Situation Awareness - a Commander’s View

Gavin A. Thoms
Situation Awareness Project
Centre for Sensor Signal and Information Processing
Melbourne, Australia.
gthoms@ee.mu.oz.au

Abstract – The essentiality of situation awareness and supporting sensor, communication, fusion and inferential systems to attainment of military objectives is demonstrated. Disjunction between previous approaches to sensor, communication and fusion system design and the needs of situation awareness is examined. The structure of situation assessment functions and semantic inconsistencies within the field of situation awareness are identified as impediments to systematic resolution of the disjuncture. A lexicon for situation awareness is defined and the context of command in terms of organizational, operational, informational and inferential needs is examined. Essentiality of mutual understanding among subordinate commanders of the commander’s image of the battle-space is confirmed, and the model-building processes that underpin creation and maintenance of the commander’s model are explained. Information and inferential capabilities that underpin model-building processes are examined. Synthesis of syllogistic and inferential processes is identified as a weakness of the image building process. Approaches to implementation of inferential management are identified and directions for future research are proposed.

Keywords: Adaptation, command, communication, control, fusion, inference, sensor, situation assessment, situation awareness.

1 Introduction

War is a continuation of policy by military means [1]. Military commanders are provided with objectives, policy guidance, resources and legal authority to ensure attainment of politico-military objectives [2], [3], [4]. Under conditions of international crisis or war, operational environments are characterised by uncertainty in most of their elements. Under these conditions, commanders must draw inferences from uncertain data, identify appropriate sequences of objectives and optimally assign resources to ensure their attainment. Across millennia, the profession of arms has developed qualitative procedures for managing conflict under uncertainty. One product of those procedures has been situation awareness.

During recent decades, sensors, and data fusion and communication systems have been employed to obtain information that supported inferential reduction of uncertainty in a battle-space. To a large extent, design of sensors and communication systems has been optimised for their singular roles. Subsequent employment of sensors has been tailored to characteristics of systems so designed. The composite of sensor, data fusion and communication systems has not in general been constructed to ensure technical optimisation of the whole. Even less has the totality of sensor, data fusion, communication and decision support systems been integrated in an adaptive manner that permits optimal reduction of uncertainty and appropriate resource assignment [5]. From a commander’s viewpoint, sensor, communication and decision support systems appear to have delivered a small fraction of their potential.

Commanders require near real-time reduction of critical uncertainties in their dynamic battle-spaces. Robust inferential analysis is needed to underpin that reduction. Resolution of critical uncertainties demands capabilities for optimal focusing of sensors and communication systems. Requirements for near real-time reduction of uncertainties imply extensive use of automated inferential support.

The aim of this paper is to outline commanders’ needs for situation awareness and the supporting informational, information fusion and inferential functions that are central to its attainment. The impact of situation awareness on functional requirements for real-time control of sensor selection, sensor focus and assignment of supporting communication systems is also identified.

2 Approach

The approach adopted outlines linguistic requirements, establishes a lexicon, and then identifies the complete context of command and relevant causation within that context. Command of air defence operations is the chosen illustrative vehicle. Situation awareness is outlined and is shown to be essential to attainment of objectives. Inferential and decision support processes essential to
attainment and maintenance of situation awareness by a commander are identified. A need for optimal resource allocation based on situation awareness is demonstrated. Together these requirements for situation awareness and optimal resource allocation indicate a need for optimal control of the sources of information.

Requirements for information and control are outlined for four contexts of command; they are the organisational, operational, informational and inferential contexts. Situation awareness, the long-established key to military success is identified as the focus of all four contexts of command. In particular, situation awareness is the metric for optimal control of information sources and communication networks. Functional requirements are identified for adaptive control of sensor, communication, inference and decision elements in all four contexts of command. These requirements are consistent and form a canonical set in that they are applicable to all environments and to levels of command.

Effective command depends largely on situation awareness which in turn should be based on robust inference. To date the situation awareness research community appears not to have achieved broad agreement on the bases of robust inference. Such an agreement is essential to sustained progress. Accordingly, the approach adopted herein commences with an identification of essential linguistic and lexical foundations.

2.1 Language and Lexicon

Robust inference requires a language that affords precise description of relevant entities in a battle-space. Precision requires that two conditions be satisfied [6], [7]:
- For each entity there is a name for the properties of that entity and for its relationships with other entities
- Different entities, their properties and intervening relationships have unique names; i.e., each of the foregoing is uniquely defined.

If the first condition in not satisfied, the language is incapable of describing all objects within a battle-space. Similarly, if the second condition is not satisfied, the language is ambiguous. For various historical reasons, natural languages exhibit ambiguity. During the past two centuries the discipline of mathematical logic has been developed to ensure greater inferential rigour. Accordingly, in a situation awareness context and wherever practicable, one should apply mathematical logic. Further, commanders’ requirements for near real-time reduction of uncertainty suggest that mathematical logic should be implemented automatically. The products of largely automated inference should be symbolically and linguistically interpreted in effective human-machine interfaces.

The practicability of automated inference depends on a language that uses a comprehensive set of unique definitions. Situation awareness literature is replete with definitions [8] but exhibits little standardisation. Most of the terminology has derived from perceptual or ‘bottom-up’ analyses [9]. Such approaches are valuable but provide a partial view of the system under consideration. A structural, functional or ‘top-down’ approach is also needed to ensure an accurate representation of the subject system’s goals and functionality.

Steady progress in situation awareness cannot be made until semantic inconsistencies are resolved. As a first step, one might establish definitions that satisfy the fundamental requirements of philosophy [10], mathematical logic [7] and of the field of study while retaining sufficient generality as to ensure that consequences of their use are widely applicable. A complete, non-redundant set of definitions has been identified. A justification of the definitional set follows.

Definitions may be stipulative, persuasive or analytical. Stipulative definitions limit, proscribe or constrain functions or characteristics. Persuasive definitions explain or relate to some aspects of functions and usually support a preconceived view. Stipulative and persuasive definitions have little utility in analysis. On the other hand, analytical definitions afford a ‘clear, informative, and general account of the way a word or phrase is actually used’ [10]. Purtill’s requirements lead to six guidelines for construction of effective analytical definitions.
- Clear (not obscure or metaphorical)
- Positive expression of requirement (not negative if it can be positive)
- Directed at the subject (not self-referential or circular)
- Uses a consistent and preferably dominant characteristic of the subject (not an accidental characteristic)
- Sufficiently broad in meaning that consequences of its use may be applicable in related fields
- Sufficiently well focused (narrow) in meaning that its intent within the current analysis is clear

These guidelines have been observed in the fundamental and analytical definitions used herein. Each definition has a close analogue in all fields of goal-directed behaviour.

Several fundamental definitions [11] underpin more complex analytical forms. For example, data are known facts or things used as a basis for inference. Similarly, information is something told or knowledge. Knowledge is a truth or justified belief. Awareness is possession of knowledge about a field of concern.

The analytical definitions essential to semantic clarity are of battle-space, entities, situation, situation awareness, situation assessment and battle-space condition:
• Battle-space: Battle-space is the totality of air space, surface and sub surface land and sea space, and near-earth and cislunar space relevant to a commander’s objectives.
• Entities: Entities include actors, their instruments and relevant geographic and physical conditions.
• Situation: Situation is the totality of entities and their relationships within a defined battle-space.
• Battle-space Condition: Battle-space condition is the state of entities, their relationships and rate of change of those relationships within a defined battle-space. That is, battle-space condition is the situation state and rate of change of situation state.
• Situation Awareness: Situation awareness is derivation of the intent of an antagonist from an observed battle-space condition.
• Situation Assessment: Situation assessment is the totality of processes that lead to situation awareness; i.e., to identification of the intent of an antagonist.

An antagonist’s intended action may impede achievement of a commander’s objectives. An assessment of battle-space condition, from which an antagonist’s intent may be inferred, is essential to satisfaction of the commander’s objectives.

2.2 Restatement of Objective

The purpose of this study may now be restated. Identification is required of information, communication, inferential and decision capabilities needed by a commander to establish a justified belief in an assessment of an antagonist’s intent. The impact of those needs on management of sensors and communication systems, and on the functionality of automated inferential support and of human-machine interfaces is also required. The scope and detail of these needs is determined by the context of command.

3 Context of Command

At every level, military command is embedded in a structured politico-military control system. The context of command consists of organisational, operational, informational and inferential components. Each is examined in turn.

3.1 Organizational Context of Command

Command is a legal authority assigned to an individual to permit his achievement of objectives [2], [4]. The method by which a commander achieves his objectives (i.e., his strategy) is constrained by the extent of assigned resources and by policy directives from higher authority. A commander’s strategy is, inter alia, an assignment of means to objectives. The assignment is based on the commander’s observation of the state of play within his area of operations (battle-space condition), and of the relationship between his command and the entire politico-military context. Each command is identified within a hierarchy of commands that terminates usually with the national executive.

Military command is also nested within political control systems that extend from national, through regional and allied to global political control. At the highest level, national governments may be locked in competition for control of a particular resource. In those cases where diplomacy fails to resolve the dispute, a crisis may evolve. Should diplomacy fail to resolve the crisis, national governments may choose to respond militarily. Military operations may include activities in all elements (land, sea and air).

Air defence forces are a subset of the capabilities that may be employed to resolve a crisis. Control of air defence forces requires an abstraction (model) of air defence functions that should identify the following [3]:
• The politico-economic context that gave rise to the crisis in hand
• The relationship of the air defence function to the structure of military operations that may be invoked to resolve of the crisis
• The functionality of principal components of the air defence system, including the decision function
• The relationship of the decision function to situation awareness
• A generic structure for situation awareness and its supporting situation assessment processes
• A method of optimizing each resource allocation

3.2 Operational Context of Command

At each level of command, the commander assimilates information in the form of objectives, policies, own force (resource) disposition, antagonist’s disposition and constraints, approves an appropriate strategy and monitors the performance of his forces in the large. Objectives are set by the superior commander and are defined in the context of the superior commander’s image or model of the conflict. This image should be shared in detail with the subordinate commander(s) to ensure appropriate interpretation and timely attainment of objectives [12]. Constraints on command decisions include political and military policy such as rules of engagement [14]. Situation assessment is performed by specialist staff supported by automated inferential systems. Situation assessment together with the commander’s prior knowledge ensures the commander’s situation awareness. All command decisions are made in the context of the superior commander’s objectives, political and military constraints and that commander’s situation awareness.
Command decisions are essentially an identification of courses of action. The commander’s assignment of means to ends ensures the practicability of those actions. Decisions are communicated to protagonist forces that subsequently engage those of the antagonist. Engagements are monitored by active and passive sensors and through real-time and post-mission reports that together produce qualitative and quantitative descriptions of outcomes.

The situation assessment process commences with intelligence preparation of the battle-space. This function is essentially inferential analysis of a priori knowledge. Next, real-time information from battle-space sensors is acquired. The second stage of inferential analysis then generates knowledge of relationships between entities within the battle-space (Battle-Space Relations). Battle-Space Relations comprise a snapshot (instantaneous model) of the contents of the battle-space.

A third stage of inferential analysis identifies the rate of change of relationships within the battle-space. The rate of change of relationships provides a dynamic view (model) of behaviour within the battle-space; i.e., it yields the Battle-Space Condition. The rate of change of relationships implies intent on behalf of the antagonist and, together with capability, indicates the extent to which the antagonist’s current actions and focus are likely to frustrate (threaten) attainment of the commander’s objectives. Battle-Space Condition is the commander’s model of operations within his area of responsibility and together with his objectives and concept of operations is the image that he should always be able to share with his subordinate commanders.

Required is an automated method of evaluating Battle-space condition that ensures prompt and accurate identification of threats. Satisfaction of this function implies a need to identify those elements, knowledge of which would minimise uncertainty within the battle-space [15], [16], and [17]. In turn, this identification process implies a need (a functional requirement) for real–time control of sensor, communications and inferential systems. Ultimately, effective and timely identification demands that sensors exhibit rapid adaptation of focus and variable duration of observation. In summary, the operational environment of command affords insight of the extent to which sensors, communications, inference engines and decision functions should comprise an integrated, real-time, adaptive control system that takes as its focus attainment of situation awareness via the situation assessment process.

### 3.3 Informational Context of Command

A commander’s information selection and decision-making processes are effected within the context of an abstraction of the real operational situation (the battle-space condition). This abstraction is a causal model which approximates reality but which contains the principal determinants of operational outcomes. There is always a very large volume of information potentially available to the commander. Accordingly, he must so prioritise his demands for and processing of that information that he ensures initially, that relevant elements of his model are an adequately faithful representation of reality for immediate decision–making. Subsequently, he may update other elements of his model in an appropriate priority. A sufficiently accurate model then forms the basis of his decision making and his subsequent control of forces, which in turn assists attainment of the objective.

Commanders identify information that relates to progress toward the objective. This criterion markedly narrows the field of relevant information. In practice, relevant information is either volunteered or demanded. Volunteered information consists of routine and exception reporting. Routine reports afford standard content at a suitable schedule. Supply of this type of data is usually delivered in ‘pipeline mode’ [12]. Exception reporting identifies data or incidents that are inconsistent with expectations of the commander’s model. Exception reports are the most critical form of information and must be communicated immediately to the commander.

Demanded reports serve to resolve uncertainties. Such reports may serve one of two functions. First, demanded information may serve to confirm the validity of the current model. Alternatively, it may establish a new structure for the commander’s model following disruption by an exception report. Processes that deliver demanded reports usually respond to urgent real-time demands and function in a mode analogous to a query function of an intelligent database. When fresh data is required, sensors must be identified and scheduled, and their observations communicated at appropriate priority via data fusion processes to the relevant inference engine. Scheduling of sensors includes specification of focus and duration or reliability of observation, which in turn imply further functional requirements for sensors. Identification and scheduling of sensors also implies a capability for timely reassignment of communication channels. Again, the functional requirements needed to support commanders’ information requirements indicate that sensor, communication, inferential and decision systems should comprise a single, adaptive control system. The metric of control should be the state of situation awareness (battle-space condition).

### 3.4 Inferential Context of Command

Commanders’ require real–time inferential processing of data and of derived knowledge. Complexity of the battle-space quickly overcomes the ability of the human
mind to assess interactions between numerous factors. For example, the maximum number of elements that the human mind can process at one time is reckoned to be eight. The dynamics of any military operation quickly overwhelms this capacity; accordingly, almost any computational support no matter how approximate would be of benefit.

Current computational technologies offer potentially adequate functionality in that their speed and data volume permit evaluation of derived knowledge and simulation of potential strategies at adequate levels of fidelity. The staff who perform inferential analyses in support of situation assessment and who evaluate alternative strategies for consideration by the commander require such automated tools. Given the products of those tools, a commander requires access to a meta system that would provide an explanation of various inferential products of situation assessment and components of simulated strategies. Inferential and meta systems should be closely matched to the commander’s model (image) building processes.

4 Commanders’ Model Building Processes

The purpose of information acquisition and processing is to reduce the apparent uncertainty of the commander’s operational environment. Reduction of that uncertainty is affected through the commander’s construction of an image (a model) of the battle-space, of the relevant entities that populate it and of the rates of change of relations within the battle-space (ie. the battle-space condition). Appropriate communication and information displays should ensure that the commander and his subordinates share a common image of the objectives and of the meaning of the current battle-space condition.

4.1 Commanders’ Core Model-building Processes

The commander’s model-building processes are more complex than implied by the higher–level outline so far employed. First, routine reports constructed and delivered in accordance with a standard operating procedure provide the basic environmental and engagement data. Exception reports identify events that are not consistent with the current model of the battle-space. Accordingly, exception reports are communicated simultaneously to inferential systems and to the commander. The latter is thereby afforded an immediate alarm of possible dysfunction within his model of the battle-space.

Routine reports together with exception reports comprise the totality of environmental and engagement data. Specialist analysts using inferential support (preferably automated) transform the environmental and engagement data into evaluated environmental and engagement data. Subsequently, products from co–flow processes (the battle-space model dysfunction and battle-space model clarification processes) are correlated with the evaluated environmental and engagement data to produce the next adaptation of the battle-space model.

4.2 Co-Flow Modelling Processes

Two separate sub-model building processes complement that of the core process. These processes are conducted in parallel with the core process and their products are co–flow models. They are the co-flow clarification model and the co-flow exception model.

Model clarification is a ‘demand-pull’ process that is driven by the commander in response to a need for amplification of some factor in the core model [12], [13]. Additional data may be required to clarify either the scope or characteristics of an entity or the relationship between entities in the core model. Data demanded for clarification may be extracted from intelligent databases operating in quasi real-time or from sensors, the foci of which are determined by the situation assessment (clarification) processes themselves. Clarification is an adaptation process that in most cases addresses lesser discrepancies between the commander’s model and reports from the battle-space.

On the other hand, reports of exceptions carry data that is at considerable and possibly (in the case of strategic surprise) complete variance to the current model. Exception reports are the most critical of all communications and are brought to the immediate attention of the commander. They are formulated in accordance with the commander’s guidance and in the context of the commander’s intentions and of the shared image that subordinate commanders and specialist staff hold in common with the commander. Potential exception reports are evaluated against the commander’s guidance (the sum of exception guidelines and commander’s intentions); those that survive qualify as exception reports. Specialist staff evaluate the exception reports against the current model to derive a battle-space model dysfunction. The validated dysfunction is communicated to the commander who may respond (or have already responded) with a request for clarification or face-to-face discussion with specialist staff. The outcome of exception generation and clarification processes is a real-time demand for information and an adaptation of the battle-space model that affords more accurate situation awareness and a better basis for decision-making.

Exception generation and clarification processes are demanding of specific information characterized by
highest practicable quality. These requirements imply an ability to schedule communication systems and sensors to focus on particular entities in the battle-space for durations appropriate to the desired data reliability. Within sensors themselves, capabilities are needed for beam shaping and scheduling in response to demands of situation awareness in the principal inferential system. These capabilities have not been evinced by earlier sensors or communication systems but are available in some modern phased array systems [18], [19], [20]. Effective adaptive control of sensor and communication networks operating in support of situation assessment functions is an essential prerequisite of effective control of a battle-space.

5 Management of Inferential Processes

The context (model of the operational universe) and mechanics of inferential and decision making processes bear heavily on a commander’s information requirement. Inference is a support function of management and command and has potential to consume considerable resources. Accordingly, inference should be subject to appropriate controls. A concept of control is appropriate in this context because a decision-maker brings to his task a rich background of information and a personal approach to synthesis of qualitative information and decision making based on that prior information. Little is known of the qualitative decision making processes and of the impact those processes have on acceptance of results of related quantitative inference. The vast body of research focuses on inference as a rigorous quantitative process that appears to operate in isolation from qualitative processes. Such is not the case. Human decision making uses an amalgam of qualitative and quantitative products. The purpose of this discussion is to identify key determinants of conviction and inference and their joint contribution to the belief that underpins decisions.

In greater measure, information received by military staffs and their commanders is evaluated qualitatively. To a lesser extent, particular decisions are supported by closely targeted quantitative analyses. When the rate of evolution of the battle-space exceeds the information processing capabilities of commanders and their staffs, decisions are made collectively or executively ‘on balance’ of evidence. These decisions are based on (abbreviated) qualitative analyses using largely qualitative data and experience (a priori knowledge). Conclusions are drawn using logical processes that are essentially syllogistic. That is, qualitative evidence \( E_{QUAL} \) and arguments based on Aristotelian (syllogistic) logic \( A_{SYLL} \) lead to conclusions \( C \).

\[
E_{QUAL} + A_{SYLL} \Rightarrow C
\]

On the other hand, more rigorous probabilistic assessments lead to quantitative results (inferences). In other words, quantitative evidence \( E_{QUAN} \) and probabilistic assessments \( A_{PROB} \) lead to inference \( I \).

\[
E_{QUAN} + A_{PROB} \Rightarrow I
\]

Under conditions where commanders have the benefit of quantitative and qualitative analyses, the products of both processes must be integrated and balanced against the backdrop of perceived conditions in the battle-space and of the commander’s experience (a priori information). The result of such a balanced integration of judgements is a degree of belief in the battle-space condition. That is, the commander’s belief \( (Be) \) is the sum of conclusions and inferences.

\[
C + I \Rightarrow Be
\]

This potentially simple model is subject to some complication. Massey [16] demonstrates that little evidence is needed to reinforce a conclusion but much evidence is needed to change it. Similarly, little evidence is needed to strengthen an inference but much evidence is needed to reverse the same. These effects would be manageable if both operated in similar ways and to similar extents but that is not the case. Syllogistically derived conclusions abound in a commander’s decision space. Quantitatively derived inferences are much harder to find. Further, a syllogistically derived conclusion (or several related conclusions) may override an inference if the conclusion supports an existing view and the inference does not. Under these conditions there is a greater propensity to reinforcement of belief by qualitative argument than to reversal of belief by quantitative inference.

One might prefer an intellectual discipline that automatically integrated conclusions and inferences in a balanced manner. Such a discipline appears distant. A more practicable shorter-term goal would be a decision aid that guides a commander through a process that ensures a more orderly integration of conclusions and inferences than is currently the case. A more robust state of belief might thereby be obtained.

5.1 Approaches to Inferential Management

In the shorter term, two approaches to inferential management appear practicable. The less ambitious approach would automatically integrate observation, inference, and recommendations for resource allocation (decision) as follows:

- automate observation and data fusion processes
• link data fusion processes directly to inferential processes
• perform quantitative (probabilistic) inferential processes automatically
• link inferential products directly to resource allocation analyses
• compute optimal resource allocation
• present the recommended resource allocation to the commander
• allow the commander to integrate his qualitatively derived conclusions with quantitatively derived recommendations
• commander accepts, rejects, or modifies the recommendations as he decides.

This approach is practicable but carries three main risks. The first is that the commander’s synthesis of qualitatively argued conclusions with quantitatively assessed inferences may be less than accurate. Second, countervailing evidence and inferences are not readily available. Third, the time required for the commander to effect his synthesis might be operationally unacceptable. In the latter case, decisions will be made within the required intervals (they must be); consequently, syntheses and decisions may be suboptimal.

In the medium term, a more rigorous solution may be practicable. A suitable approach to ensuring a balanced synthesis of conclusions and inferences might consist of the following:
• conversion of all qualitatively derived conclusions to quantitative form using a probabilistic metric
• probabilistic integration of conclusions and inferences.
• explicit recognition of the contribution of qualitative conclusions and quantitative inferences through an appropriate display
• display of the traceability and robustness of all supportive inferences and conclusions
• presentation of relevant countervailing inferences and conclusions
• display of the traceability and robustness of all countervailing inferences and conclusions

6 Conclusions

Maintenance of a robust state of situation awareness is essential to attainment of a commander’s objectives. Situation awareness must be underpinned by situation assessment processes that in turn depend on an adaptive system of sensor, communication, data fusion, database and inferential functions. Earlier approaches to attainment of situation awareness have been thwarted by two main problems. The first was an insufficiently systematic integration of situation assessment processes and technologies. The second was semantic inconsistency occasioned largely by linguistic and definitional deficiencies. The former challenge may be satisfied through integration of sensor, communication, data fusion, and situation awareness and decision support (resource allocation) elements of command systems in a single adaptive system that takes the state of situation awareness as its principal control metric. The second challenge (semantic inconsistency) may be overcome through implementation of the revised lexicon proposed herein and by use of automated mathematical logic. The products of the latter should be rigorously integrated with those of syllogistic processes that pervade all command systems.

Organizational, operational, informational and inferential needs determine requirements for sensor, communication, data fusion, database and inferential systems. The principal need is a real–time capability for adaptation of sensor focus, communication path and communication bandwidth. Again, sensor, communication, data fusion, and situation awareness and decision support (resource allocation) elements of command systems should be integrated as components of a single adaptive system, the principal control metric being the state of situation awareness.

Further research should emphasise integration of situation assessment functions with sensor, data fusion and communications system performance, and with management of inferential processes. The latter should include indicators of inferential robustness, and synthesis and display of syllogistic and inferential products. The structure, distribution and integration of intelligent databases within the total situation awareness system should be optimised with respect to real-time delivery of robust inference. Finally, effective human-machine interfaces should be identified to ensure timely, accurate interpretation of inferential products. A suitably comprehensive and robust state of situation awareness may then underpin attainment of objectives.

Acknowledgement

This work is supported by the Defence Science and Technology Organisation (DSTO), the Centre for Sensor Signal and Information Processing (CSSIP) and the University of Melbourne. The author thanks Neill Smith of RLM Systems Limited for many useful discussions.

References


