaluation Framework (MRMEF)

APL has developed a methodology for evaluating the impact of technology on C2. Figure 4 illustrates the Multi-Resolution Modeling Evaluation Framework (MRMEF). More information on this approach can be found in the referenced CCRTS paper [3], as well as North's paper on the 2007 C2 experiments [7].

The generalized probability model contributes to MRMEF in two ways. The first is as a simple, low resolution model. Simple models can be used effectively when time is limited or the model serves as a basis for an end-to-end analysis; with detailed modeling, simulation, or analysis adding higher fidelity to one or more pieces of the general C2 model. In addition to serving as a simple C2 model, analysis of the model suggests appropriate metrics to evaluate the performance of a commander's C2 system. Each piece of this model has a probability associated with it assuming that the prior C2 functions were successful. Just as probability of detection and probability of kill are key parameters in the kill chain model, the probability of opportunity selection and the probability of COA selection are key parameters in our model.

The APL experiments in 2007 analyzed the probability of correct COA selection under conditions of varying data consistency, extraneous data, incomplete data, and time. While the focus was on demonstrating the methodology and tools due to our limited

fidelity, our initial findings indicate that additional time used by the decision maker can overcome much of the effect of extraneous data and incomplete data, but inconsistent data appears to have a significant impact on the probability of correct COA selection and additional time is only marginally effective at overcoming the problem.

Future Research

This model is part of a larger effort that is looking at building a fundamental, mathematical model of C2 to assist in enterprise engineering, system engineering, testing and analysis. This overall approach is to view C2 as an optimization problem where the commander must allocate resources and develop a schedule of activities in order to meet his objectives while minimizing risk. APL has recently started an internal effort to examine strike battle group planning and the possibility of improving the integration of planning across the warfare areas in support of the battle group commander.

The test of any theory is how well it helps solve problems. APL will be using this theory as one of the tools to examine the C2 of a carrier battle group, and the potential of various technologies such as modeling and simulation to support the commander in COA selection and resource allocation decisions.

Conclusion

This paper provides a more generalized, probabilistic model of the C2 problem than the more commonly accepted F2T2EA model. A brief overview of C2 models is presented and our approach is defined. There is much research that remains to be done; this paper represents an attempt to define a general probabilistic model of C2 that can aid in future C2 research as well as assist the warfighter in analyzing and understanding today's complex C2 environment.

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