Title: Communications, C2-Entropy and Military Command:

Tracks:
Track 1 - C2 Concepts, Theory and Policy;
Track 4 – Cognitive and Social Issues;
Track 5 – Organizational Issues

Dr Alexander Kalloniatis
Command & Control Division,
Defence Science & Technology Organisation, Australia
Contact: Dr A. Kalloniatis
Department of Defence
DSTO, Fernhill,
Canberra
ACT 2600, Australia
Tel: + 61 2 625 66194
Email: alexander.kalloniatis@dsto.defence.gov.au

Abstract:
The concept of *C2-Entropy* is introduced, which seeks to build on heuristic principles such as
Parkinson's Law applied to signalling, as well as approaches such as Perrow's Normal
Accident Theory and Berniker's Organisational Cognitive Thermodynamics. This approach
offers a quantitative framework for determining how entropy is distributed between the nodes
and links of a C2 network. It both describes how the complexity of a C2-system, such as that
of a network-enabled force, can lead to system failures while also giving the framework for
understanding its capacity to deal with complex adversaries or environments. An intuitive
explanation of "entropy" is given, with an illustrative explanation of the underlying formalism
of non-equilibrium statistical mechanics given in terms of a simple model for John Boyd's
OODA loop. The full development of this program of research is ambitious; nevertheless
initial conclusions can be drawn about the role of C2 structure in the order/disorder properties
of a military force, and the role of Military Command styles, such as Mission Command.
Reference to historical military engagements will be made.

Classification: Unclassified.

Paper Outline:
Network-enablement of military forces in the 21st century is driven by the promise of vastly
improved Situational Awareness (SA) through the sharing of data from diverse agents,
utilising increasing bandwidth and computing power. On the other hand, heuristic principles
such as Parkinson's Law applied to signalling ("signalling expands to fill available
bandwidth") suggest that the future might not realise the hoped for level of SA. To
successfully realise a network enabled capability there is a need to weigh the costs and
benefits of network enablement within a dynamical description of C2 systems of high
complexity.

This paper proposes a concept the author denotes *C2-Entropy* to provide such a framework.
Colloquially, the term entropy is often understood to mean the state of disorder of a system.
This is too loose a definition because of the *spatial* notion it suggests. Rather, the entropy
concept utilises the idea of the set of all possible configurations available to a system -
including spatial, kinetic and *other internal* properties - and the ability of an observer to
discriminate between them. The degree of uncertainty in this discrimination represents the
system entropy. For the concept of C2-entropy it is recognised that amongst the degrees of

freedom in a Command & Control system are the agents who represent C2-nodes *and* the links between them. C2-links are not static but vary with time subject to changes in the properties of nodal entities. Communication links, for example, can be created on the fly, can go from being idle through to overloaded and destroyed. Therefore, network links contribute to system entropy. Such a description encodes the fact that the configuration of a system encompasses more than just its spatial organisation and therefore, for example, that a state of *high entropy* can also be a state of spatial *order*.

The C2-entropy concept extends Berniker's Organizational Cognitive Thermodynamics (Berniker, 1999) which itself builds on Perrow's Normal Accident Theory (Perrow, 1984). Both of these approaches give a context for understanding how the complexity of an organisational structure *of itself* leads to system failures, even in the absence of adversaries. Both also ground the temporal development of an organisation in its inherent complexity. Most measures of complexity draw on the mathematical definition of entropy as given by Boltzmann (1844-1906) and reinterpreted for information by Shannon (1948). However, many such approaches typically eschew the Thermodynamic significance of entropy, namely the notion of irreversibility in growth of this entropy with time. The exceptions to this are approaches based on the generalisation of Thermodynamics by Jaynes (1957) known as MaxEnt. This method enables statistical analysis via maximisation of the system entropy of general systems in equilibrium or steady-state. A system can be of any type with quantifiable elements and states, not merely conglomerations of subatomic particles. Because of the steady-state criterion, these approaches are still inapplicable to war-fighting C2-structures. Ironically, the last step required for this takes us back to Boltzmann in the form of his little-appreciated Non-Equilibrium Statistical Mechanics. This gives a mathematical framework for understanding how a system dynamically evolves toward an equilibrium configuration of maximum entropy from an initially prepared state through non-equilibrium dynamics. This approach has been advocated by Ingber (1993) for analysing tactical combat dynamics, though also identifying nodes (tanks, personnel carriers and missiles) as the only types of system entities and thereby overlooking the C2-links.

Put simply, C2-Entropy yields the insight that as a system evolves it undergoes a "walk" through the set of all system configurations available within environmental and structural constraints. Over time there is a degradation of the precision with which an observer can determine the state of the system. Where those uncertainties are greatest (in its nodes or in its links) is *determined by the environment and system-structure*. The emergent heuristic is that if a system entity has degrees of freedom available to it *they will be exercised and will with time overload and become uncontrollable.*

The paper will give a more complete explanation of these concepts with technical details left to an Appendix. Nevertheless it is worth here stating the key equation underlying the approach. A considerably simplified setting for illustrative purposes is given. Consider a single random variable function of time $\Theta_i(t)$ for agents at nodes i of a network. Let $P(\theta_i, t)$ be the probability that at time t the variable Θ_i takes values in the interval $[\theta_i, \theta + d\theta_i]$. The system is subject to both a "driving force" via a function $F(\theta_i)$ and noise. Altogether, the equation governing these dynamics takes the form of a Boltzmann-(Fokker-Planck) equation

$$\frac{\partial P(\theta_i, t)}{\partial t} = -\sum_j \frac{\partial}{\partial \theta_j}\Big(F(\theta_j)P(\theta_i, t)\Big) + \tfrac{1}{2}\sum_{j,k} Q_{jk} \frac{\partial^2}{\partial \theta_j \partial \theta_k} P(\theta_i, t).$$

For a "simple" C2-system, the various pieces in this equation can be translated as follows: θ_i represents the position of agent i in progressing through Boyd's (closed) OODA loop, $F(\theta_i)$ describes both how the agent's position in the OODA cycle influences its future progress through the cycle, and how the agent responds to the progress through their OODA loop of other *connected* agents. The last term quantified by the constants Q_{jk} specify the degree of randomness in the agent's cycling through the decision loop. The entropy is itself dependent

on the time-dependant probability $P(\theta_{i,},t)$. The equation describes then the growth of uncertainty in the state of system components in $P(\theta_{i,}t)$ subject to its structure, driving forces and the noise in its elementary components. Elegant methods of manipulating and thereby simulating such equations naturally allow one to introduce auxiliary variables ω_{ij} which describe the communication of OODA information between nodes i,j. The introduction and activation of such variables, namely the transition to a description in terms of a new probability distribution $P(\theta_i, \omega_{ij}, t)$, is a key mathematical innovation of the author's approach.

In application to military systems, C2-entropy leads to the following insights.

A military force in complex combat will tend to genuine spatial disorder in the absence of a viable C2 structure to compensate for its increasing entropy. A classical historical example of this is the routed army of the Roman co-emperor Maxentius at the Battle of the Milvian Bridge in 325 AD. Driven to retreat by the cavalry of Constantine the Great, Maxentius' army largely annihilated itself in the ensuing chaotic rush for the single narrow bridge, the Milvian, across the Tiber.

Conversely a military force can achieve spatial (re-)organisation only through extension into its C2-dimensions for moderate entropy growth. As anecdotal military experience suggests "a successful withdrawal is almost entirely about C2". An historical example of this is the withdrawal of ANZAC forces in WWI from Gallipoli. This scenario suggests that entropy is not always "bad": some entropy simply indicates *activation* of precisely the degrees of freedom required to enable the system, the military force, to respond to a threat.

As C2 entropy builds so too do the risks associated with centralised command thereby demanding a transition to mission command mode. Large entropy implies loss of precision in determination of the states of system agents. The magnitude of entropy is determined with reference to a particular observer who is able to subdivide the system or subsystem in a specific way and thereby aggregate and track the behaviour of agents within a fixed accuracy. Militarily, a senior commander may have broad situational awareness of the battle-space to some level of fidelity. The preparations encoded in the initial order of battle permit identification of own-forces with high precision. As battle ensues the SA provided by network connectivity will permit tracking of the system state only within the predetermined accuracy or to within a finite update time. This is the manifestation of entropy increase as observed by a central commander. The scope for informed *detailed* decision making thereby passes to subordinate commanders, namely Mission Command becomes the appropriate C2-mode. Anecdotal examples of this adaptive change of command style with time have been given in (Stewart, 2006). This requirement to change command style in the "fog and friction" of naval engagements was also intuitively appreciated in the "tactical action principles" (a type of Mission Command) of Sir George Tryon (1832-1893), as discussed in (Gordon, 2000). The response to this is that network connectivity and information sharing will precisely diminish entropy, supporting centralised command. This is where the inclusion of the entropy in C2-links is significant in systematising the diminishing return from increased sources of data, namely the reduced ability of a node to extract meaningful information. Data fusion is a mechanism for managing, not defeating, this entropy growth.

The alternative argument for network enablement is that information sharing will support Mission Command, in giving all subordinates the same global and local SA. C2-entropy suggests a hidden danger *in the network providing a channel for unintended entropy growth down to the subordinate command level, undermining the scope for Mission Command.*

The starkly simple alternative is reflected in the words of Gen. E.C. Meyer, (cited by (Fialka, 1981) with reference to the operation of the US' most sophisticated C2-system of the time, WWMCCS, during a mobilisation exercise in 1980) "We must discipline ourselves to only

get at the level of data needed to cause decisions to happen … Clearly we are passing too much data back and forth". C2-entropy pushes this requirement further in the related technical concept of "latency" in critical degrees of freedom: *layers of means and lines of communication should be kept in reserve until the heat of battle*. This must be literally hard-wired into a C2-system.

Beyond these initial insights (or confirmation of existing military heuristics), the formalism developed in the paper will enable future quantitative analysis of these respective and related phenomena.

The paper is envisaged to be structured as follows:
- Introduction
- Precursors to C2-entropy concept
- Defining entropy
- A simple application of Non-Equilibrium Statistical Mechanics: Boyd's OODA loop
- From nodes to links.
- Military applications:
  - C2-entropy and spatial order
  - C2-entropy and Mission Command
  - C2-entropy, NCW and the future of information management
- Future work
- Appendix: A survey of Relevant Methods in Non-Equilibrium Statistical Mechanics.

References:
E. Berniker, "The Thermodynamics of Organizing: Information and Noise in Terms of the Second Law", 43rd Meeting of The International Society for Systems Science, 1999.
C. Perrow, "Normal Accidents: Living with High Risk Technologies", New York: Basic Books, 1984.
C.E. Shannon, "A Mathematical Theory of Communication". Bell System Techn. J 27, 370-423, 623-656 (1948).
E.T. Jaynes, *Phys. Rev*. 106, 4, 620; 108, 171 (1957).
L. Ingber, "Statistical Mechanics of Combat and Extensions", in *Toward a Science of Command, Control & Communications*, ed. C. Jones, American Institute of Aeronautics and Astronautics Washington DC, pp. 117-149, 1993.
K.G. Stewart, "Mission Command in the Networked Era", 11th ICCRTS, 2006.
A. Gordon, "The Rules of the Game: Jutland and British Naval Command", London: John Murray, 1996, paperback 2000.
J. Fialka, "The Pentagon's Exercise `Proud Spirit': Little Cause for Pride," *Parameters* 11:1 p.40, 1981.