Managing System-of-Systems Complexity for Distributed Command and Control (C2)

ART-010

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Complexity Management in (C2) System-of-Systems

A challenge for Systems-of-Systems is discovering the right "lenes" (and then metrics) on complexity, combined with the right performance metrics, to reason about design alternatives characterizations.

Study Research Questions

- What defines complexity for C2 SoS?
  - Uniqueness of C2 SoS – in both military and civil/commercial contexts

- How to measure complexity in C2 context?
  - e.g., Design, Extensibility, Maintainability, Adaptability, Hierarchic, Dynamic, Others?

- How can we manage the complexity of SoS in a distributed C2 environment?
  - How will we know that the complexity has been allocated appropriately?

- How to define effectiveness of measures in C2 context?

Not a 'static design' challenge...instead a 'dynamic management' challenge

When done right, allocating complexity across the various dimensions of its manifestation is a winning strategy to manage scale, disruption, evolution.

**Managing Scale:**
- How does the size of a system increase complexity?
- How can distributed approaches help to manage?
- A large enough system will fail under its own weight without effective management.

**Managing Disruption:**
- How can we measure the ability for a system to endure disruption?
- How is complexity a good lens to do it?

**Managing Evolution:**
- How can we manage incremental changes of a system?
- How do we measure the effects a change will have?
- Are we actually making things worse?

In a distributed C2 context, this can help design human (H) and machine (M) roles in well-balanced architectures.
Introduction to Complexity

• What is Complexity
  • “It is uncertain, unpredictable, complicated, or just plain difficult” *(INCOSE CxSWG)*
  • The inability of a human mind to grasp the whole of a complex problem and predict the outcome *(Sillitto 2009)*
  • A complex system is a system where there is uncertainty between cause and effect.
  • When there is a great degree of *temporal, horizontal, and diagonal* interdependence between elements *(Taleb 2007)*
    • Temporal (a variable depends on its past changes)
    • Horizontal (variables depend on one another), and
    • Diagonal (variable A depends on the past history of variable B)
  • Consequence: *Central Limit Theorem doesn’t work*

Cynefin Domains

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Traits of Complex Systems*

• 14 distinguishing traits of complex systems

<table>
<thead>
<tr>
<th>Diversity</th>
<th>Dynamics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connectivity</td>
<td>Representation</td>
</tr>
<tr>
<td>Interactivity</td>
<td>Evolution</td>
</tr>
<tr>
<td>Adaptability</td>
<td>Emergence</td>
</tr>
<tr>
<td>Multi-Scale</td>
<td>Disproportionate Effects</td>
</tr>
<tr>
<td>Multi-Perspective</td>
<td>Intermediate Boundaries</td>
</tr>
<tr>
<td>Behavior (unpredictable)</td>
<td>Contextual Influences</td>
</tr>
</tbody>
</table>

• Complexity Management Strategies
  • **Balance** instead of optimization
  • **Tension** between large-small, agile-planned, centralized-distributed
  • **Bounded** within simpler structure
  • **Architecture** to understand interactions
  • **Social-Political Complexity** relationship between engineered, natural & governance environment

Synopsis:
Multitude of Trade-Offs in C2 Design When Viewed as a Distributed SoS

Primary Hypothesis:
There is utility in a framework that provides a holistic view on complexity, and related management approaches, allowing designers to “ask the right questions” as they seek to balance risk and reward in distributed C2.
Key Finding: Beyond technical complexity, the "other dimensions" of complexity are as important, if not more, for understanding C2 systems

- While complexity is most often thought to pertain to technical aspects and technicality of functions, our study findings indicate that other dimensions of complexity (e.g., organizational complexity, process complexity, data complexity, and environment complexity) may be as important, if not more, for understanding (and designing) C2 systems.

- Our research uncovered eight different viewpoints on distributed C2 system complexity and one overarching concept of Panarchy to tie it all together.
Panarchy and its Implications for Distributed C2

- Panarchy proposes that adaptive cycles within a complex systems are connected via multi-scale hierarchies and remain interdependent on one another across both spatial and temporal scales (i.e., spatial spans and timescale).
- Panarchy is a “conceptual model that describes the ways in which complex systems of people and nature are dynamically organized and structured across scales of space and time”

<table>
<thead>
<tr>
<th>Adaptive Cycle Phase</th>
<th>Description</th>
<th>Application to C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploitation/Growth</td>
<td>Rapid expansion</td>
<td>Establish military presence and form C2 network</td>
</tr>
<tr>
<td>Conservation</td>
<td>Slow accumulation and storage of energy</td>
<td>Perform operations, collect data according to plan</td>
</tr>
<tr>
<td>Release</td>
<td>Rapid reaction to new threat or changed situation</td>
<td>Response to new threat/adversary</td>
</tr>
<tr>
<td>Reorganization</td>
<td>System changes and endures under new conditions</td>
<td>Changes to C2 structure/operations to better respond to threats</td>
</tr>
</tbody>
</table>

Systems will inevitably change, driven by disruption and evolution from internal and external sources.
<table>
<thead>
<tr>
<th>Component</th>
<th>Spatial Span</th>
<th>Timescales</th>
<th>Aspects of Adaptive Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warfighter/Flight</td>
<td>Narrow region of space</td>
<td>Short, Single engagement or mission</td>
<td>Quickly deploy, most immediate response to adversaries, flexibly change tactics to deal with new threats, most vulnerable to casualties</td>
</tr>
<tr>
<td>Squadron</td>
<td>Larger regional coverage</td>
<td>Several missions over weeks/months</td>
<td>Deployed to fill a certain role, operations may be adjusted or removed based on performance or changing threat environment</td>
</tr>
<tr>
<td>Base</td>
<td>Expanded area of responsibility</td>
<td>Persistent presence in an area</td>
<td>Established to control an area, houses certain types of military units for its mission, might be reorganized or abandoned based on adversary actions</td>
</tr>
<tr>
<td>Regional Command</td>
<td>Large, diverse area of responsibility</td>
<td>Long-term management and deployment of troops in a region, allocation of resources</td>
<td>Development of regional strategies and capabilities, strategies may evolve but unlikely to experience drastic structural reorganization</td>
</tr>
</tbody>
</table>
Collaborative Air Traffic Management: Useful Example

- C-ATM is a useful analog for distributed C2 in military domain

- Graphic on right is Operational View of the FAA’s NextGen Air Traffic Management Modernization for 2025 (adapted from Eldredge 2012)

- Eight complexity types manifest clearly in C-ATM

<table>
<thead>
<tr>
<th>Component</th>
<th>Spatial Span</th>
<th>Timescale (Network Structure)</th>
<th>Timescale (Control Operations)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airport ATC</td>
<td>Local to airport</td>
<td>Reorganization due to changes in airport capacity or use</td>
<td>Minutes</td>
</tr>
<tr>
<td>Terminal Radar Approach Control (TRACON)</td>
<td>5-50 miles from airport(s)</td>
<td>Reorganization due to local changes in airport usage or traffic</td>
<td>Minutes - Hours</td>
</tr>
<tr>
<td>Air Route Traffic Control Centers (ARTCC)</td>
<td>Sub-Regional (22 in US)</td>
<td>Long term reorganization due to changing traffic patterns/demand</td>
<td>Minutes - Hours – tracking flight across a region</td>
</tr>
<tr>
<td>ATC System Command Center</td>
<td>National traffic management</td>
<td>Long term changes in national ATS management and technology</td>
<td>Hours – tracking flight across the country</td>
</tr>
<tr>
<td>National/Global Traffic Management</td>
<td>National/International traffic Management</td>
<td>Long term changes in national ATS management and technology with global cooperation</td>
<td>Months – Years</td>
</tr>
</tbody>
</table>
Technical Complexity occurs when one seeks to “design a system to achieve a predefined purpose by organizing the various components and subsystems in the most efficient way possible.”

<table>
<thead>
<tr>
<th>Management Methods</th>
<th>Examples/Implications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Systems Engineering</strong></td>
<td><strong>Air Traffic Management</strong></td>
</tr>
<tr>
<td>• Transcapillary methods tools and processes for life-cycle development and management of technical systems</td>
<td>• Development of new aircraft and systems</td>
</tr>
<tr>
<td><strong>Operations Research</strong></td>
<td>• Communication interfaces between pilot and ATC</td>
</tr>
<tr>
<td>• Quantify the risks and benefits of choosing different alternatives, strategies, or controls</td>
<td><strong>Distributed C2</strong></td>
</tr>
<tr>
<td><strong>Systems Analysis</strong></td>
<td>• Development of new systems and technologies for distributed control</td>
</tr>
<tr>
<td>• Study of how components of a system interact in order to design their operations to most efficiently achieve the system’s goal</td>
<td>• Limited support to include socio-technical considerations, particularly when quantifiable design metrics are lacking</td>
</tr>
</tbody>
</table>
Process Complexity “arises when we have to put together a series of interdependent actions to achieve a purpose”

Management Methods

- The Vanguard Method
  - Shift from hierarchy to align the system as organization to meet customer need
  - Identify value demand and waste demand
  - Add flexibility and decision making at the edges

- Tools for Implementing Vanguard Method
  - Check, Plan, Do
  - Identify Demand analysis, Flowcharts, and Capability charts

Examples/Implications

- Air Traffic Management
  - Process oriented view of ATC
  - Sequence of action taken by ATC and Pilot for air traffic managed
  - Identify waste demand and insert new technologies such as Controller Pilot Data Link Communications

- Distributed C2
  - Military C2 is rich with process definitions, providing guidance via doctrine on the methods and ordering of tasks to manage and execute joint and coalition operations
  - Shift to decentralized C2, or “power to the edge” requires adjusting these process to be more flexible and allowing junior commanders to make decision based on how a situation is unfolding (e.g., conditions-based authority).
Coercive complexity is “associated with the exercise of power, which can operate to ensure some individuals or groups have the capacity to control the behaviors of others and benefit as a result.”

**Management Methods**

- **Team Syntegrity**
  - Framework to support discussion and sharing of ideas in a way that minimizes the impact of hierarchy or personal influence
  - Structured around a set of key points associated with a given problem with an emphasis on idea-sharing and reworking between groups to arrive and beneficial solutions for each key point

- **Critical Systems Heuristics**
  - Understanding the different reference frames that stakeholders bring to decisions
  - Systematic boundary critiques and examinations of the boundary judgements that inform an individual’s view of relevant facts and values

**Examples/Implications**

- **Air Traffic Management**
  - Pilot/Co-Pilot Interactions (Asiana Air Crash 214 Crash)

- **Distributed C2**
  - Strict hierarchical and command structure of the military
  - Coalition Operations
  - Coercion by adversaries
Data complexity is associated with the collection, storage, processing, and use of large amounts of data.

### Management Methods

- **Data Quality**
  - Transcapillary methods tools and processes for life-cycle development and management of technical systems

<table>
<thead>
<tr>
<th>Data Quality Category</th>
<th>Data Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>Accuracy, Reputation, Believability, Objectivity</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Accessibility, Access Control</td>
</tr>
<tr>
<td>Contextual</td>
<td>Relevancy, Timeliness, Completeness, Amount of Information, Value Added</td>
</tr>
<tr>
<td>Representational</td>
<td>Conciseness, Consistency, Interpretability, Understandability, Ease of Operation</td>
</tr>
</tbody>
</table>

- **5V’s of Big Data**
  - Velocity, Veracity, Value, Variety and Volume

### Examples/Implications

- **Air Traffic Management**
  - National Airspace Aircraft Tracking
  - Weather monitoring
  - Emergency Codes

- **Distributed C2**
  - Data is key for situational awareness and decision-making
  - Identification of relevant data to be shared across hierarchal command structure
  - Metadata and interoperability in systems
This type of complexity is based on the arrangement and dynamic relationships between different system elements.

### Management Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Network Theory</strong></td>
<td>• System representation as a network of connected nodes</td>
</tr>
<tr>
<td></td>
<td>• Rich mathematical foundations to study structures</td>
</tr>
<tr>
<td><strong>System Dynamics</strong></td>
<td>• System representation as casual flows with feedforward and feedback loops</td>
</tr>
<tr>
<td></td>
<td>• Investigate interdependencies between system elements</td>
</tr>
</tbody>
</table>

### Examples/Implications

<table>
<thead>
<tr>
<th>Example</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Traffic Management</strong></td>
<td>• Delays caused by weather propagate through the network</td>
</tr>
<tr>
<td></td>
<td>• Hub and spoke networks</td>
</tr>
<tr>
<td><strong>Distributed C2</strong></td>
<td>• Direct implications for control</td>
</tr>
<tr>
<td></td>
<td>• Multiple nested feedback and feedforward loops</td>
</tr>
</tbody>
</table>
Organizational complexity is seen as driven both by the internal interactions of the parts of a system and by the interactions between the system and its turbulent environment.

### Management Methods

- **Socio-Technical Systems Thinking**
  - Methods consider both the structure of an organization as well as the social, economic, and political environment
  - Perceptions and worldviews with semi-autonomous groups

- **Organizational Cybernetics**
  - Manage complexity by systematically breaking down an organization into 5 groups:
    - Implementation, Coordination, Operational Control, Development, and Policy

### Examples/Implications

- **Air Traffic Management**
  - Response to closures of large airspaces or major airports

- **Distributed C2**
  - Optimizing local-level vs. maximizing collaborative efforts (within C2; with coalition forces)
  - Impact of operational environment and uncertainty
  - Shifting from a capability-based structure to an outcome-based
People complexity is rooted in differences in the worldviews, perspectives, and assumptions of individuals, and its larger impacts through culture, politics, religion, and other social constructs.

**Management Methods**

- **Strategic Assumptions Surfacing and Testing**
  - Four key stages: group formation, assumption surfacing, dialectical debate, and synthesis
  - Convergence in perspectives within groups but maximum divergence in perspectives across groups
  - Validate assumptions across groups

- **Soft Systems Thinking**
  - Creating conceptual models called “rich pictures” that capture the social and technical elements
  - Identify “root definitions” or key assumptions held by stakeholders
  - Study relationships between socio-technical elements with root definitions

**Examples/Implications**

- **Air Traffic Management**
  - Managing Disruption-- Responses to “ATC Zero” event at “Chicago Center” ARTCC in 2014
  - Leveraged to advantage in creative tactical responses (controllers driving to adjacent facilities)
  - Disadvantage due to lack of coordinated plan for these scenarios (see FAA IG report)

- **Distributed C2**
  - Establish a new operating base in a foreign country; e.g., Asia-Pacific or Middle East
  - Multiple nested feedback and feedforward loops
This complexity arises when different parts necessary to perform a task (or reach a goal) interact or conflict

Goal Complexity

Management Methods

- Task Complexity Framework
  - Multiple components effect task completion including goal complexity that has five contributing factors evaluated over different dimensions

Examples/Implications

- Air Traffic Management
  - Managing Evolution: Capacity Management function for collaborative ATM involves design decisions where Goal complexity, may be high as the appropriate objectives for airspace and staffing design decisions may be conflict.
  - Contention in goals of a networked system with finite capacity

- Distributed C2
  - Assigning a “span of control” for decentralized execution may falter if the insight and tools are not provided for deconfliction between and among assigned goals
Complexity Dominance in Distributed C2 and Interdependence

- Nested hierarchies in adaptive spatial and temporal scales
- Different complexity types are dominant at different hierarchical levels but remain interdependent due to Panarchy

How to objectively assess these interdependencies?
Way Ahead

**Complexity Types**

Instrumentation for Complexity Types

- Complexity due to evolving technical systems interacts with other complexity
- Lack of techniques to identify complexity types and assess their interdependencies
- How can a commander understand the implications of people complexity and relate it to evolution of technical systems or disruption of structural complexity.

**Measures**

Stable Intermediate Forms and Measures

- Evolution of C2 systems, due to variation in scale or a response to disruption will always remain inevitable
- Imperative to provide a stable intermediate form within any adaptive cycle of evolution in the C2 system
- Qualitatively and Quantitatively measure complexity and relate to stability of distributed C2

**Panarchy**

Panarchy Constructs, Methodologies, and Tools

- Examination of Panarchy and constructing a response due to its implication remains an open problem
- How to link the different scales both spatial and temporal and ensure adaptations taking place faster timescales at the local level are consistent with how the system needs to adapt at the higher levels?
- How to develop measures to study Panarchy in distributed C2---singular measure such as profitability are rarely effective
Thank You