THE QUEST FOR A C^3 THEORY: DREAMS AND REALITIES*

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PROLOGUE

Σαν βγης στον πηγαιμο για την Ιθακη,

να ευχεσαι νάναι μακρυς ο δρομος,

γεματος περιπετειες, γεματος γνωσεις.

Κ. Π. Καβαφης

INTRODUCTION

A new symposium on Command and Control research is being inaugurated today at the National Defense University. The new symposium is sponsored by the Joint Directors of Laboratories. Both the sponsorship and the venue are most appropriate, since they reflect that command and control research is relevant to all the services.

This is taking place ten years after the first Workshop on C^3 Systems was held at MIT with sponsorship by the Office of Naval Research. Then, as now, the question was: is there, or will there ever be, a C^3 theory? For ten years, researchers in government, academia, and industry have been working on the development of such a theory. Their continuing efforts can be characterized as a quest, with a C^3 theory as the grail. There were ambitious dreams when the quest was started; ten years of realities have affected these dreams, changed them and adapted them.

In this talk, together, we shall try to travel the path of the quest quickly by selecting, with perfect hindsight, some of the ideas that formed the current thinking. We shall then venture to present a view of the now and future theory. This is a personal view, tempered by the wise counsel of the many researchers and users who shared their views in lively debates during the past ten years.

To begin the story of the quest, it is important to fix a starting place and time. In the late seventies a number of meetings, panels, and workshops were held on various aspects of Command and Control. One that stood out was held right here at the National Defense University, on October 1979. The title of the workshop was "Quantitative Assessment of Utility of Command and Control Systems". Its stated goal was the development of a community with a sense of immediacy and purpose, a shared conceptual framework and language, and a coherent research and evaluation program [1].

The chairmen of the workshop, Andrew W. Marshall and Harry L. Van Trees, observe in their opening statement in the proceedings that "The ubiquitous nature of command and control systems makes it difficult to define and coalesce a community to deal with this problem" [1]. The presence of so many people in this room, a few of whom attended that workshop in '79, is evidence that a community has been created and is growing. We would like to believe that the MIT/ONR Workshop contributed over the years in defining and forming that community.

It is in the proceedings of the '79 Workshop that one finds explicit mention of the need for a C^2 theory. While the concept was discussed for several years prior to that, it is David S. Albert's statement "To provide a framework in which progress towards a 'Theory of C^2' can be achieved ..." [1] that articulates the goal — the grail — of our quest.

But what is a theory? The Random House Dictionary tells us that it is "A coherent group of general propositions used as principles of explanation for a class of phenomena". The phenomenon of concern here is the command and control process. Note that it took a number of years to agree that command and control <u>is</u> a process that is <u>supported by</u> the C^3 systems. Indeed, we have a family of systems: C^2, C^3, C^3I, C^4I, where communications, intelligence, and

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"When you start on your journey to Ithaca, then pray that the road is long, full of adventure, full of knowledge", from "Ithaca", by K. P. Kavafy.

computers have been added explicitly to emphasize different components and functions of the underlying systems. The challenge that we set for ourselves is to develop a theory that not only explains, but can also be used to design and evaluate C^3 systems.

So, meeting this scientific challenge — is it a dream, or can we make it a reality?

THE NOBLE QUEST

A broad definition of the process of command and control that is amenable to a variety of valid interpretations is the one given in Pub 1 of the Joint Chiefs of Staff:

"Command and Control: The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of his mission. Command and Control functions are performed through an arrangement of personnel, equipment, communications, facilities, and procedures which are employed by a commander in planning, directing, coordinating, and controlling forces and operations in the accomplishment of his mission".

Certain words that are key to the understanding of command and control as a process have been underlined. They have led to the conceptualization of C^2 as a cybernetic process. Joel S. Lawson, Jr., in the middle '70's, postulated the representation shown in Figure 1, in which the overall process characterized by the verbs "sense, process, compare, decide, act". Important concepts introduced in this diagram were the desired state and the interaction between our forces and the environment.
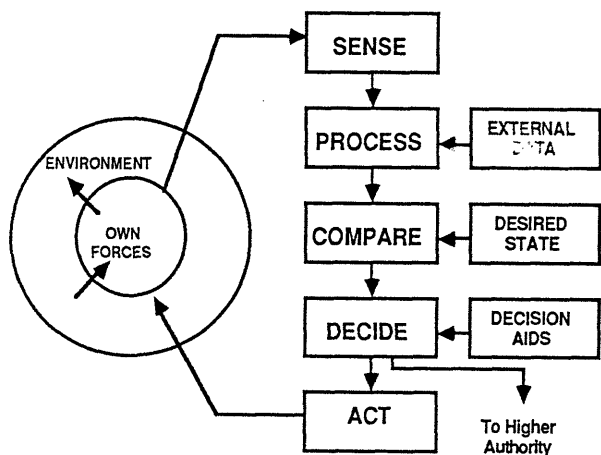

Figure 1. C^2 Process: The Lawson Model (c. 1980)

This attempt to divide the process in its component parts is a basic tenet of systems engineering, founded on Descartes' dictum: "Break down each problem you are trying to solve into as many parts as you can and as many as you need to solve them easily".

We have been tinkering with this diagram ever since. The one shown in Figure 1 is Jay's own version, circa 1980. In Figure 2 a more recent version is shown. Note the subtle differences. There are six stages now, and the verbs have been modified. Comparison of the two figures begins to give us a hint of the difficulties to come. It is not self-evident how the total process can be partitioned, as the changes in the verbs indicate. Furthermore, it is even more difficult to serialize the stages of the process. It has been argued that "planning" can be inserted at different places in the diagram, all equally valid, but each describing a different instantiation of the process.
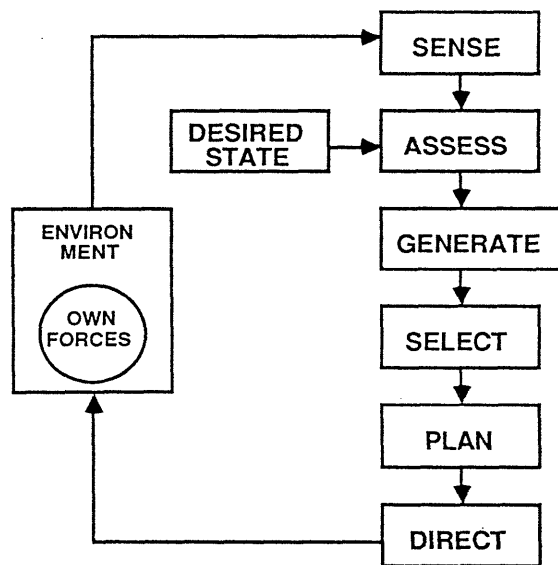

Figure 2. The Conceptual C^2 Process Model

While these diagrams are invaluable in helping us undertand the C^2 process, the abstractions and idealizations they include are very limiting. The realities are that command and control in a military organization contains a large number of nested C^2 processes; likewise, C^2 processes are concurrent, e.g., the AAW, ASW, and ASUW processes in a naval battle group. The reality is also that often there is no single C^2 entity; tactical decision making is often distributed, as in joint or combined operations.

Attempts to generalize the simple cybernetic loop of Figures 1 and 2 by introducing nested and concurrent processes has led very rapidly to the Achilles heel of systems engineering: the curse of dimensionality. A simple argument shows that the number of interconnecting links in such expanded representations increases as

$$(\text{number of processes})^2 \times (\text{number of stages})^2$$

By then, the simplicity and elegance — the strengths - of the cybernetic loop have been lost.

As if these realities were not enough, Tom Rona, in 1982, articulated his axiom that put into question many of the then existing conceptualizations and models of command and control. The axiom stated: "Wars are fought against the enemy - The enemy is the most important element in the C^3 design and operation" [2].

Tom's statement brought into focus another class of problems referred to here as "the curse of complexity". The environment, in Figures 1 and 2, contains the enemy, and this enemy is intelligent, active, and unpredictable. It is not clear that worst case designs come to grip fully with the complexity issue. Consideration of counter measures, counter-counter measures, etc., which include misinformation and deception, only begin to show the dangers of oversimplification.

A major source of the complexity is that many human decisionmakers are integrated in the C^2 process. These humans, intelligent, active persons, are not just components or users of C^3 systems, but an integral part of the process itself - on both sides, ours and the adversary's.

There is still a third perspective on command and control that introduces other aspects of reality: the commander's perspective. Lt. General J. Cushman, USA (Ret) has articulated this perspective [3] by pointing out that for a commander to use his forces effectively, the C^2 process must exist, it must meet essential needs, and his forces must be practiced in its use. These conditions translate into the requirements for survivable and effective command and control and for C^3 systems that are operable by their users. This last requirement is often taken for granted in discussions of interoperability. This curse of complexity, both in the real systems and processes as well as the models that attempt to describe them, makes one sympathize with a modern warrior's lament as expressed by General Moshe Dayan: "Where, oh where are the good old days of the simple wars when, as the hour of battle approached, the commander got on his white horse, someone blew the trumpet, and off he charged toward the enemy".

The dream, then, of developing a theory of command and control by dividing the process into its component parts, has been tempered by the reality. Unfortunately, as the twin curses of dimensionality and complexity have shown, Leibnitz's response to Descartes' dictum applies in the case of command and control: "The rule of Descartes is not effective, since the art of separation does not yield to interpretation".

THE NOW AND FUTURE THEORY

Given all these considerations, we are forced to question whether there is reason to believe that the quest will lead to the grail. What are indeed the prospects for a C^2 theory? Or, at a more fundamental level, we may ask whether a unifying concept has emeged in C^2 research that can form the basis of a theory.

The answer to this question is not found in mathematical treatises but, most fittingly, in a book by a military historian. M. Van Creveld writes in Command in War [4] that "The history of command in war consists essentially of an endless quest for certainty about the state and intentions of enemy forces, about the... environment, and about the state, activities, and intentions of one's own forces".

Thus, we may postulate that the unifying concept in C^2 is the need to cope with uncertainty. And uncertainty will be given a broad definition that is independent of the mathematical model used to desribe it. Let K_N represent the knowledge needed to carry out a mission, or solve a problem, or make a decision effectively, and let K_A be the knowledge that a decisionmaking entity has at the point in time and place that a choice needs to be made. Then, uncertainty can be defined as the difference between these two quantities,

$$U = K_N - K_A$$

namely, the difference between what one needs to know and what one knows. Note that it is axiomatic that K_N is larger than K_A. Note also that the terms K refer to knowledge, not to data or to information. The relationship between these three quantities is shown in Figure 3.

DATA
⇓ ⇐Technological
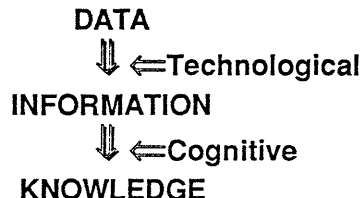INFORMATION
⇓ ⇐Cognitive
KNOWLEDGE

Figure 3. Data, Information and Knowledge

Data are transformed to information, primarily by technological processing: an electromagnetic pulse is converted into a set of symbols on a radar screen. Humans, can also do part of this processing. Transformation of information into knowledge is, however, a cognitive process that is done by humans, if humans are the decisionmaking entities. Leon Tolstoy, a hundred years ago, wrote that "Knowledge is knowledge only when it is acquired by the powers of one's own mind, and not by memory".

As a corollary of the above characterization of uncertainty, it follows rather obviously that reduction of uncertainty is not synonymous to more data flow.

If we accept this definition of uncertainty and Van Creveld's remark, then the C^2 process can impact both knowledge terms in the equation: it can increase the available knowledge through the "Sense" and "Assess" functions of the cybernetic diagram in Figure 2, and it can decrease the needed knowledge through the "Generate", "Select", and "Plan" functions in the same diagram. Thus, we can recognize two approaches to reducing uncertainty to

acceptable levels.

The first approach, called The Technology Fix, emphasizes the collection of data and their processing into information that, when presented to the human decisionmakers, will be converted to knowledge. The second approach, The Human Fix, entails the designing of the process itself, so that decisionmakers have more knowledge or the problems are framed in such a way that they need to cope with less uncertainty. Let us now explore both "fixes"

In the last ten years, we have been making major advances in technology. For example, better sensors, algorithms for data fusion, data bases, and networks, have been improving the collection and distribution of data, while better tracking algorithms and target acquisition algorithms have improved the quality of information generated.

We have also been making substantial progress in modeling uncertainty. Different models have led to a variety of rich theories: stochastic systems theory, information theory, fuzzy set theory, belief function theory, and catastrophe theory. All of them have been seen contributing to the modeling and analysis of command and control.

However, while we improve our tehnology and extend our theories, the parameters that characterize the missions have been changing. In a very short period of time, we have gone from tens, to hundreds, to thousands and tens thousands of threats. From localized events, we have gone to global events and now we have began to consider space, too. And from single service forces, such as a self-contained naval battle group, we now consider joint and multi-national forces. The scale and the tempo of the problems have been changing with time.

As technology advances to solve some problems, it also changes them. For example, the use of satellites has changed forever the collection and transmission of information; it has also introduced the problem of satellite survivability; the very nature of the survivability problem for C^3 systems has changed.

The same applies to theoretical research. The moment we solve a problem, we also bring to focus the next one. Thus, in pursuing the technological fix, we must look for evolutionary technological solutions to address the continuously evolving needs, their evolution triggered to some extent by the solutions themselves.

We have explored, thus far, the twin curses of dimensionality and complexity, and focused on some of the pitfalls inherent to the technological fix. It is time to turn now to an upbeat theme, the human fix, or the blessing of human intelligence.

Reduction in uncertainty can be achieved by increasing the available knowledge through the conversion of information into knowledge. This can be accomplished through training, simulations, war games, exercises, etc.

One the other hand, reduction of the needed knowledge by an individual commander can be achieved through organizational design — for example, the introduction of doctrine that implements distributed decisionmaking — or the use of decision aids.

Decision aids in the C^2 context should be thought of as integral components of the C^3I system (not as post facto add-ons) and as enhancers of a commanders intelligence - not as substitutes for it. It is a more fitting image to think of decision aids based on constructs from Artificial Intelligence as being in support of Human Intelligence. A well designed decision aid should be able to provide information in a form easily convertible to human knowledge. Recent research results have shown that there is a subtle interplay between automated and human decisionmaking. Indeed, the assumption that we can transition from decision aids to automated decisionmaking is often based on the fallacy of perfect understanding.

We must also remember that modern commanders command complex organizations and are themselves members of other organizations. Theoretical advances are needed in the area of human decisionmaking, including better models that address the cognitive limitations (bounded rationality) of humans. Furthermore, we need to continue our efforts to understand the case of multiple decisionmakers because of its extreme relevance to the command and control process where distributed decisionmaking is the rule rather than the exception. These theoretical efforts are being coupled with experimental designs for the collection of empirical data. We are beginning to understand the relationship between the architecture of a C^3 system and its performance by including explicity the human decisionmakers in the C^2 process. The increased emphasis in the human fix has been evidenced by the number of sessions and papers that address these issues in this Symposium and in the more recent MIT/ONR Workshops.

CONCLUSION

So, what can we conclude? Is a "Theory of C^2" a dream or a reality? In this talk, we have tried to show that, while the attainment of a comprehensive theory may be a dream, the quest for it is very real. And, it is a never ending quest, because what we discover, very qucikly, sows the seeds of tomorrow's challenges. New problems, new challenges, arise before the solutions to the previous ones have had a chance to be tested, let alone be implemented.

But, if as Van Creveld says "The attainment of certainty is, a priori, impossible," [4], we may also want to conclude that the grail may not be, ultimately, the prize; what we are discovering in out quest may be the real prize.

To close the circle, started in 1979 with the workshop on C^2 in this same place, let us observe that there is now a community with a sense of

immediacy and purpose, with somewhat shared conceptual framework and language, and with a research program that is beoming more focused and coherent. And, we can still dream...

EPILOGUE

"Ithaca has given you the beautiful voyage, without her you would never have taken the road.

....

With the great wisdom you have gained,
          with so much experience,
you must surely have understood by then
          what Ithacas mean".

          K. P. Kavafy

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