REPORT OF THE TRI-SERVICE WORKING GROUP ON THE ROLE OF PROBABILITY AND STATISTICS IN COMMAND AND CONTROL

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EXECUTIVE SUMMARY

The purpose of this report is to provide a focused view of some of the conclusions and recommendations resulting from the deliberations of the Tri-Service Working Group on the role of probability and statistics in command and control. A first, clear, and unanimous view of the working group is that this role can and should be substantial, as essentially every aspect of command and control deals with the handling or digesting of information and with reasoning in the presence of uncertainty, activities that are the heart and soul of probability and statistics. A second, equally clear and equally resounding conclusion is that the particular challenges to probability and statistics that command and control presents represent exciting and substantive areas for research that call out for a sincere effort to engage the prob/stat community, so that these practically important and intellectually stimulating problems receive the attention that they require and deserve.

The body of this report describes our answers to a series of questions that we posed and discussed in detail, aimed at identifying major problem areas in command and control to which probability and statistics could and should contribute; outlining critical characteristics of these problems and the environment in which command and control takes place that have significant implications for the types of basic research problems that need to be addressed; and then identifying a set of research questions that we recommend as the focus for any initial investment in this very large and challenging area.

More specifically, our deliberations began with the following question:

A. What are the major topics in command and control to which probability and statistics can contribute?

The working group identified and discussed at length six such topics, each of which is described in the body of the report:

- **Situation and Informational Awareness and Understanding**
- **Planning**
- **Monitoring and Discovery**
- **Performance Assessment**
- **Interactions with Human Decision-makers**
- **C2 Structure**

As our discussion progressed, we began to examine these topics with an eye toward identifying issues that were of most importance, most unique, and of most significance in defining the research challenges C2 presents to the fields of probability and statistics. More specifically, we addressed the following question:

B. What are some of the important characteristics of the environment in which command and control must operate and of the functions that must be performed that make these problems challenging and require new formalisms and methods?

The body of the report describes in some detail the results of our discussions in this area, which identified the following characteristics:

• The data and information available are voluminous and of many different types and character.

• The spaces over which inference is to be performed--i.e., the reasoning and decision spaces--are extremely large and complex.

• The phenomena, activities, and environment that make up a tactical or strategic engagement are distributed, concurrent, hierarchical, and interacting.

• One of the most critical factors is TIME.

• The command and control system is intrinsically distributed.

• The "pedigree" and accuracy of information is of great importance.

• In military situations, there are many users of information and many decision-makers with very different "apertures" into the battlespace and very different objectives.

• Disruption and opportunity are the rules rather than the exception.

• The dynamics of warfare cannot be described by physical laws.

At this point in our deliberations we had identified a number of areas for fruitful and important research investment. Some of these areas are clearly within the domain of the probability and statistics program, while some others equally clearly make contact with other disciplines (e.g., operations research, man-machine interactions, and signal processing). The vision we put forward here involves the initial investment of resources in the former, with alliances being built with other disciplines as the activity in this area grows and takes form. Thus, while we present a full slate of topics in the body of this report, we also recommend that initial effort be focused on a subset of them, which we have identified in response to the following question.

C. Where do we start?

Our recommendation is that any initial investment of probability and statistics resources in this area focus on:

• **Situation and Informational Awareness and Understanding**
• Monitoring and Discovery
• Performance Assessment

More specifically, in the report we identify and describe the following specific challenges to probability and statistics in support of these three areas:

• Development and study of probabilistic frameworks for situation awareness.

• Developing scaleable algorithms for situation awareness.

• Building models for situation awareness.

- **Dealing with decentralized situation awareness systems.**
- **Change and anomaly detection.**
- **Sequential decision-making for situation awareness.**
- **Methods for assessing performance.**

In the body of the report we identify some particular technical areas that appear to us to be relevant to these challenges, but we also want to emphasize that these specific technical directions should be viewed as examples to clarify what we have in mind rather than an all-inclusive listing of the specific mathematical formalisms that deserve investment. Indeed we fully recognize that the history of basic research tells us that the breakthrough that is needed in any of the areas we have identified may very well come from a direction or formalism that cannot be anticipated today.

This last point deserves a bit more elaboration. In particular, as we briefly describe in this report, DoD in general and the Navy in particular has had a long history of active and very successful engagement of the probability and statistics community. This partnership between basic research and DoD has served both groups well, on the one hand providing support and a never-ending sequence of intellectual challenges to the basic research community and on the other leading both to important breakthroughs that have had considerable impact in military systems and to the training of young professionals at research universities who now occupy positions of technical leadership throughout the DoD and industrial communities. The foundation on which this successful collaboration has been built represents a true partnership, with enough freedom given to basic research so that real innovation and unanticipated breakthroughs can be pursued, but also with a sincere commitment by the research community both to understand the technical challenges that the future presents to DoD and to make significant contributions to meeting those challenges. While we fully recognize that we live in a time of limited resources for research, we believe that this same strategy of partnership will provide an excellent return on investment in the areas we have outlined in this report.

I. GENERAL COMMENTS

Before delving into the technical discussion, there are several general points that need to be made:

1. The deliberations of this working group began by taking as broad a view as possible of the issues involved in command and control, both to identify the major problem areas in command and control that are of particular relevance to the focus of this study, and also to outline the characteristics of those problems and of the environment in which command and control is to be exercised that together define important areas of research in probability and statistics. This rather broad-ranging investigation led to the definition of a number of areas for fruitful and important research investment. Some of these areas are clearly within the domain of the probability and statistics program, while some others equally clearly make contact with other disciplines (e.g., operations research, man-machine interactions, and signal processing). The vision we put forward here involves the initial investment of resources in the former, with alliances being built with other disciplines as the activity in this area grows and takes form. Thus, while we present a full slate of topics, we recommend that initial effort be focused on a subset of them.

2. We have organized the discussion of research areas around subtopics that relate directly to issues in command and control rather than around particular research problems in probability and statistics. Indeed, while it is certain that we have not been completely successful ourselves, we believe that it is very important not to prejudge which prob/stat research paradigm is appropriate for which problem area nor to limit the scope of investigation within each topic. For example, while we certainly have our own strongly held opinions about which types of statistical models and problems are appropriate for the examination of issues related to situation awareness (and, in fact, we will briefly mention several of these as concrete examples), we urge the program to keep an open mind to the possibility (and, given history, the highly likely event) that the breakthrough that is needed comes from a direction that cannot be anticipated today.

3. In putting together the list of topics we have also kept in mind what it is that basic research (and, in particular, university research) can and cannot do well, especially in a field such as command and control in which DoD labs, agencies, and private industry are expending so much energy and resources. In particular, basic research in this area should be viewed as a complement to what is done in DoD and industry at more applied levels. More precisely, basic research should be aimed at those areas in which revolutionary rather than incremental enhancements are needed, and the topics listed here are all in that category. Without question, DoD does not need university research to generate engineering enhancements to existing systems or to lead large-scale demonstration programs, especially when engineers with years of experience can achieve objectives such as these so much more expeditiously. Rather universities should be focusing on delivering the two things they do well: the generation of truly new ideas and ways of thinking about command and control, fostered by working in an environment unrestricted by the constraints of deliverables and deadlines that dominate applied projects; and the training of

a new generation of professionals equipped with both the skills and the problem-solving perspectives that future command and control systems will demand.

4. The preceding point, however, does not imply that we recommend "funding the academics and then getting out of their way." Indeed we see a very strong need for interaction with more applied programs within DoD. To be sure, in part this is to fulfill the desire for transitions, but we believe that the need is much broader than this. In particular, we envision a partnership that allows transition of ideas and experience in both directions. Academics will need to draw on the experience of applied researchers and engineers, in order to build on their experience rather than reinventing what is already known or following paths that have already been explored and discarded. Academics will also need these connections to help define contexts, scenarios, and data sets that in some sense span the types of problem areas that are to be investigated in this 6.1 program. And certainly we will need vehicles that promote and incentivize transition, recognizing that realizing such transitions will require expertise not typically found at universities.

Achieving these goals is not easy, but they can be accomplished with some thought and commitment using a variety of vehicles. In particular we point to the ATR area in which such a partnership between applications and demonstration programs and university basic research has begun to emerge through a combination of initiatives. Given the importance of command and control and the challenges that must be met for the future, we feel strongly that the potential payoffs in establishing an analogous set of initiatives and community of activities are substantial.

Some specific initial recommendations begin with working closely with ONR's Command and Control and Combat Systems program, including, perhaps, joint meetings. The principal benefits of such meetings, especially initially, will not be to alert the 6.2 and beyond world to hot new ideas coming out of basic research but rather to help basic researchers understand more deeply what command and control is (something that will be much more beneficial than listening to each other at the standard PI meetings) and to develop contacts that will grow over time. Other mechanisms include encouraging summer jobs for graduate students in industry and DoD labs, providing them with insights into real command and control problems that they can use as they define and execute their basic research projects. Vehicles such as STTR's and SBIR's also represent excellent mechanisms for encouraging partnerships that can produce some of the disciplinary infrastructure that is needed in such a challenging and important area. Finally, other, broader and larger initiatives, such as MURI's provide ways in which to create a critical mass of basic research activity that opens up the possibility of a much broader and richer engagement of the prob/stat community than the one with which we recommend starting here. All of these mechanisms and vehicles have been used in the ATR context and the fruits of that investment can now be seen not only in the substantial number of basic researchers who participate in ATR-related activities but also in the infrastructure and network of activity that has developed and, perhaps most importantly, in the students who have worked in this area and are now leading major development programs in government and industry. Thus, while we must start small, we strongly believe that there are compelling reasons to build toward something much more substantial.

II. FROM COMMAND AND CONTROL TO PROBABILITY AND STATISTICS

The discussions and investigations in which the working group engaged can roughly be described as beginning with an examination of what command and control is and in particular, what are the elements and problem areas that present the challenges that DoD faces for the future. Our objective was not to redo the thorough and detailed examinations that this area has had in the recent past, and, in particular, we refer to these strategic planning documents and program reports[1] for detailed descriptions of the areas we are about to list. Rather, our objective was to define a short list of command and control areas that satisfy two criteria: (a) they are of critical importance and represent stressing challenges for the future vision of command and control; and (b) they involve problems in which there is a clearly identifiable need for contributions from the probability and statistics community.

` The next stage of our discussions involved identifying some of the characteristics of the environment in which command and control must operate that make C2 problems hard and, more particularly, have significant implications for prob/stat research. Our objective in doing this was to begin to translate some of the challenges and characteristics of command and control into the language and domain of probability and statistics. We make no claims of completeness in what we present in this area, but we believe that the list we have compiled captures many of the most critical and stressing characteristics of the challenges in command and control to which probability and statistics can contribute.

This second stage then led to a far-ranging discussion of more specific problem areas in command and control as well as the narrowing of focus to a subset of command and control topics and problems which we believe provides an extremely rich starting point for the process of engaging the prob/stat community in what is both a very important and an intellectually stimulating area of investigation.

In the next two subsections we summarize the results of the first two stages of our deliberations, leading up to a discussion in Section III in which we outline some specific recommendations and some final thoughts.

1. What are the major topics in command and control to which probability and statistics can contribute?

The following is a very short list, containing six topics, each of which represents a very large component of command and control and each of which has a nontrivial requirement either for dealing with data or reasoning in the presence of uncertainty or both.

[1] A list of references is provided at the end of this report.

Situation and Informational Awareness and Understanding: For us this topic title includes what is commonly referred to as situation awareness in the C2 community as well as other aspects of the information infrastructure on which command relies. Thus the information here includes sensor databases--e.g., target tracks, intelligence reports, etc.--as well as databases with other sources of information--e.g., terrain, road networks, weather, shipping lanes and fishing vessel patterns, numbers of enemy vehicles of different types in an military zone, site models, etc. Maintaining a consistent picture of what is known (and what is uncertain) and digesting this into usable forms for different users and decision-makers at different levels in a command hierarchy is the nature of the challenge.

Planning: This topic includes planning at all levels in a C2 context--i.e., at different levels in granularity in time, space, and organizational hierarchy--in the presence of uncertainties and space, time, and sequencing constraints with the other components in a military engagement (e.g., reconnaissance information needs to be collected before a military engagement is begun), including dealing with deconfliction of concurrent activities (e.g. don’t shoot into or through areas in which other friendly activities are taking place). It also includes dynamic replanning in the face of plan disruptions and the planning of information gathering operations in order to enhance situation awareness.

Monitoring and Discovery: Within this topic we include several distinct functions. One is plan monitoring--i.e., the collection and use of information to determine if successive steps in a plan have been executed successfully or if replanning or plan repair are necessary. It also includes the detection of changes or anomalies potentially indicative of a new activity or threat. Finally, it includes the concept of discovery of unforeseen or unmodeled modes of behavior (e.g., unanticipated or unusual deployments of assets) or the isolation and extraction of mission-critical pieces of information from very large volumes of data.

Performance Assessment: The development of figures of merit and methods for their computation are important for a variety of reasons. For example, one important topic is the assessment of the relative contributions of different sources of information to the accuracy of a situation assessment function. Such a tool is of use for determining (a) how to structure informational queries in a distributed system (i.e., what information is needed in what circumstances); (b) how to schedule data collection activities in support of a particular military task; and (c) how to assess the impact of enhancements or augmentation of different information sources.

Interactions with Human Decision-makers: The purpose of the C2 system is to provide information and coordination tools that assist the human decision-maker. Developing methods that allow automatic functions and humans to complement each other, taking advantage of the strengths and compensating for the limitations of each is critical. In particular, while humans are remarkably good at recognizing situations that are not quite like situations they have seen before, they are also limited in terms of the cognitive load that they can handle. In contrast, computers are extremely good at handling large amounts of data and quickly executing functions that they have been programmed to perform but have limitations in terms of their ability to adapt quickly and to rapidly recognize situations that differ from ones that they have seen before.

C2 Structure: A major question, especially in the envisioned future of Network-Centric Warfare, is that of specifying C2 architecture. How is information distributed? Where is it processed and coordinated? What is the relationship of the distribution of information and the distribution of command authority across a C2 network? How do we keep this structure consistent and synchronized?

2. What are some of the important characteristics of the environment in which command and control must operate and of the functions that must be performed that make these problems challenging and require new formalisms and methods?

The following list represents a distillation of our discussions in this stage of our deliberations. The objective here was to bring out salient characteristics of C2 problems and environments that both need to be kept in mind in formulating research problems that are relevant to C2 and that also by themselves suggest many such directions for research. By no means do we believe that a good research problem needs to deal with **all** of these characteristics simultaneously. Indeed, while the development of operational systems does indeed require dealing with all of these issues, the constraints of delivering something that works on a tight time schedule does not generally allow for deep and fundamental reflection on any of these issues individually or in combination. In contrast the whole point of an investment in basic research in this area will be to allow such fundamental work to take place recognizing that its fruits may not impact the design being developed today but will provide the basis for the revolutionary advances needed tomorrow. With that as a preface, here are some of the characteristics that, with an eye toward the prob/stat community, appear to us to be critical and present interesting and important challenges:

a) The data and information available are voluminous and of many different types and character. For example the types of information available may include SAR or other types of imagery, intelligence reports of various types, databases with information on the types and numbers of different enemy units in the region of interest and the composition of these units (e.g., how many vehicles of what type make up a SAM battery), topographical maps, site models of areas of interest including road and building locations, information about deployment strategies of enemy assets (e.g., "the British wear red coats and walk in a straight line down the center of the road"). What is critical here is that the amount of information can be extremely large and extremely varied in character, ranging from measurements of individual vehicles to information on the tactical activities of entire units and the mapping of fixed assets over the region of interest.

This leads to at least three different challenges. The first is simply developing algorithms that are **scaleable**, i.e., that can deal with the vast amounts of data that may potentially be available. Taking one real example, a single Global Hawk system is capable of providing SAR imagery of an area of the size of Iraq every day. Yet another extreme is the Discoverer II program which aims to be able to collect 2 million square kilometers of imagery per day. These, of course, are on top of the steady stream of military communications, ELINT, TACINT, HUMINT data, NIMA maps, weather reports, data provided by other sensing systems such as JSTARS and localized tactical information gathering assets.

The second challenge is transforming all this information into a concise and clear **understanding** of the military situation. Ultimately this requires presenting those in command with very compact and clear representations of the information that is of interest to them. Thus from the perspective of such a person, most of the details of the military situation are simply nuisance parameters that should not clutter the representation that the decision-maker needs for his or her purpose.

The third, closely related challenge is that of sifting through the haystack to find the needle: which **bits of information in the vast volume are important?** Incidents and anecdotes abound both in military and nonmilitary contexts (e.g., blackouts in interconnected power systems) in which the volume of information available made it impossible to identify if there were any particular bits of information that would significantly alter operational decisions or to determine which bits were the most critical for decision-making.

b) The spaces over which inference is to be performed--i.e., the reasoning and decision spaces--are extremely large and complex. The number of variables of interest ranges from the detailed tracks of individual vehicles to the coordinated activity-level descriptions of military units. They also include reasoning about space and time: determining the spatial deployment of enemy assets and their relationship to terrain and topographical features and other spatially-distributed features such as road networks and fixed sites (all of which are also being estimated, mapped, and updated). For example, ships engaged in mine-laying activities may follow trajectories with particular characteristics, while mobile launchers or other targets of interest may hide near tree lines, and ground forces may deploy in particular patterns to defend given areas or to prepare for an attack. For different purposes, many of the degrees of freedom in such an inference space may be nuisances. For example, estimating the precise geometric pose of an object may not be critical to a commander interested in knowing if his forces are threatened, but estimating that pose may be critical in order to do a good job of classifying the object. Similarly, knowing the detailed kinematic trajectory of individual objects may not be important to a commander, but knowing about overall enemy movement will be. Whatever the situation, the bottom line is that the variables of interest or that affect our sources of information are **high-dimensional and involve very different granularities of behavior across time, space, and military interpretation.**

c) The phenomena, activities, and environment that make up a tactical or strategic engagement are distributed, concurrent, hierarchical, and interacting. A very basic example of this is the interaction of terrain and roads with the movements of objects: different types of objects may have different constraints on the types of terrain on which they can navigate--some may need to stay on roads, others may have terrain slope constraints, most cannot cross bodies of water other than over bridges. Another example is that of a mobile launcher that may need to go to a storage site in order to reload and then may head to an area in which it can hide until used again. Similarly, different components of a force can be engaged in concurrent activities aimed at a coordinated goal: mine clearing activities may be going on at the same time that attack forces are being readied and surveillance assets are being deployed to obtain up-to-date information on strike areas. Such military activities also have a natural hierarchical structure: from a commander's point of view, all of this activity may be a natural consequence of a single decision which then acts as a set of goals for the concurrent activities of minesweeping, surveillance, and attack preparation.

d) One of the most critical factors is TIME. This involves both the inclusion of time and dynamics in models, and the need for time-critical information and decisions**.** In particular, a major objective of any C2 system is to allow rapid response allowing decisions to be made faster than the enemy can--i.e., to stay within the enemy's decision cycle time. A second related challenge is shaped by the move toward more economy in military resources: in the future there will be greater reliance on rapid reaction and deployment of a limited set of assets, thereby leveraging the utility of each such asset. One critical aspect of this emphasis on time is that a fast but not statistically optimal decision may be far better than a statistically optimal one that takes too long to produce or that requires gathering information that takes too long to retrieve or collect. In addition, planning and the execution of an operation involve an entire range of time scales, from mission planning to detailed execution of elements of a plan that require the reaction of the shooter on the ground. Thus, what one means by "too long" depends very much on the context and its associated tempo.

e) The command and control system is intrinsically distributed. In particular, both the information and the command actions are distributed in space and time. This leads to major issues of consistency of information across the C2 system, synchronization of activities, coordination and deconfliction of distributed actions, ensuring that the right information is in the right place when it is needed, etc. Furthermore, all of these concerns are made more challenging by the likely limitations on communication bandwidth with which coordination can be accomplished.

f) The "pedigree" and accuracy of information is of great importance. While these may seem like obvious statements to prob/stat people, this is a major issue for a variety of reasons. First, there are differing levels of reliability of different sources of information. For example, a target track from a national asset may not only be of higher quality and reliability (i.e., many fewer false tracks), but the resulting track may be far more "pure" (where track purity refers to the percentage of measurements used to form a track that did in fact come from the same real target). For some of these information sources, all one has is experience that says that some sources are "trusted" more than others and should be used instead of others when available; that is, we may not be given any statistical characterization of the quality of the information they provide. Pedigree may also allow what is often referred to as "drill-down" in databases--e.g., a track with a pedigree associated with it may point to an associated SAR image, which could then be accessed in order to classify the object or to fuse it with new SAR imagery or other related information. A more subtle potential use of pedigree arises when one considers the distributed nature of command and control in which several C2 nodes may be fusing sources of information including querying each other. In this case, a vicious cycle of reincorporating one's own information after it has been incorporated into another node's database can lead to obvious statistical inconsistencies unless the interdependencies of these information sources are taken into account.

g) In a military situation, there are many users of information and many decision-makers with very different "apertures" into the battlespace and very different objectives. The overall command authority for an engagement will generally want to have a coarse but all-encompassing view of the engagement and will make decisions at that level of granularity. Thus, for example, the details of terrain in part of the area of engagement is at far too fine a level to be of interest, as is the exact location of each and every enemy vehicle. On the other hand, a decision-maker down in the battlespace may not care at all at the moment about the big picture of the overall battle but is in great need of very fine level information about terrain and enemy positions in his or her immediate vicinity. Furthermore, the objectives that these decision-makers are trying to achieve or optimize are generally very different: success of the engagement versus survival and achievement of a goal such as securing an airfield. Thus, different pieces of information may be of value or irrelevant depending on the decision-maker's aperture and objectives.

h) Disruption and opportunity are the rules rather than the exception. First, to use a quote presented at the May 1998 ONR Command and Control 6.2 Review at the SPAWAR System Center, "No plan survives contact with the enemy.[2]" Thus the execution of any plan requires continual monitoring of its execution, verification of the completion of elements of the plan, and the detection of disruptions and failed elements of the plan that require replanning or plan repair. In addition, surprise is always an element of warfare, and thus there is the need for continual monitoring for the presence of anomalies, changes, unexpected behavior, or opportunities that present themselves and thus may preempt previously planned sequences of activities. Furthermore, it is almost a certainty that in any military engagement, one of the things that will be disrupted is the command and control system itself. Indeed, the initial Coalition efforts in Desert Storm were aimed precisely at disabling essential elements of the Iraqi command and control structure.

i) Warfare is not described by the laws of physics. A major issue in developing inference and decision algorithms for command and control is that we do not have the luxury of beginning with irrefutable laws of behavior that provide constraints on spatio-temporal behavior. On the other hand, behavior of interest in command and control is not completely erratic: indeed, there is a "situation" that can be assessed and planned against.

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[2] Field Marshal Moltke

Thus there are coherent patterns of behavior which need to be estimated, but we don't have laws of physics that gives us these. Therefore, the development of models of behavior and the discovery of new modes of behavior are of critical importance.

III. PROBABILITY AND STATISTICS RESEARCH FOR COMMAND AND CONTROL

We have organized this section by attempting to provide responses to several questions:

• Why are probability and statistics relevant to command and control?

• What evidence is there to suggest that investment in basic research in probability and statistics can be successful and yield the types of contributions that command and control needs?

• What are the particular aspects of command and control on which an initial investment should be focused?

• What are some of the problems in probability and statistics associated with these aspects of command and control?

Our answers to these, taken two at a time, are provided in the following two subsections.

3.1 Why probability and statistics?

As we stated at the start of this report, the basic answer to the question of the relevance of probability and statistics to command and control is simple: probability and statistics provides a unified, coherent, remarkably flexible, and rich framework for the formulation, study, and solution of problems involving reasoning under uncertainty and analyzing uncertain, indirect, or incomplete data or information. Since every aspect and function of command and control involves problems with these characteristics, the relevance of probability and statistics is clear.

Certainly one of the strengths of the framework of probability and statistics is that it provides a consistent way in which to formulate carefully problems of interest and to examine them deeply and with precision. Given modeling assumptions, including models of what we know and how well we know it, prob/stat provides a rational framework that allows us not only, on occasion, to seek "optimal" solutions but also to characterize performance limits, to assess robustness to model assumptions, and, perhaps most importantly, to provide a guide to design in cases in which full statistical solutions are not feasible for one of a variety of reasons (problem size, the need for time-critical answers, the unavailability of complete models, etc.). In particular, probability and statistics provides a way to not only come up with solutions and algorithms, but also to deepen our understanding of a complex problem in order both to exploit its structure and to uncover its most critical features.

The successes of the prob/stat framework can be found in many settings, and, in particular, the contributions of probability and statistics to DoD programs and missions are myriad and clearly demonstrate that there has been a successful and extremely fruitful partnership between DoD (and in particular the Navy) and basic researchers stretching back for many years and continuing up to the present. In particular, statistical research for the Navy started with the Statistical Research Group, an all-services group of statisticians working full-time from 1942-1945. This group assembled the most prominent U.S. statisticians of the day, and many of the most famous statisticians of the century. The group solved many Navy problems, and the solutions were used almost immediately in operations. Some of these problems were: determining lead angles for torpedo attacks on warships; assessing the vulnerability of merchant vessels; and developing procedures for the acceptance testing of Naval ordnance.

These early contributions have been followed by a continuing engagement of the prob/stat community in problems of importance to DoD generally and to the Navy. For example, the celebrated Kalman filter, developed in the early 1960's has had and continues to have a profound influence on a vast array of military systems. Similarly, probabilistic reasoning plays a considerable role in the recent flurry of R&D in automatic target recognition and minefield detection--for example, likelihood calculations are a key component of DARPA's current ATR program MSTAR, and statistical inference about spatially distributed phenomena (terrain, roads, rivers, forests, etc.) is at the core of DARPA's recently initiated Dynamic Database (DDB) program. Also, thanks in large part to initiatives by ONR's statistics program, probability and statistics methods have been and are being developed for the solution of very large data assimilation and remote sensing problems that are finding application not only in ocean mapping and mine countermeasures problems of direct interest to the Navy but also in a substantial range of other problems ranging from whaling to environmental monitoring.

Thus, not only is probability and statistics clearly relevant to command and control, but the ability of this discipline to contribute to complex problems of national importance has been clearly demonstrated for decades and continues to be evident today. Indeed, the probability and statistics community requires and thrives on close contact with "clients" such as the Navy both to suggest problem areas of great concern and to provide the data and contexts on which to base investigations and test ideas and methods. Consequently, we are confident that an initiative to engage the prob/stat community in command and control will be met with enthusiasm and a sincere effort by that community and with a return on investment that is consistent with the outstanding track record that this partnership has produced in the past and continues to produce today.

3.2 Where do we start?

In Section 2.1 we listed six distinct topic areas within the domain of command and control. Each of these presents important problems involving reasoning under uncertainty, analyzing the effects of uncertainty, assimilating uncertain and incomplete information, etc., and consequently all six of these represent potentially fertile areas for contributions by the prob/stat community. However, at the start, we believe it is important to focus on a narrower subset of topics, especially since some of these six areas are intrinsically interdisciplinary and thus may be better served by a collaborative effort once a core prob/stat thrust in C2 has been established. In particular, we suggest that the initial investment of prob/stat program resources be focused in the areas of:

- **Situation and Informational Awareness and Understanding**
- **Monitoring and Discovery**
- **Performance Assessment**

In addition, as we discuss in what follows, there are some aspects of planning that are both closely related to these three areas and that also have strong connections to probability and statistics, and these may also be appropriate for inclusion as part of the agenda for this initial investment.

In the next subsection, we discuss some aspects of the probability and statistics challenges related to these three areas and to the characteristics listed in Section 2.2. In subsequent subsections, we then include some brief comments about the other three areas (Planning, Interactions with Human Decision-makers, and C2 Structure) and the roles that probability and statistics might play in these as well.

3.2.1 What are some of the prob/stat challenges?

To repeat a disclaimer, we present the following list of ideas and topics as representative of the types of questions and issues of importance and as our attempt to begin the process of engaging the prob/stat community in thinking about these important problems. While it is certainly the case that we believe that the specific topics mentioned here are important and definitely worthy of serious investigation, we make no claims that this list is exhaustive.

a) Development and study of probabilistic frameworks for situation understanding. This is a very large topic dealing with developing and studying ways in which to represent the interactions among the variables of interest in a situation awareness problem and for performing inference and estimation on these representations. Situation awareness involves reasoning over space, time, and military situation/hierarchy using data that may also come in at multiple granularities, ranging from MTI radar tracks on individual objects to models for the coordinated activity of sets of vehicles. Also, as DARPA's DDB program makes clear, maintaining geographic databases, including measures of uncertainty in their contents, is an important component of situation awareness, as the activities of objects of interest are constrained and affected by and interact with the environment in which they must operate. The geometric information that populates such databases may come from maps (e.g. of terrain) and from real-time imagery from which one may wish to extract higher-level objects that are important for estimating the situational environment: forests, tree-lines, road networks, buildings, rivers, weather systems, the Gulf Stream, etc.

The critical issue here is the development of ways of combining information from different and very diverse sources. This was identified as one of the major challenges facing statistics in the 1992 National Research Council Report, "Combining Information", and has been the subject of statistical research since. Hot current statistical research topics relevant to this include hierarchical models, graphical models, spatial statistical models, and ways of making inference about such models using Markov Chain Monte Carlo (MCMC), bootstrapping, Sampling Importance Resampling (SIR) and other sampling methods. Also relevant is the active area of inference about quantities linked by complex deterministic models.

So far the statistical community has focused on relatively simple models within these model classes, and it is clear that situation understanding presents problems that go substantially beyond what has been done so far. The basic statistical philosophy of building a probability model and basing inference about questions of interest on the likelihood function given the information at hand seems likely to be successful as a basis for an overall framework. However, a whole range of new and radically innovative ideas seem needed to obtain solutions in practice. For example, existing hierarchical models tend to assume that the information sources are "exchangeable" (i.e. roughly similar), and would need radical generalization to be able to synthesize information from sensors, maps, images and reports in text or voice form.

For any class of models considered, there are many questions that need to be examined. For example: What are the algorithms for parameter and state estimation for these model classes? How do these algorithms scale with problem/model size and complexity? How can one best select the most appropriate models in the class? How can one account for the uncertainties associated with this choice? For which parts of the situation awareness problem is this class of models useful?

b) Developing scaleable algorithms for situation awareness. While we refer to this under (a), we also wanted to list it as a separate topic. In particular, the complexity of military situations is such that the hypothesis/reasoning spaces of interest are enormous. Thus, not only do we need to seek representations as in (a) with structure that can be exploited but we will no doubt also need to develop approximate algorithms that overcome the inevitable computational problems caused by problem size. For example:

- Optimal inference algorithms for graphical models can have complexity that grows quickly with problem size if the graph structure has many loops. Are there suboptimal algorithms that scale better and that lead to near-optimal performance at least in some cases--and can we characterize those cases? Are there simpler graphical structures that are equally accurate in representing a given situation but that yield simpler algorithmic structures.

- Parts of situation awareness problems deal with discrete-valued variables (Is it target type A or B? Are these three objects engaged in coordinated activity or not?). Because of combinatorial explosion, complete investigation of such discrete hypothesis spaces is out of the question, and thus there is a need for methods for what might be called "hypothesis navigation and management". Can we develop efficient ways in which to eliminate large parts of the hypothesis space with modest computational load and minimal loss in performance? Can we find effective ways of zooming into this hypothesis space?

- A variety of rich representations of geometric quantities have been introduced- e.g., polygonal representations of regions, principal curve and stochastic snake models for boundaries between regions, etc. How can we develop scaleable methods for keeping track of uncertainty in such representations and fusing additional sources of information?

- Any statistical inference algorithm involves the evaluation of quantities such as likelihood functions, expectations, and probabilities. For the models of interest in situation awareness, the evaluation of such quantities can be extremely complex, and thus there may be considerable value in considering methods for efficient *estimation*, rather than approximation, of these quantities instead. That is, can Monte Carlo sampling methods and other simulation-based methods for estimating statistical quantities of interest be of value as components of scaleable inference algorithms?

c) Building models for situation awareness. There are a variety of issues related to the basic question: How do we build probabilistic models (of any of the types that might arise through consideration of topic (a)) for situation awareness? Certainly one aspect of this is developing algorithms for parameter estimation for such models and the associated and very important problem of studying the identifiability of model parameters: if some parameters cannot be well-estimated from the types of information that are available, then the model may either be inappropriate for situation awareness, poorly parameterized, or simply more complex than is necessary given the types of data on which inference is to be based. A closely related topic is that of developing statistical methods for model validation and selection.

A second, very important and very challenging question is: When is a model "good enough?" The point is that these probabilistic models are being developed for specific purposes, namely to provide reliable assessments of situations for different decision-makers. Thus, what is really important is the mapping from available information to situation assessment, which is defined implicitly through the use of a probabilistic model. For example, a mission leader may not need a very detailed model of individual force component movements but only a much coarser picture of activities. For such a commander a coarser-scale, global situation model may be all that is needed. Similarly, a commander in the field may need a very fine-grained model of local activity but an even coarser and partial description of everything else. Thus the real issue in asking the question of when is a model good enough is: when is the solution based on that model good enough?

Note that the previous paragraph suggests that producing situation assessments for different decision-makers may involve different models. Since a military engagement is a very fluid and dynamic phenomenon, it is unlikely that one will know ahead of time what types of information each decision-maker will need. This leads to the idea of "just-in-time modeling." In response to a decision-maker query, an appropriate situation model is constructed adaptively and then used as the basis for fusing all available information to provide an accurate estimate of the situation tailored to the needs of that decision-maker. Is it possible to construct situation model primitives that can be readily assembled in response to particular queries?

Another major issue concerns the information on which model construction is to be performed. Here we have in mind the issue of "off-line" model construction, i.e., the construction of a model that captures what we know about a military situation, tactics, etc., before any engagement takes place. Clearly some prior data and results of war games and exercises may provide useful information for such model construction, but there may very well be a need once again to use simulation and Monte Carlo based methods to augment real data in order to construct models with an adequate level of statistical confidence.

It goes without saying that there is no "correct" model for situation awareness, as there are many quantities and variables about which our knowledge or understanding is limited or missing completely. This, of course, provides considerable motivation for finding the simplest possible models that are "good enough", since true optimality may not even make sense. However, it also suggests the relevance of several other very important areas of statistical inquiry, namely robustness of models to unknown effects and adaptability of models to the emergence of unmodeled or incorrectly modeled effects.

Finally, while the structure of parts of a situation model may be clear and irrefutable (e.g., the kinematic equations of motion for vehicles), there are many other parts--e.g., how forces are deployed for different purposes, the particular patterns of communication and activities associated with different actions, etc.--that are not defined by the laws of physics. In some cases there may be doctrinal or tactical knowledge that provides some model structure, but in many envisioned military scenarios such knowledge may not be available or if it is, there is always the considerable chance that an enemy force may elect to violate its doctrine or change its mode of operation. For these reasons, there are clear needs for the ability to perform model discovery, that is, the extraction of coherent patterns of behavior from complex and heterogeneous sets of information. How can this be done? For example, are there new data mining concepts or emerging methods of nonparametric statistics that can enable such model discovery?

d) Dealing with decentralized situation awareness systems. Another interesting and challenging research area is the development of decentralized inference algorithms for situation awareness. How do we deal with the facts that different and possibly overlapping sets of information are available at different nodes in a C2 network and that these information sets are constantly being updated, fused, and queried from other parts of the network? In addition, different parts of the network may be using the information to estimate different situation models (e.g., focusing on different areas of activity). How do we maintain either exact or at least adequate levels of statistical consistency across the entire network?

e) Change and anomaly detection. There are two related but distinct and very strong motivations for the development of algorithms for the detection of change points and outliers from the current estimate and model of a military situation. The first of these is for the purposes of focusing attention. In particular, in preparation for a military engagement and as that engagement evolves, a very complex estimate of the situation is constructed and maintained. Because of this complexity, there is a critical need to be able to quickly zero in on pieces of information and aspects of the scenario of importance. For example, in preparing for an engagement, geographical models will be assembled, describing terrain, roads, objects, etc. Such maps then provide the basis for detecting statistically significant changes (e.g., the appearance of a fence, the massing of large numbers of objects in particular areas) in a spatial scene. In addition, the detection of mission-critical pieces of information from the volumes of collected data is a critical problem. The second motivation is for the detection of success, failure, and surprise. In particular, a military plan is characterized by a sequence of events that need to take place or be executed, and a critical function is the monitoring and detection of the successful or unsuccessful completion of these events. Similarly, there is a need to detect enemy behavior that represents a statistically significant deviation from the situation estimate and the assumed model of enemy behavior (for example, while they did wear red coats, the British did **not** all walk down the center of the road in a straight line). Such detection would then trigger the process of uncovering the new mode of enemy operation. Closely related to this is the detection of enemy deception--e.g., a mine-laying ship that attempts to mask its activity by appearing to behave like a fishing trawler.

f) Sequential decision-making for situation awareness. There are several aspects of situation awareness functions that involve decision-making and thus that touch on some issues that are also of importance in planning activities (see the next section). In particular, as we indicated previously, time represents a very dear and critical commodity in command and control, and thus there is a need to assemble a situation assessment that is accurate enough as quickly as possible. This leads to at least two different classes of sequential decision problems. The first class involves the sequential collection of information in order to form a situation estimate. This can involve both the tasking of sensing assets to gather particular information (often referred to as sensor resource management) and the querying of remote databases to collect the relevant information already available somewhere in the C2 network (sometimes referred to as “pull” fusion, as there is a proactive step taken to ask for information rather than a reactive mode of simply fusing what is made available). For either of these, there are costs and constraints. Time is, of course, the biggest of these, but there are others, such as the dynamic constraints of steering a sensing asset so that it can collect the desired information (where this might involve mechanical slewing of an antenna or the modification of the flight path of an airborne platform), the constraints of avoiding flying assets through areas in which they may be threatened by hostile fire, communications constraints on the rate at which information can be transmitted across the C2 network, and the computational requirements in accessing and processing each information source. Thus, while this is, broadly speaking, what is known as an experimental design or measurement sampling problem in statistics, it has very special characteristics in the C2 context, namely, the constraints are unlike the usual ones faced in science and engineering.

The second class of decision problems actually involves the choices of algorithms that might be used to perform the situation assessment once all of the required information is made available. In particular, different algorithms may have very different computation-versus-accuracy tradeoffs, and, depending on a variety of characteristics of the scenario (e.g., the speed with which an assessment is needed, the size of the assessment problem the difficulty of the problem, etc.), different algorithm choices may be preferable. For example, there are a variety of algorithms that currently exist for what is known as multisensor correlation--i.e., the correlation of sets of target measurements from several different sensors in order to produce a single fused list of target estimates. If there are more than two such lists to be correlated, the resulting problem is NP-complete. However, there exist a variety of suboptimal correlation algorithms--from very greedy and fast algorithms to more complex methods for pruning correlation hypotheses--that present very different tradeoffs between performance and computational load (for example, greedy algorithms work very well when targets are sufficiently well-spaced that there is not very much contention among alternate ways of associating measurements from one list with measurements from others; however, such algorithms are decidedly inferior to more sophisticated methods in higher target densities). That this is an important problem can be inferred from the investment that has been made by DARPA (in the DMIF program) and that will soon be made by AFRL (the Adaptive Fusion Program).

g) Methods for assessing performance. As a first comment, it is important to note that either of the classes of decision problems just described in (f) **requires methods for assessing performance**. For example, in deciding between different data collection alternatives, we need to be able to quantify the value of the information to be collected under each alternative. Similarly, in order to decide among several different algorithms for assimilating data into a situation estimate, we need to use quantifiable measures of the performance of each algorithm. However even beyond these reasons, there are other compelling reasons to seek tools for performance assessment. In particular, a basic question is: how well can we possibly do in situation assessment given a particular set of sources of information? If that level of performance is not good enough, then the issue is not one of building a better algorithm or designing a better C2 network and database structure. Rather, what is needed is better or more information. Moreover, performance assessment tools can, in principle, allow "what if" analyses to assess the potential impact on performance of different enhancements to the information sources or the C2 structure.

3.2.2 Planning

As we indicated previously, there are some areas of overlap between the types of problems arising in situation awareness and those arising in planning. One of these is in the area of sequential decision-making. As we described in the preceding subsection, sensor resource management and pull-fusion, which are both important functions in situation awareness, are fundamentally sequential decision problems. Sequential decision theory is also of obvious importance in the actual execution of a military plan, as feedback from the observed situation is used in order to make decisions and execute a plan.

An important aspect of such sequential decision problems is decision-making under uncertainty, and it is here that we see an even deeper interrelationship between planning/operations and situation assessment. In particular, it is well known in statistical decision theory that providing a best estimate of a situation is not a sufficient statistic for optimal decision-making. Indeed, knowledge of the uncertainty in that situation is critical. Moreover, the question of what is a sufficient statistic depends in a very deep way on the criterion being optimized. For a large class of criteria, that sufficient statistic is the full conditional probability distribution for the current state of the military situation. Obviously this is far too unwieldy an object to maintain, so the question then becomes what is the right set of information to keep, and that very much depends on the nature of the criterion. For example, if there is some circumstance that would lead to catastrophic performance, then maintaining an estimate of the probability of that circumstance, no matter how unlikely, might be critical. Moreover, there is also a large class of criteria--those that are often referred to as risk-sensitive criteria--in which the sufficient statistic for optimal decision-making is **not** the conditional distribution but in fact a very different object. Consequently, if risk-averse behavior is desired, the implications for situation awareness may be that very different sets of information need to be maintained.

Another area of overlap between situation awareness and planning is the topic of planning for sensing. While this may sound as if it were the same as sensor resource management, we mean here to distinguish between the feedback control-like function of sensor resource management (e.g., changing modes on a radar, slewing its antenna) and the longer time-scale, more open-loop function of planning data collection activities. Such problems involve very similar large-scale optimization and dynamic programming problems as one finds in other aspects of planning for military operations.

As a final note, it is worth pointing out that even in areas in which situation awareness and planning may seem comparatively distinct, there still remain strong intellectual ties and similarities between the issues of importance in each. For example, dealing with decentralization is a critical problem in planning as it is in situation awareness (and there is an important point of contact between these, namely that the right information needs to be available at the right place for each part of the planning network). In addition, planning problems suffer from the same explosion of dimensionality that one finds in situation awareness, requiring the use of a variety of simplifications and approximations. When is a simplified model good enough given the intrinsic uncertainties in our knowledge of the details of a military engagement? In addition, simulation can play an important role in developing solutions that are “good enough”--e.g., through so-called methods of neuro-dynamic programming.

3.2.3 Interactions with Human Decision-makers

There are a number of very interesting problems involving direct interactions with humans which we believe deserve mentioning, both because they represent potentially fascinating areas of research and also because being aware of these may be important in work that is undertaken in the other areas. In particular we can point to three distinct areas:

• **Humans as parts of algorithms**. While the idea that a human will in general task or instantiate an algorithm to perform a particular task (e.g., "tell me how many tanks there are in a particular region and the directions in which they are heading"), it may also make sense to have the algorithm task a human when it needs help. In particular, humans are remarkably good at quickly zooming in on areas of interest and discarding irrelevant information, while algorithms often suffer with the apparent combinatorial explosion of a large number of possibilities that a human would discard instantly. The problem, of course, is that the human is easily overloaded, and thus must be viewed by an algorithm as a very dear resource only to be used when really needed to help an algorithm focus attention on the parts of its reasoning space of real significance. This involves teaching algorithms "humility" ("Beats me--let's ask a human") and a resource allocation problem in using a very dear resource.

• **Visualization**. This is perhaps the most obvious topic. How do we present information to a human decision-maker concerning a complex situation, including representing the uncertainty in the situation assessment weighted to reflect the "cost" of different aspects of the situation (commanders may not only want to see the most likely situation estimate and a measure of confidence in it but also may want to have information on the "scariest" or "craziest" situation interpretation). Visualization tools are also of value in using the human to help guide discovery of modes of coherent behavior present in very complex data.

• **Learning what the human wants**. As we indicated previously, each decision-maker will have a different aperture through which it views a military engagement and thus has objectives and needs that may be quite different from those of other decision-makers. Thus a common operational picture must be able to present different, compact views of itself tailored to individual commander needs. While it is certainly possible to anticipate many of these different needs and thus to structure a situation assessment, the associated databases and the related query languages to meet these needs, an alternative or at least a complement to such efforts would be to develop intelligent statistical agents, that is adaptive processes that are capable of learning what a particular individual really needs and interfacing with the situation database in order to provide that information. A model here might be the counterpart to an intelligent web browser, which learns a particular user's pattern of behavior and can then take high-level requests from the user and retrieve the information the user wants and no more. Moreover such an agent can also learn to detect events of interest to the user (e.g., updates to web sites or databases) and alert him or her to these changes. Without question, this is a very speculative topic but it also represents a very important issue in making any advanced C2 system do what it is supposed to do, namely satisfy the needs of the decision-makers that rely on it.

These three areas all have statistical aspects but also clearly involve many other aspects as well such as man-machine interactions, human factors, and computer science.

3.2.4 C2 Structure

This is a big and very challenging topic: how does one map the **functions** of a command and control system onto the structure of a command and control **network?** There are many issues connected with this, including ideas of resiliency to disruptions and functional stability. For example, post-mortem analyses of significant events such as blackouts in interconnected power systems often point to the fact that local control actions in an interconnected system can in fact propagate and lead to system oscillations and collapses. The nominal military command and control model of hierarchical decision-making does not have this same catastrophic error propagation character, but if this hierarchical structure is to be replaced by a more network-centric structure, strategies that avoid such dynamic instabilities need to be developed and understood.

A second, even more complex problem deals with the issue of robustness in the face of the destruction of part of the C2 network itself--a likely occurrence in any real military engagement. Biological neural systems are remarkably robust to destruction of parts of the system, as severe disruptions may cause degradation in the ability to perform certain functions but not catastrophic failure. Developing an understanding of how to characterize such functional stability and developing methods for determining either how to pinpoint weaknesses in a given structure or how to design good structures are important but very complicated topics. It is worth noting, however, that probabilistic methods have been developed and used to analyze some problems of this type for interconnected systems, such as computer networks and flexible manufacturing systems, and thus will likely be of importance in analyzing C2 structures.

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