Gaining advantage from Complexity in Defence: a new DST research initiative

Alexander Kalloniatis,
Keeley Hoek [ANU], Mathew Zuparic
Joint & Operations Analysis Division
Outline

- Complexity – Good or Bad (for us)?
- DST Modelling Complex Warfighting SRI
- Models of Warfighting
- What’s missing?
- Decisions & Attrition: a ‘Kuramoto-Lanchester’ model
- Complexity advantage
- What are we looking for?
- Conclusions
Complexity – Beauty ...

Motor and Somatosensory Cortex

The Internet
Complexity – and The Beast?
 Complexity ‘phenomena’

Can these properties be exploited to advantage in national defence?
The problem

- How can ‘emergence’/’criticality’/’self-synchronisation’/’self-organisation’ be exploited by a Force
  - To make it robust against shocks – resilience
  - To give it advantage against a near-peer adversary

- We know some of the answers in abstracto – now is the time to see it for things that look like national defence.
Creating a Future Force: how DST supports Force Design

- What are the parts?
- How do they connect?
- What else should we get?
- How do we gain advantage from them as a system for the future?

Modelling Complex Warfighting SRI*: Revolutionising the analytical approach to force design

*SRI = Strategic Research Investment

**Conquering Uncertainty**
Scientific methods to enable robust Force Design decisions to produce a resilient force through the understanding and management of uncertainty in Defence.

**Innovative simulations**
Novel modelling and simulation techniques to enable exploration of whole-of-force warfighting concepts and force options.

**Knowledge synthesis**
Synthesis of analytical and simulation results to support development of a joint force which is integrated by design.

**Modelling complexity**
Methods to enable understanding of properties of the joint force emerging as a result of nonlinear interactions between the many constituent elements.
Modelling Complex Warfighting SRI: *Revolutionising the analytical approach to force design*

- **Conquering Uncertainty**
  - Modelling unknowns
  - Modelling complex human systems

- **Innovative simulations**
  - Capability decision evaluation under uncertainty

- **Knowledge synthesis**
  - Force design data culture

- **Modelling complexity**
  - Concepts for complexity-enabled warfare
  - Simulation-based concept exploration
  - Machine discovered behaviour

*Project Leader: A. Kalloniatis*
Mathematical Models of Warfighting

- Lanchester 1916 – (“Directed”) Force-on-Force Attrition
  \[
  B(t) = \alpha_s B(t) - \alpha_{RDA} R(t) \\
  R(t) = \beta_s R(t) - \beta_{BDA} B(t)
  \]
  B = Size of Blue Force, R = Size of red Force

- Protopopescu et al 1989 – Diffusion, Advection, Inhomogeneity

- Hughes 1995 – Missile Salvos, Staying Power

- McLemore et al 2016 – Manoeuvre, Dispersion, Swarming, Swarming
What’s missing – in one or another – or all?

- Logistics
- Deception/Reconnaissance
- Manoeuvre
- States of Readiness/Damage
- *Command and Control (ie organisational decision-making)* – *hierarchical or networked*
A model for C2 – the Kuramoto Model (1984)

Rate of progress through decision cycle

Tightness of Organisational Coupling

Organisational Interactions

\[ \beta_i = \omega_i + \sigma \sum_j A_{ij} \sin(\beta_j - \beta_i) \]

Measure of synchronisation:

\[ r(t) = \frac{1}{N} \left| \sum_j e^{i \beta_j(t)} \right| \]

Socio/technical applications:

- Rhythmic applause (Neda et al 2000);
- Opinion dynamics (Pluchino et al 2006);
- Pedestrian crowds (Strogatz 2005);
- Decision making in animal groups (Leonard et al 2012);
- Planar vehicle coordination (Paley et al 2007);
- Control systems (Jadbabie et al 2004);
- Consensus protocol (Sarlette & Sepulchre 2009).

Low \( \sigma \): “Loosely Coupled”

High \( \sigma \): “Tightly Coupled”

Spontaneous synchronisation through network interactions
External C2 driven resupply and symmetric direct attrition

- **Kuramoto**

\[ \dot{\beta}_i(t) = \omega_i + \sigma \sum_j B_{ij} \sin(\beta_j(t) - \beta_i(t)) \quad \text{Blue C2 system} \]

\[ \dot{\beta}_i(t) = \nu_i + \sigma \sum_j R_{ij} \sin(\rho_j(t) - \rho_i(t)) \quad \text{Red C2 system} \]

- **Order parameter**

\[ r_B(t) = \frac{1}{N} \left| \sum_j e^{i\beta_j(t)} \right| \]

\[ r_R(t) = \frac{1}{N} \left| \sum_j e^{i\rho_j(t)} \right| \]

- **Lanchester**

\[ B(t) = r_B(t)B(t) - r_R(t)R(t) \]

\[ R(t) = r_R(t)R(t) - r_B(t)B(t) \]

C2 capability *sits outside* the combat force

Good C2 ⇒ Good resupply of own and good firepower on adversary
Resupply and internal C2-direct attrition

Attrition undermines ability to couple on the network

- **Kuramoto**

\[
\beta_i(t) = \omega_i + \frac{B(t)}{B(0)} \sum_j B_{ij} \sin(\beta_j(t) - \beta_i(t))
\]

Blue C2 system

\[
\beta_i(t) = \nu_i + \frac{R(t)}{R(0)} \sum_j R_{ij} \sin(\rho_j(t) - \rho_i(t))
\]

Red C2 system

- **Order parameter**

\[
r_B(t) = \frac{1}{N} \left| \sum_j e^{i\beta_j(t)} \right|
\]

\[
r_R(t) = \frac{1}{N} \left| \sum_j e^{i\rho_j(t)} \right|
\]

- **Lanchester**

\[
B^*(t) = r_B(t)B(t) - r_R(t)R(t)
\]

\[
R^*(t) = r_R(t)R(t) - r_B(t)B(t)
\]

C2 capability **resides in** the combat force

Good C2 ⇒ Good resupply of own and good firepower on adversary

Blue C2 system

Red C2 system

Attirion undermines ability to couple on the network
Resupply and internal C2-direct attrition

- **Kuramoto**
  \[
  \dot{\beta}_i(t) = \omega_i + \sigma_B \frac{\chi_B}{N_B} \sum_j B_{ij}(t) \sin(\beta_j(t) - \beta_i(t)) \\
  \dot{\rho}_i(t) = \omega_i + \sigma_R \frac{\chi_R}{N_R} \sum_j R_{ij}(t) \sin(\rho_j(t) - \rho_i(t))
  \]
  Blue C2 system
  Red C2 system

- **“Order” parameter**
  \[
  \chi_B(t) = \left| \sum_j e^{i\beta_j(t)} \right| \\
  \chi_R(t) = \left| \sum_j e^{i\rho_j(t)} \right|
  \]

- **Lanchester**
  \[
  \mathcal{B}(t) = -\kappa_R \chi_R(t) + \eta_B \chi_B(t) \\
  \mathcal{R}(t) = -\kappa_B \chi_B(t) + \eta_R \chi_R(t)
  \]

Attrition undermines coupling on and links of the network

C2 capability is identical to the combat force
Detecting criticality

- Kuramoto order parameter
  \[ r_B(t) = \frac{1}{N} \left| \sum_j e^{i\beta_j(t)} \right| \]

- Fisher information
  \[ \mathcal{F} \equiv \mathbb{E} \left[ \left( \frac{\partial}{\partial \sigma} \log P(X; \sigma) \right)^2 \right] \]
  \[ = \prod_i \int dX_i P(X_i; \sigma) \left( \frac{\partial}{\partial \sigma} \log P(X_i; \sigma) \right)^2 \]
  \[ \mathcal{F}_n \equiv \frac{\mathcal{F}}{\mathcal{F}_{\text{max}}} \leq 1 \]

- Minimum description length
  Proxy: in numerical solution, the minimum number of points required to describe time-series for a given value of coupling.

Time-averaged synchronisation measure, \( r \)
Normalised Fisher information

[\text{Kalloniatis, Zuparic, Prokopenko – PRE subm.}]

\[ K_c = \frac{2}{\pi g(\omega)} \]
\[ \Rightarrow \sigma_c = 0.000398 \]

(Kuramoto, 1984)
A Scenario

Blue – pseudo-hierarchical – headquarters entity covering two task groups of complete networks

Red – pseudo random network

Strategy:
1. Solve ordinary Kuramoto dynamics for criticality indicators as function of coupling
2. Solve Kuramoto-Lanchester dynamics with static network
3. Solve Kuramoto-Lanchester with attrition of network

Does (1) give insight into (2) and (3)?
Complexity Advantage?

Three measures of Criticality

1. Boost in synchronisation at low coupling for Blue – due to complete graph connectivity – gives it early advantage that is maintained

2. Crit. Ind. Blue

Crit. Ind. Red

Coupling

r_B, r_R

t

18

DST Group
Science and Technology for Safeguarding Australia
Attrition of networks - HQ ‘protected’
Attrition of networks - HQ ‘protected’
3. Attrition of networks - HQ ‘unprotected’
Attrition of networks - HQ ‘unprotected’
Attrition of networks - HQ ‘unprotected’

This is the more typical behaviour – unless the ‘full connectedness’ of the Task Groups is preserved, the ‘boost in r’ for Blue is lost.

Conservation of criticality?
Early days ...

- Approach to statistical limit – convergence of criticality indicators?
- Criticality indicators for dynamical network scenarios?
- Stochasticity, Advection – Gaussian and non-Gaussian
- Generalisation to more sophisticated representations of modern combat?

- *Is concentration of mass/increase of number of actors the only way to achieve complexity/criticality?*
**What are we looking for?**

- Collaboration

- Just completed – initial Expression of Interest (EoI) process for start-up collaborations.

- First of many ...
Conclusion

- Complexity – feared but exploitable
- Marrying complex systems dynamical models with mathematical combat models enables generation of new warfighting concepts.
- New DST Strategic Research Initiative “Modelling Complex Warfighting” to pursue this.
- Opportunities for peer-to-peer collaboration with academic partners in ranges of areas:
  - Statistical physics
  - Network Theory
  - High Performance Computing
- Watch this space – or contact me ...