15TH ICCRTS

"THE EVOLUTION OF C2"

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PHASE SPACE SHIFTS IN COMMAND STRUCTURES IN NETWORKED SYSTEMS

TOPIC 2: NETWORKS AND NETWORKING

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Abstract

This paper presents the rationale behind an important enhancement to the NATO SAS-050 approach space, combined with empirical results which take advantage of these enhancements. In Part 1 a new theoretical legacy for the NATO model is presented. This legacy inspires a number of developments which allow live data to be plotted into it, and we demonstrate that the model is well able to discriminate between alternative C2 structures. Part 2 illustrates this feature with multinational data from the ELICIT community. It is surprising to see that teams in both C2 and Edge conditions operate in broadly the same area of the phase space cube. The structure of the pre-ordained ELICIT 'classic C2' hierarchy and the deterministic nature of the shared task are put forward as explanations for this, and as future enhancements to the ELICIT paradigm.

Introduction

Modelling Command and Control

Command and Control faces many challenges in the digital networked era, including the design of organisational structures and the communications technology to support them. Traditionally, command and control systems have evolved over centuries to produce highly efficient structures in what has been called the classic hierarchical model. With the advent of digital technology that holds the promise of better information sharing, better shared understanding, better decisions, better actions and better effects (the so-called Network Enabled Capability benefits chain) there is not the luxury of time to allow the system design to evolve over decades. Coupled with this, the classic hierarchical model which has evolved in non-digital systems might not be the best structure for the new digital systems, or more specifically, for the environments to which digital systems are a response. The purpose of this paper is to explore alternative command and control structures in ELICIT and to see if a way forward can be proposed. Part 1 of the paper describes the development of metrics for the three dimensions of the NATO SAS-050 approach space (2006). Part 2 describes how data were collected from the international community of ELICIT researchers and put into the NATO SAS-050 approach space. The results show that the organizations instantiated within ELICIT appear in an unexpected octant of the cube, which suggests that people in networked systems do not necessarily behave as the command and control theory would have us believe.

Review of C2 Modelling Approaches

A review of the modelling literature in command and control shows four dominant approaches: cybernetic, network, agent-based and socio-technical. The cybernetic modelling paradigm is concerned principally with the structural aspects of command and control, reducing it to functional entities linked through specific causal pathways according to a deterministic idiom. These models can be subject to various known inputs and the specification of the functional entities enables the resulting output to be completely described. Network models blur somewhat the strict formalism of the cybernetic perspective. The focus widens to emphasise not just the functional entities themselves but also the links that exist between them. The links can be defined according to various parameters, including communications between functional elements and logical relationships. When functional entities are linked in this manner a network is formed. The network rather than the functions can be summarised and analysed mathematically to reveal emergent properties. The emergent properties are not necessarily planned a priori thus the network approach provides an alternate perspective on, as well as a prediction of several command and control system attributes and outcomes. Agent modelling perspectives appear to represent a form of synthesis between cybernetics and network models. Whereas cybernetic models attempt to model the ‘aggregate behaviour’ of a group of entities, doing so with often complex mathematics, agent approaches focus on the emergent behaviour arising from the interaction of (mathematically and computationally) simplistic entities. That is, complex group behaviour need not be a function of complex individual behaviour. Agent modelling results in less formal and more organic behaviour from which complex emergent properties arise. Socio-technical models of command and control emphasise the human roles. Rather than the strict formalism of the previous approaches cognitive models tend to be a more general characterisation of agent behaviour (and psychology) in command and control systems. Socio-technical systems, being a mixture of people and artefacts, aim to specify the environmental factors that influence human cognition and which form model constraints. Effective decision making and behaviour can be assumed to be the key emergent property, in which the interest is couched within the key determinates of command and control scenarios that facilitate or indeed hinder this outcome. The approach taken within the current research was a combined network modelling and sociotechnical approach. In particular, social network metrics are used to understand the structure of command and control networks.

Part 1: NATO SAS-050 Phase Space Cube

The NATO SAS-050 approach space shown in Figure 1 *"is intended to serve as a point of departure for researchers, analysts, and experimenters engaging in C2-related research"* (NATO, 2006, p. 3). In their consideration of command and control, Alberts and Hayes (2006) consider the SAS-050 'cube' to represent a space of possible command and control structures. This assumes three broad Independent Variables:

1. Distribution of information – this could be sent from one person to another, or could be broadcast to all members of a network;
2. Patterns of interaction – this could take the form of a top-down, hierarchical command structure or could take a more open, or 'distributed' form of management;
3. Allocation of decision rights – this could have Intent originating from a single source, for example, a Commander, or arising from some form of 'democratic' decision making.

Figure 1 shows how these three Independent Variables can be mapped onto a cube. If it was possible to measure organizations on the three cube axes, then different forms of command and control structure could be plotted in the approach space. For example, conceptually a 'traditional' hierarchical command structure could be located in the bottom, front, left-hand corner, whereas an 'edge' structure could be located in the top, rear, right-hand corner. Other forms of command and control structures could be located throughout the cube. In a historical analysis of the organisational studies literature, Walker et al (2009a) were struck by the similarities between the dimensions investigated in the UK Aston Studies on organisational design (e.g. Pugh & Hickson, 1976) and those used in the NATO SAS-050 cube, as they are virtually identical – despite the fact that the latter seemed unaware of the former. Walker et al argue that this discovery lends construct validity to the dimensions of the NATO SAS-050 cube.

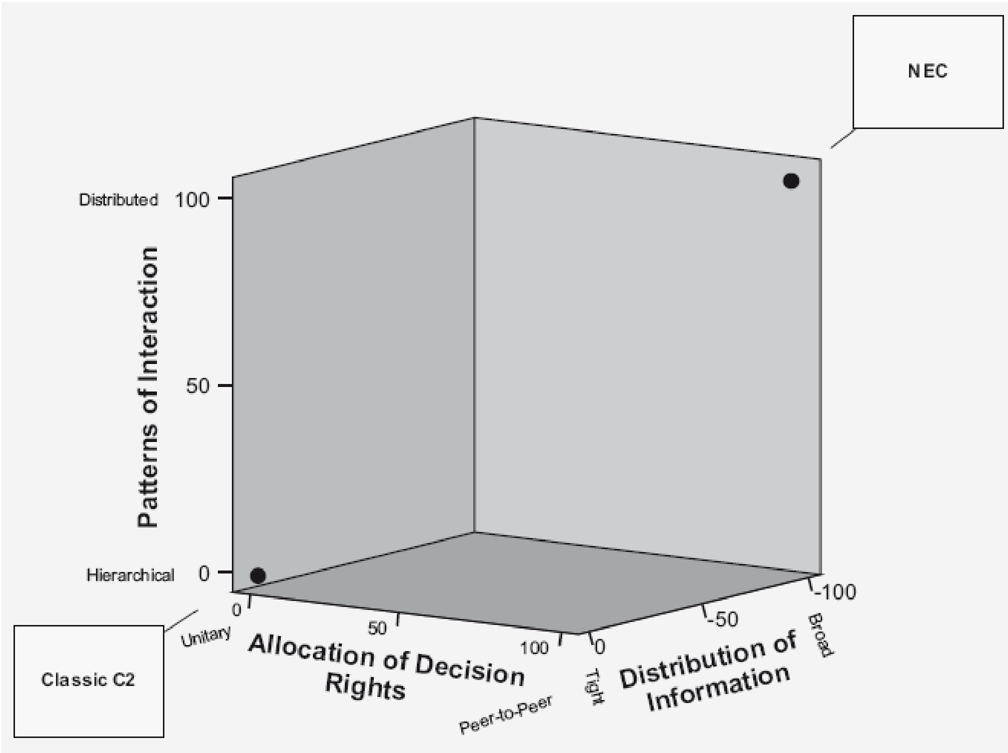

Figure 1 - The NATO SAS-050 approach space.

From Approach Space to Phase Space

Command and control is a multidimensional entity. What the NATO approach space has done is to collapse that multidimensionality down into the three variables which are felt to account for the majority of the system's (i.e. a C2 organisation's) behaviour. In other words, by manipulating any one of the three principle axes of the model, you indirectly manipulate all of the others. In complex systems research, the space created by the intersection of axes like these is formally known as a phase space. Within it, every possible state that a complex system can adopt can be plotted. Probably the most well known example of a phase space is the Lorenz attractor: it too reduces a complex system to three primary axes, but unlike the NATO approach space is able to mathematically calculate the coordinates of the system and plot it into the space with a high degree of accuracy. Because the system is dynamic, successive points can be joined to show a trajectory over time as shown in Figure 2.

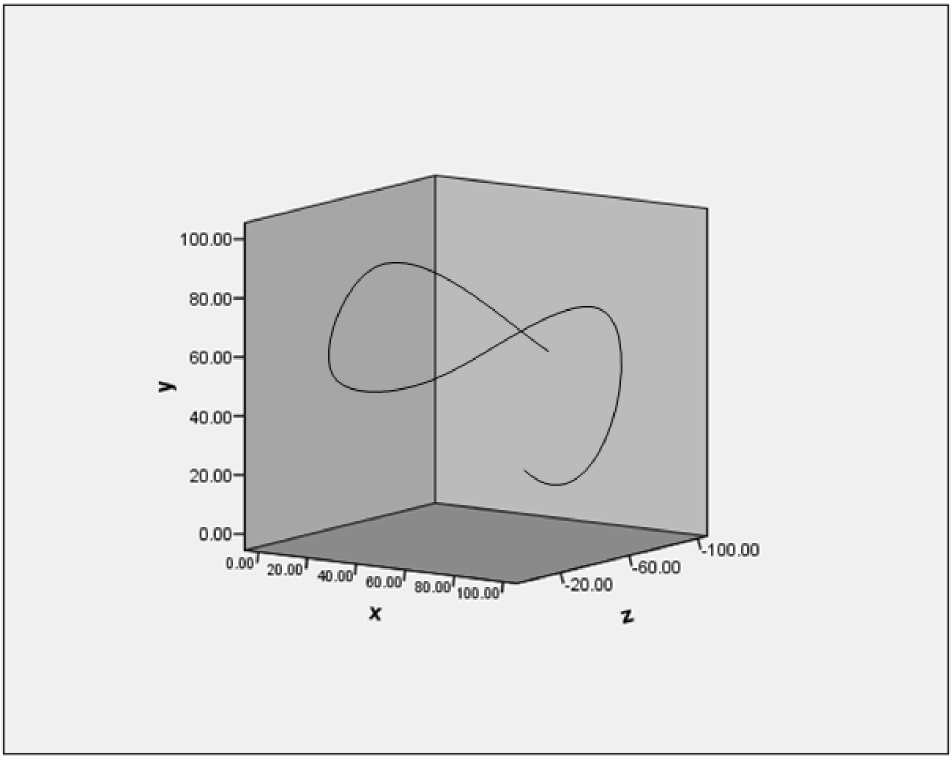

Figure 2 – The Lorenz attractor: phase space showing the complex dynamical behaviour of a physical system.

Functional Holography

Unlike physical systems, many of the variables of interest within C2 research are not easily reduced to a set of fundamental equations (despite the attempts of the cybernetic paradigm mentioned above). Alternative approaches to creating NATO SAS-050-like models have been adopted in other domains. Moving from physical and mechanical systems to biological systems, the Functional Holographic technique (Baruchi et al., 2004; 2006) represents the next level of sophistication. Functional Holography (FH) was developed as a way to analyse the activity of complex biological networks via ECG recordings. The diffuse, highly dynamic pattern of activation obtained in these settings is reminiscent of the NATO SAS-050 Reference Model, used to derive the simplified Approach Space. In the FH technique the matrix of data is reduced by subjecting it to Principal Components Analysis (PCA), with the three leading eigenvectors (or data clusters) forming three intersecting axes. The N dimensional space represented by the raw data is thus collapsed into a three-dimensional space represented by the leading eigenvectors, as shown in Figure 3. It is important to point out that the relationship between individual items of data and the clusters they subsequently form is preserved. Indeed, the clusters actively rely on interdependencies between the component variables in order to be derived. The corollary is that "if all the variables are tightly coupled, and if you can truly manipulate one of them in all its freedoms, then you can indirectly control all of them" (Kelly, 1994, p. 121). Phase spaces and Functional Holography pave the way, conceptually, for the next section, where the NATO approach space is turned from a typology (an approach space) into a taxonomy (something which we label a 'phase space').

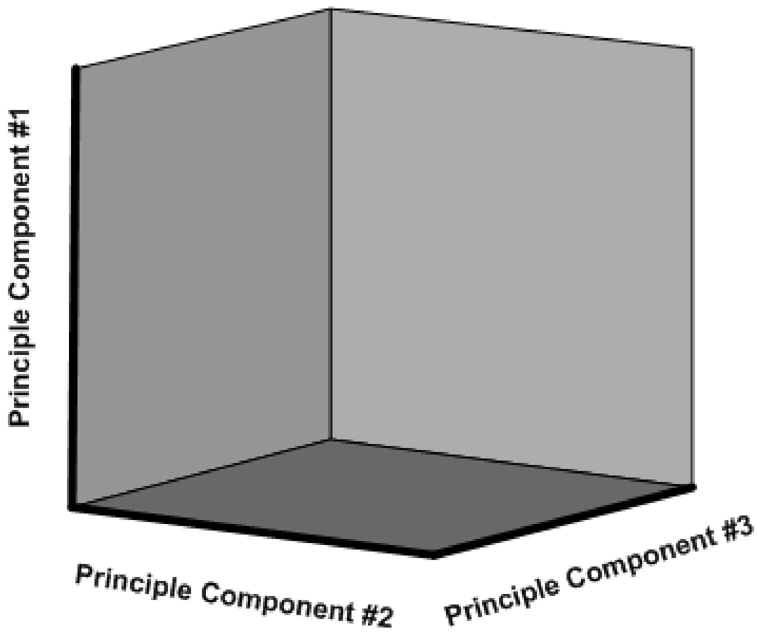

Figure 3 – Multidimensional space collapsed into three leading axes via PCA (Source: Baruchi, Ben-Jacob & Towle, 2005).

From Typology to Taxonomy

In a previous paper presented to ICCRTS (Walker et al., 2009b) it was demonstrated how social network analysis can be deployed to provide numeric measures of a C2 organisation's relative position along each of the NATO model axes. In general terms a social network is 'a set of entities and actors […] who have some type of relationship with one another.' Social network 'analysis' represents 'a method for analyzing relationships between social entities' (Driskell and Mullen, 2005, p. 58-1). A social network is created by plotting who is communicating with whom on a grid-like matrix. The entries into this grid denote the presence, direction and frequency of a communication. The matrix can be populated using information drawn from organisation charts and standard operating procedures so that it describes what communication structure 'should' occur. Much more consistent with the aspirations of the approach space, however, is that the matrix can also be populated with data which describes what communications structures ‘actually’ occur. The matrix of agents and links is what enables a social network diagram to be created. This is a graphical representation of the entities and actors who are linked together where, obviously, apart from very simplistic networks any underlying patterns extant in the cobweb of nodes and links is normally very difficult to discern by eye alone. As a solution to this, graph theoretic methods are applied to the matrix in order to derive a number of specific social network metrics (e.g., Harary, 1994). These metrics form the basis of a comprehensive diagnosis of the network’s underlying properties, which include several which have been shown to relate well to decision rights, patterns of interaction and distribution of information. This mapping of social network metrics to the NATO SAS-050 model axes is described in more detail by Walker et al, (2009a and b).

The discriminative validity of the enhanced ‘NATO phase space’ can be put to the test with reference to several theoretical network archetypes. Four of these are based on early social network research by Bevelas (1948) and Leavitt (1951) who defined the following: the ‘Chain’, the ‘Y’, the ‘Star’ and the ‘Wheel’ (shown in Figure 4).

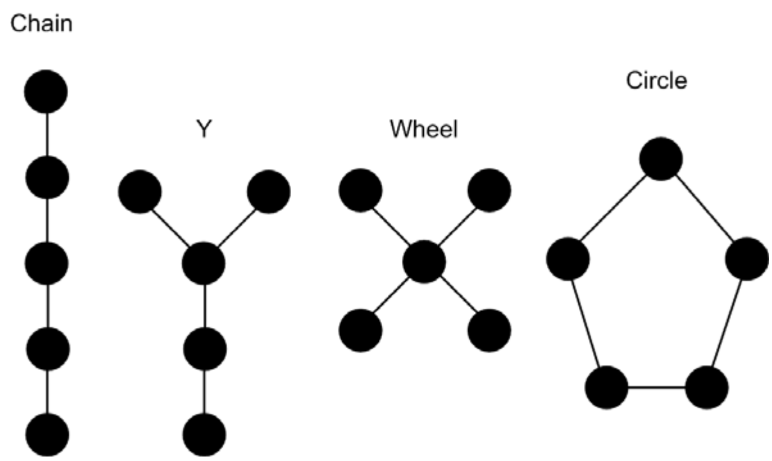

Figure 4 – Leavitt’s network archetypes (1951, p. 39).

Plotting Bevelas and Leavitt's four archetypes into the NATO phase space makes it possible to demonstrate that the metrics can discriminate between different organization types (which it does) as well as enabling a body of empirical evidence concerning their efficacy under different task conditions to be deployed. For example, the task instantiated by the ELICIT paradigm is suggestive of a deterministic task with dynamic rates of change (because the factoid delivery is phased), high familiarity (because the participants are given instructions and undertake the task numerous times) and a moderately strong information position (because whilst not all factoids are relevant, those that are critical to task success). The corresponding fix within the approach space is in close proximity to the 'Star' archetype. On the basis of Bevelas and Leavitt's empirical work this particular configuration can be judged as optimal due to the fact that information (or factoids in this case) are channeled to the centre upon which a deterministic decision making process can be performed. Figure 5 illustrates the positions that each of Bevelas and Leavitt's network archetypes occupy in the NATO phase space after the appropriate social network metrics have been calculated. Also present are a fully connected edge organization and a diverging hierarchy of the sort thought to represent 'classic C2'. These fixes provide a useful internal check on the validity of the model: firstly, in terms of construct validity, these findings support the earlier hypotheses of Alberts et al concerning where hierarchies and edge organizations 'should' plot (in the case of the hierarchy it is at least in the predicted cube octant). Secondly, in terms of discriminant validity, it demonstrates that the NATO phase space can adequately distinguish between different structures, with different archetypes falling into different cube 'octants'.

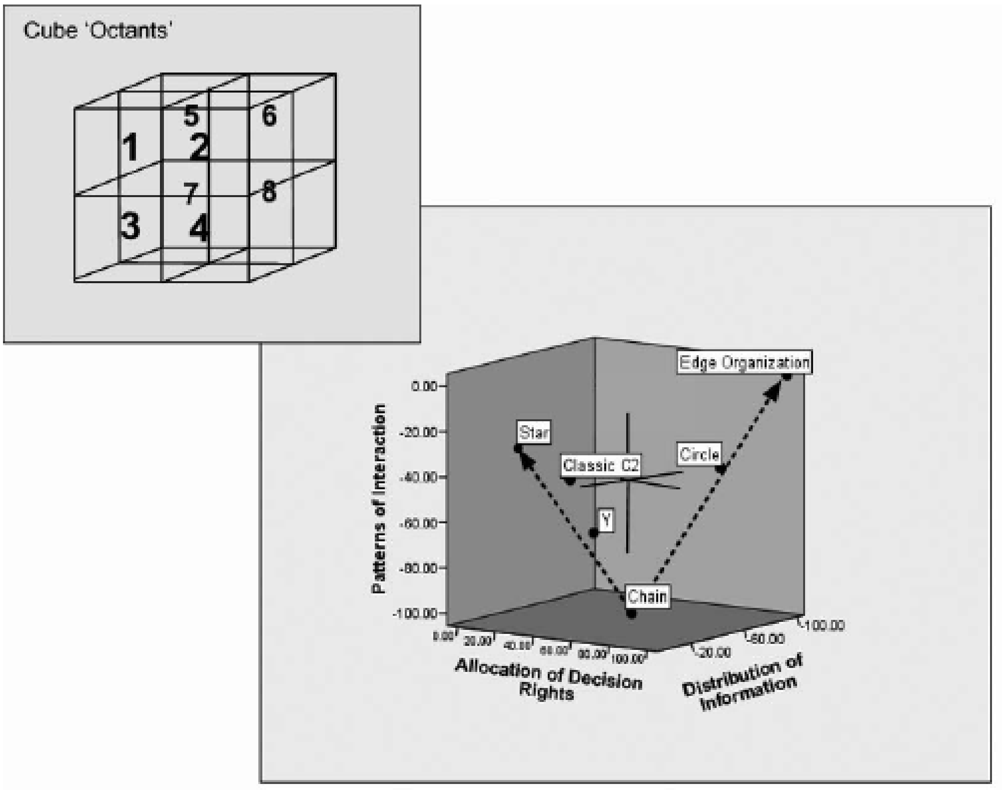

Figure 5 - Illustration of network archetypes in the NATO SAS-050 approach space.

Using this functioning taxonomic C2 phase space, it is possible to carry out experiments using the Experimental Laboratory for Investigating Collaboration, Information-sharing and Trust (ELICIT) to see what C2 organisations emerge in practice. This forms the topic of Part 2 of this paper.

Part 2: Multi-National Experiment

ELICIT Baseline Studies

Two organisational structures are used in ELICIT baseline studies, a three layer diverging hierarchy as show in Figure 6, and a fully interconnected peer-to-peer ‘edge’ organisation as shown in Figure 7. In the former case, each branch of the hierarchy is focused on who/ what/ where/ when, and their ability to share and post information is constrained accordingly. In the edge organisation, all team players have equal ability to share and post, and equal visibility of who/ what/ where/ when.

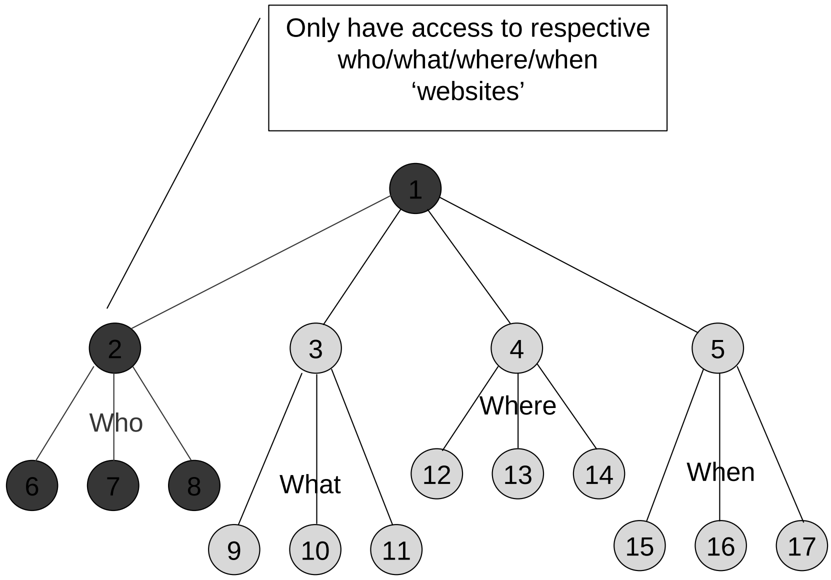

Figure 6 – Illustration of hierarchical C2 organisation

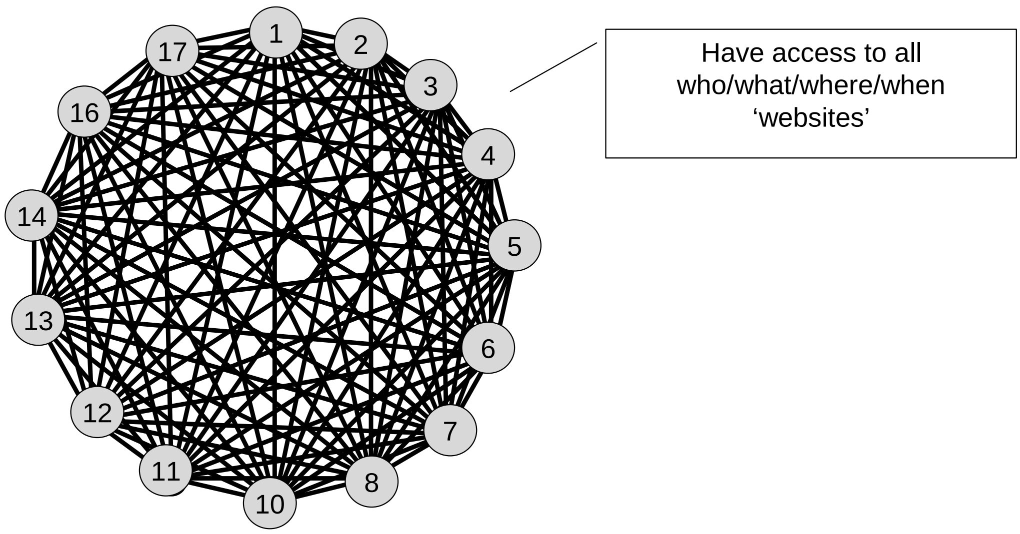

Figure 7 – Illustration of Edge organisation

The ELICIT baseline study is of a mixed design. The between subjects variable is organisation type, with two levels: hierarchical and edge. Participants are assigned at random to the two organisation groups and to their respective role within those groups (and remain in those groups/roles for the duration of the study). The within subjects variable is trial iteration, with four levels. The factoid sets, upon which the members of the two organisation types answer the who/where/when/what of an upcoming terrorist attack, are different for each successive trial, but shared across the two organisational groups. In other words, factoid set #1 applies to both hierarchy and edge organisations during trial #1, factoid set #2 for trial #2 and so on.

Meta-Analysis of Multi-National Data

The purpose of the current analysis was to study data collected within the international community of ELICIT experimenters. This was undertaken in order to a) explore the differences between Edge and C2 organisations and b) see if there are discernable differences between the nations involved. The analysis assumes that the researchers followed the same experimental protocol as laid out in the instructions for ELICIT and the data was supplied by the ELICIT user community. The analysis proceeded by taking the raw data transcripts from ELICIT and using it to construct social networks of the interactions which ‘actually’ occurred between team members. The appropriate social network metrics were calculated and the resultant position of the organizations was plotted into the NATO phase space. The results of this analysis are shown graphically in Figure 8 and in tabular format in Table 1.

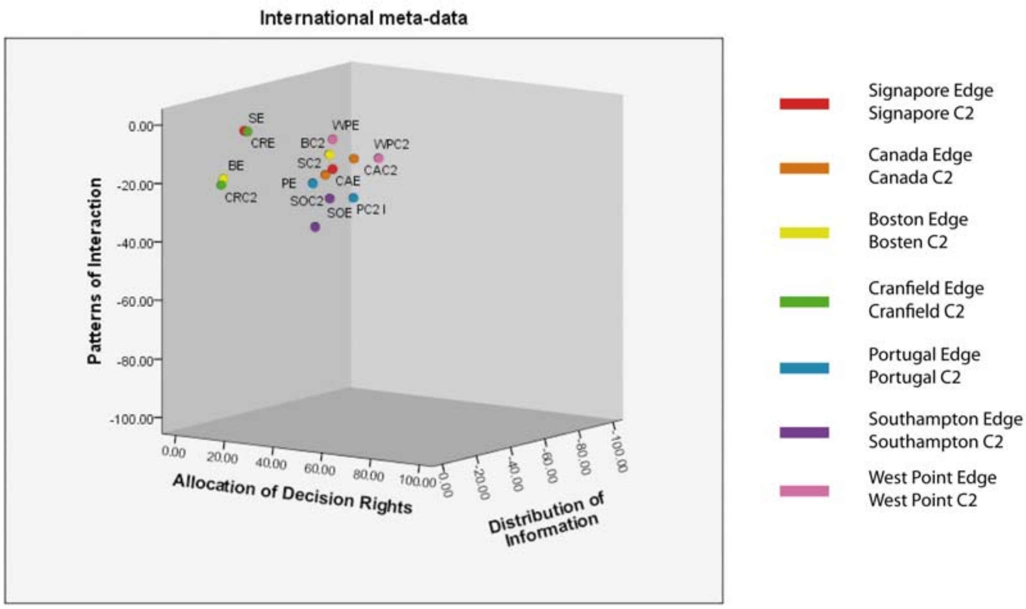

Figure 8 – Meta-analysis of multi-national ELICIT date plotted into NATO phase space using social network metrics as measures of the primary model axes.

Table 1 – Results of meta analysis showing the cube octant that C2 and Edge data fell within, the extent of change in that data between C2 and Edge conditions, and the direction of change expressed in network archetypes.

		Singapore	Canada	Boston	UK (Cranfield)	Portugal	UK (Southampton)	US (Westpoint)	Mode
	C2	1	1	1	1	1	1	1	Octant 1
	Edge	1	1	1	1	1	1	1	Octant 1
Direction of change	AoDR	-	=	-	-	-	=	=	Decreased
	PoI	+	=	+	=	=	=	=	Same
	DoI	-	=	+	+	-	+	=	Increased
	Overall	More star-like	Little change	More star-like	More star-like	More star-like	More star-like	Little change	More star-like

Note AoDr = Allocation of Decision Rights

PoI = Patterns of Interaction

DoI = Distribution of Information

Key to direction of change symbols: + = minor change (>10%)

++ = significant change (11-25%)

+++ = major change (< 25%)

Observation of the data in Figure 8 shows that the cloud of data points from the international ELICIT studies all cluster in the ‘star’ octant of the cube (i.e. octant number one, the top, left, front part of the NATO SAS-050 phase space). This occurs regardless of C2 or Edge organization type. It is true to say that there were detail differences between C2 and Edge, but they were subtle and not sufficient to cause either organization type to move bodily from one octant to another. Being based on live data, and the organization types ‘actually’ adopted, such a finding is intriguing. The NATO phase space demonstrably works: it has sufficient discriminant validity to reveal differences between true edge organizations and true hierarchies (and a range of other archetypes). It is also the case that in studies of large scale command planning exercises where this model has been deployed, far greater extents of change were also in evidence (e.g. Stanton et al., 2009). Instead, what the findings point to is a potential problem with the ELICIT paradigm. Firstly, the structure of the C2 organisation (as shown in Figure 6) is a fairly shallow hierarchy. It is interesting to note that the shallowest form of hierarchy, with a one person in charge of one layer of subordinates literally is a star network. Thus the results for the C2 baseline are reasonable. More problematic are those gained for the Edge organization, which in practice also adopted structures that were star-like in character, often more so than in the C2 condition (Table 1). This leads to the second explanation for the findings, that the ELICIT task itself propels teams towards an organizational solution that actively favours a star network. This is clear from the very deterministic nature of the task which actively relies on integrating data from a variety of sources, a task which is ideally suited to a star network (see Bevelas, 1948 and Leavitt, 1951). Taken as a whole, then, the findings actually prove to be a success. Given the freedom to adopt the structure they wanted in the Edge condition, under the ELICIT paradigm the team, quite correctly, adopted the star network. It is unfortunate that this is the same contingent response embodied by ELICIT's classic C2 condition.

Conclusions

The work described in the paper is ongoing. The results so far are both intriguing and challenging because they show a tendency for all of the data to fall into just one of the octants (the star octant), challenging our initial assumptions of network enabled, or network centric environments. In other words, despite the initial conditions seemingly placing the two types of organisations (C2 and Edge) at opposite ends of the cube, in theory at least; empirically they appear to drift toward the same point in the NATO phase space. Given that the phase space demonstrably possesses sufficient discriminate validity to distinguish between different organizational structures, a problem with the entire ELICIT paradigm is thus raised. An alternative view is to imagine what structures might have emerged in the Edge condition if instead of a deterministic task with a fixed end-state, there was a probabilistic, evolving task with no fixed end-state, a task which required teams to continually adapt and evolve with their environment. This is a truer measure of what network-enabled paradigms aspire to cope with, and an interesting avenue of future development for ELICIT.

Acknowledgements

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