Defining and Measuring Cognitive-Entropy and Cognitive Self-Synchronization

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Agenda

• Introduction
  – To concepts and base theory
  – To ELICIT, the experimentation platform used

• Self-Synchronization in the Cognitive Domain
  – Definition of Cognitive-Entropy
  – Definition of Cognitive Self-Synchronization

• Preliminary lessons from Experiments
  – A simple model
  – Enablers and Inhibitors
  – Measurements and Results

• Conclusions and Lessons Learned
Introduction

• New military challenges – new C2 approaches
• NEC as an important step?

(SAS-065, 2010, pp. 27)
Introduction

- **Self - Synchronization:**
  - NCW key-aspect
  - *Describes the ability of a well-informed force to organize and synchronize complex warfare activities from the bottom up* (Cebrowski, Arthur K. and Garstka, 1998)

Comprises 2 main aspects:

1. **Synchronization:** *as an output characteristic of the C2 processes that arrange and continually adapt the relationships of actions in time and space [...] Synchronization takes place in the physical domain* (Alberts et. al., 2001).

2. **Self:** a result from the bottom up (in this context, as a result of developing shared awareness enabled by networking) *without the need for guidance from outside the system* (Atkinson and Moffat, 2005).
Introduction

• **Self-Synchronization:**
  – An important concept (in NEC and C2)
  – Should be applied to the cognitive-domain for assessment purposes (during and after missions)
  – Challenge taken herein:
    • Define and measure it (based on existing experiments)!
    • Identify a set of enablers and inhibitors.
  – Concepts - first defined in (Manso and B. Manso 2010):
    • Cognitive Entropy
    • Cognitive Self-Synchronization
Introduction – ELICIT experimental Platform

- Research and experimentation platform
- Developed to:
  - conduct research related with collaboration, information sharing and trust
  - test hypothesis related with edge and hierarchical (traditional) command and control practices.
- Network-Enabled environment:
  - Played by 17 Subjects
  - Must determine the **who**, **what**, **where** and **when** of a future terrorist attack
  - Subjects receive pieces of information that they must share in order to develop sufficient awareness to guess the solution.
  - Subjects may share information by posting it to websites (**action post**) and/or sending it directly to other subjects (**action share**).
- The platform allows instantiating different C2 approaches (e.g., define roles and interactions allowed)
- Data was available from experiments conducted in Portugal.
Measuring Self-Synchronization

• Two variables were created:
  – Cognitive Self-Synchronization (CSSync)
  – Cognitive Entropy (CE) (its counterpart)

• First introduced in (Manso and B. Manso 2010) and based on Moffat’s work towards developing a knowledge metric (Moffat 2003) to measure the amount of uncertainty in a probability distribution (Shannon’s Information Entropy)

• Now based on the scientific field of Complexity theory, namely, the Kolmogorov complexity - a measure of the descriptive complexity of an object (Cover and Thomas 1991)
**Research Problem:** how to measure (quantitatively) the degree of convergence of a group towards the ELICIT problem?
Kolmogorov complexity

- Expected description length of dataset $D$:

$$-\log P(D) = \text{Entropy of } D$$

$$= \text{Kolmogorov Complexity of } D$$

- More generally:

$$-\sum_{i=1}^{N} p(D_i) \log p(D_i) = \text{expected description length of the datasets } \{D_1, D_2, \ldots, D_N\}$$

$$= \text{information entropy of } \{D_1, D_2, \ldots, D_N\}$$
Defining and Measuring Cognitive-Entropy

• Inputs:
  – 17 subjects playing the game (N=17)
  – 4 solution spaces: who, what, where and when (assumed independent for simplicity)
  – Subjects may ID over time (no ID=null case)

• For each solution space $i$ at time $t$, we thus define:

$$S(i, t, k) = \text{Number of IDs for solution space } i \text{ at time } t \text{ of type } k$$
Defining and Measuring Cognitive-Entropy

- **Number of Positive IDs:**
  \[
  \sum_{k=1, S(i,t,k) \neq 0}^{k=K} S(i,t,k)
  \]
  - probability of each ID description:
  \[
  p(i,t,k) = \frac{S(i,t,k)}{17}
  \]

- **Null case (no ID):**
  \[
  17 - \sum_{k=1, S(i,t,k) \neq 0}^{k=K} S(i,t,k)
  \]
  - probability of this description:
  \[
  p(i,t,k = \emptyset) = \frac{1}{17} \text{ where } \emptyset \text{ denotes the null set.}
  \]
• Cognitive entropy $CE$
  – for solution space $i$
  – at time $t$

$$CE(i,t) = - \left\{ \sum_{k=1, S(i,t,k) \neq 0}^{K} p(i,t,k) \log p(i,t,k) + \left\{ 17 - \sum_{k=1, S(i,t,k) \neq 0}^{K} S(i,t,k) \right\} \frac{1}{17} \log \frac{1}{17} \right\}$$

**Positive IDs**

**Null case (no IDs)**

**Uncertainty parcel**
Defining and Measuring CSSync

- Counterpart of Cognitive-Entropy

\[
CSSync_{\text{ProblemSpace}}(i, t) = 1 - \frac{CE(i, t)}{\text{Max Disorder}_{\text{ProblemSpace}}}
\]

- Where:
  - \( CE(i, t) \) is the Cognitive-Entropy of solution space \( i \) at time \( t \).
  - \( \text{Max Disorder}_{\text{ProblemSpace}} = -\sum_{i=1}^{N} \frac{1}{N} \log\left(\frac{1}{N}\right) = \log(N) \)
  - \( CSSync = 0 \) means system is fully disordered
  - \( CSSync = 1 \) means system is fully ordered
Defining and Measuring CSSync

• For ELICIT, the overall CSSync is:

\[
CSSync(t) = 0.25 \times \sum_{i=\text{ProblemSpace}} CSSync(i, t)
\]

• OBS:
  – used equal weights (25%) for each of the 4 solution spaces.
  – Assumed each solution space to be independent from each other.
Defining and Measuring CSSync

- Illustrative Example (1): fully-disordered system (Manso and B. Manso 2010)

\[
CE(1,0) = -\left\{ 5 \times \left( \frac{1}{17} \right) \times \log \left( \frac{1}{17} \right) + (17 - 5) \times \left( \frac{1}{17} \right) \times \log \left( \frac{1}{17} \right) \right\} = \log(17)
\]

\[
CSSync(0) = 1 - \left( \frac{\log 17}{\log 17} \right) = 0
\]
Defining and Measuring CSSync

• Illustrative Example (2): (about) half-ordered system (Manso and B. Manso 2010)

\[
CE(1,0) = -\left\{ \frac{8}{17} \log \left( \frac{8}{17} \right) + \frac{6}{17} \log \left( \frac{6}{17} \right) + (17 - 14) \left( \frac{1}{17} \right) \log \left( \frac{1}{17} \right) \right\} = 0.53
\]

\[
CSSync(0) = 1 - \left( \frac{0.53}{\log 17} \right) = 0.57
\]
Defining and Measuring CSSync

- Illustrative Example (3): fully-ordered system (Manso and B. Manso 2010)

\[ CE(1,0) = -\left( \frac{17}{17} \right) \cdot \log \left( \frac{17}{17} \right) = 0 \]

\[ CSSync(1,0) = 1 - \left( \frac{0}{\log 17} \right) = 1 \]
Use existing experimentation data to explore the following questions:

- **Q1:** What aspects enable the emergence of Self-Synchronization?
- **Q2:** What aspects inhibit the emergence of Self-Synchronization?
- **Q3:** What is the associated cost to Self-Synchronize?
CSSync Enablers and Inhibitors: an exploratory view

A Simple Model:

Network access (members and websites)
Organization goals, roles and structure
Allocation of decision rights

C2 Approach

Cognitive System (collective)

Independent Variables

Problem difficulty
Number of subjects
Distribution of Information (by server)
Subjects’ competence (assumed fixed)

Collaborative mechanisms (share/post/pull)

Other relevant variables (fixed)

Effort Spent
Extent of Correct Awareness
CE and CSSync

Subjects’ competence (assumed fixed)
CSSync Enablers and Inhibitors: an exploratory view

A Simple Model:

Conflicted C2
Deconflicted C2
Coordinated C2
Collaborative C2
Edge C2

Based on the N2C2M2 C2 Approaches (SAS-065, 2010, pp. 27)
CSSync Enablers and Inhibitors: an exploratory view

<table>
<thead>
<tr>
<th>APPROACH</th>
<th>Mean</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONFLICTED</td>
<td>0.05</td>
<td>0.00</td>
<td>0.09</td>
</tr>
<tr>
<td>DECONFLICTED</td>
<td>0.12</td>
<td>0.04</td>
<td>0.22</td>
</tr>
<tr>
<td>COORDINATED</td>
<td>0.15</td>
<td>0.10</td>
<td>0.22</td>
</tr>
<tr>
<td>COLLABORATIVE</td>
<td>0.34</td>
<td>0.22</td>
<td>0.42</td>
</tr>
<tr>
<td>EDGE</td>
<td>0.41</td>
<td>0.40</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Self-Synchronization (Cognitive)
CSSync Enablers and Inhibitors: an exploratory view

- Conflicted C2
CSSync Enablers and Inhibitors: an exploratory view

• Deconflicted C2
CSSync Enablers and Inhibitors: an exploratory view

- Coordinated C2
CSSync Enablers and Inhibitors: an exploratory view

• Collaborative C2
CSSync Enablers and Inhibitors: an exploratory view

• Edge C2
Q1: What aspects **enable** the emergence of Self-Synchronization?
Q2: What aspects **inhibit** the emergence of Self-Synchronization?

<table>
<thead>
<tr>
<th>Category</th>
<th>CSSync Inhibitors</th>
<th>CSSync Enablers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared Information Resources</td>
<td>None or a few shared (mainly kept within own entities)</td>
<td>Shared across members. All information accessible across entities.</td>
</tr>
<tr>
<td>Patterns of Interactions</td>
<td>Non-existent or highly constrained</td>
<td>Unconstrained / broad and rich across entities and subjects</td>
</tr>
<tr>
<td>Allocation of Decision Rights</td>
<td>None / fixed task-role based</td>
<td>Distributed (to all subjects)</td>
</tr>
</tbody>
</table>
CSSync Enablers and Inhibitors: an exploratory view

Q3: What is the associated cost to Self-Synchronize?

Effort (cost)

- Ids per Hour
- Pulls per Hour
- Posts per Hour
- Shares per Hour

Cognitive Self-Synchronization
Q3: What is the associated cost to Self-Synchronize?

Relation between Effort and CSSync

![Graph showing the relation between Effort and CSSync, with linear trend line.](image)
Conclusions and Way Ahead

- CE and CSSync concepts defined and measured in experiments.
- We raised first indicants for enablers and inhibitors for CSSync (as well as cost).
- The ability to self-synchronize in the cognitive domain shows a steady improvement with the C2 Approach adopted in the game.
- This steady improvement in cognitive self-synchronization with C2 Approach is also directly related to the level of activity (the energy or activity ‘cost’) required to sustain that C2 Approach.
- ELICIT has been shown to give important insights for the attack scenario used.
Conclusions and Way Ahead

- Increase the experimentation data set and observe values for CSSync beyond 0.5
- Measure CE and CSSync to C2-related experiments using different experimentation platforms, including DSTL’s WISE wargame. (Moffat 2003).
- Manipulate additional relevant input variables. Cover multiple levels of complex networks including (i) Base level (network characteristics), (ii) Median Level (intelligent node interactions) and (iii) Top level (NEC Effects) (Moffat 2007).
- Further extend the application of entropy to network-entropy (Lin et. al. 2010) and information-entropy (Jin and Liu 2009) and identify relations between them.
Thank you for your attention

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Cognitive Self-Synchronisation