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Modeling and Evaluating Irregular Warfare in the Age of Complexity

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Outline

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  - Fractal Dimension
  - Hurst coefficient and self-similarity
  - Intermittency
- Modeling Complex Warfare
  - ABMs as a supplement to wargames
  - ABMs and complexity
- Criticality and Intermittency of real conflicts

Background

- Current security environment – new challenges
- Traditionally:
  - two forces trying to eliminate one another
  - model focus largely physics-based
  - the primary measures of effectiveness (MOEs) attrition-related, end state-focused
- Current security environment:
  - need for wider range of combat modeling capabilities
  - many competing parties considered
  - attrition of the opponents not always desirable
  - complicated assessment of the simulation outcomes

Measuring Effectiveness

- attrition often the primary measure of effectiveness
  - directly (number of killed, loss-exchange ratio, etc.)
  - indirectly (attrition-based definition of mission success)
  - focus on the end-state only – missing the entire complexity of the system dynamics
- complexity-based measures of effectiveness (CMOEs):
  - measures appropriate for dynamical analysis of a wide range of combat systems
  - the applicability of a given measure is situation-specific
  - none of them universally relevant
  - the list of measures compiled herein not complete

Entropy-Based MOEs

- Shannon definition based on the probabilistic character of the information

$$S = \sum_i p_i \ln \frac{1}{p_i}$$

- Carvalho-Rodrigues (CR):
  - attrition-based, applicable to each force individually
  - not monotonous, peaks for $C/N_{TOTAL} \sim 0.37$
- Spatial Entropy
  - spatial distribution of soldiers relative to a regular grid
  - closely related to the fractal dimension
- Symmetropy
  - proposed on the basis of Shannon entropy
  - measures the symmetry and entropy of a given spatial pattern or shape
  - applied to investigations of critical behaviour
  - pattern symmetries belong to four main classes: vertical, horizontal, centro, and double symmetry

Fractal Dimension

- measure of spatial distribution, quantifies the self-similarity of the distribution
  - clustering properties related to firepower concentration
  - can act as a rough criterion for the transition from linear to nonlinear combat dynamics
- box-counting (or capacity) dimension D_F
  - connects size of a box a, and minimum number $N(a)$ of boxes needed to cover all of the subject units.

$$N(a) = (L / a)^{D_F}$$

Hurst Coefficient and Self-Similarity

- Temporal and spatial correlations in agent velocity (speed and direction) provide additional insights into complex system dynamics
- Correlations:
  - Calculated independently for each velocity component of moving entities
  - Described in terms of the Hurst coefficient *H* and/or the self-similarity parameter (SSP).
- H and the SSP display the same basic pattern
  - scaling between the number of steps and the root mean square distance traveled
  - H or SSP equal to 0.5 -> the motion is random
  - Between 0.5 and 1 the motion is correlated;
  - Between 0 and 0.5 the motion is anti-correlated;
  - Differences most evident in interpretation of SSP values > 1

Intermittency and Point Processes

- A sequence of events (point process) is called *intermittent* if its dynamics sometimes deviate from the usual behaviour
- The intermittency can be measured using the correlation co-dimension C_2 connecting the variance of the data series with ‘box size’ via power law
- An alternative measure of intermittency is the Fano factor α, which connects via a power law the ratio of the variance to the mean with the box size
- Fractal point processes (FPP)
  - $\alpha = 1 - C_2$
  - Medium to high intermittency
- Fractal rate point processes
  - Timing between events is intermittent
  - the relationship between the co-dimension and the Fano factor does not hold.
  - lower intermittency, Fano factor related to the Hurst coefficient H

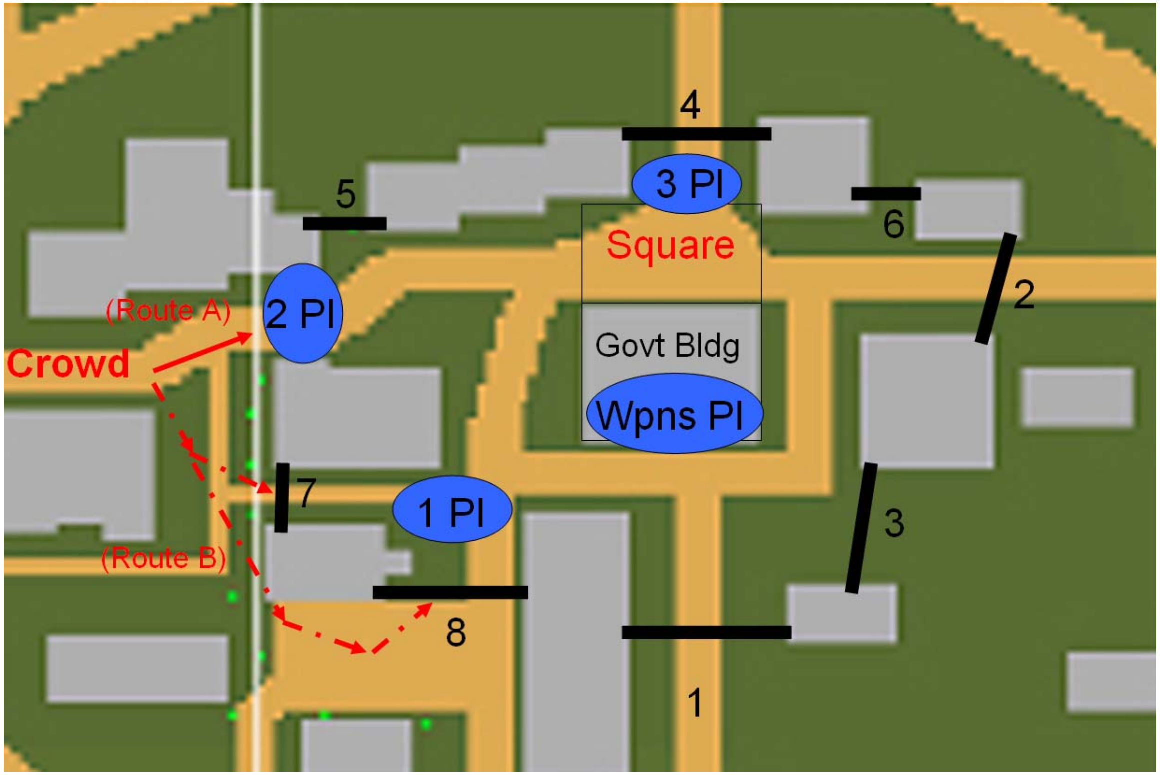
Wargames and Agent-Based Models

- Computer-assisted wargames have become an integral part of option analysis, requirement identification, and operational analysis in general.
- Traditional interactive wargames
  - Human interactors make decisions on behalf of the modeled entities
  - Computer calculates outcomes of engagements, manages detections
  - Ability to react in real time to the changes in the battlefield dynamics and to adapt to opponents' tactics
  - Possible alternative: semi-automated models
- Constructive simulations
  - Entity decision-making completely pre-programmed
  - Entities follow their COAs based on their interactions with other entities, the environment, and predefined decision points.
- Major limitations
  - Reducing complexity of combat by separating the system into subsystems and by making assumptions about human behaviour

Wargames and Agent-Based Models

- An alternative: non-interactive agent-based models (ABM)
  - Focus primarily on the representation of the emergent behaviour
  - The entities represented as autonomous agents making own decisions
  - Complexity of the many-on-many interactions is captured
- Use: as a supplement to or a replacement of traditional wargames
  - LFORT implemented MANA to support wargaming program.
  - Utilized to model hostile crowd management or confrontation.

ABMs in Supplementary Role



- Problems requiring autonomous decision-making not conducive to interactive wargaming
- Example: modeling crowd confrontation using non-lethal weapons
- Crowds difficult to model using interactive wargames:
  - Necessity of global rules of engagement for the crowd in wargames
  - But: Global crowd behaviour is an emergent property arising from complex interactions between crowd members and the security force at a local level.
- ABMs provide bottom-up approach – local interactions drive global behaviour

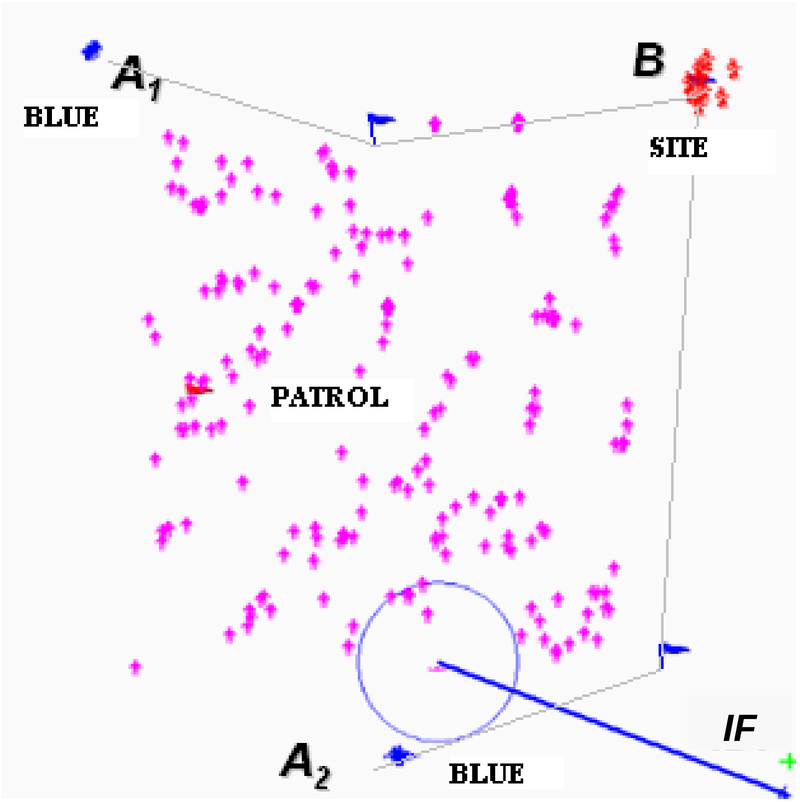
Strengths and Weaknesses of ABMs

- **<u>Wargames:</u>**
- <u>Strengths:</u>
  - expert judgments and insights
  - high fidelity of representing technical details such as weapon characteristics.
- <u>Weaknesses:</u>
  - crowd representation (too artificial given the need for global prescription for the crowd dynamics)
  - scope limitations due to resource requirements (trained interactors, computer stations, …)
  - Time consuming for a single game, replications of a game have problems.

- **<u>ABMs</u>**
- <u>Strengths:</u>
  - efficiency of modeling
  - scope increases
  - better crowd representation consistency in the crowd behaviour
  - state-based definition of dispersal
- <u>Weaknesses:</u>
  - high level of weapon abstraction
  - lack of immediate subject expert insights
  - results of individual runs less reliable

ABMs in Modeling Complex Systems

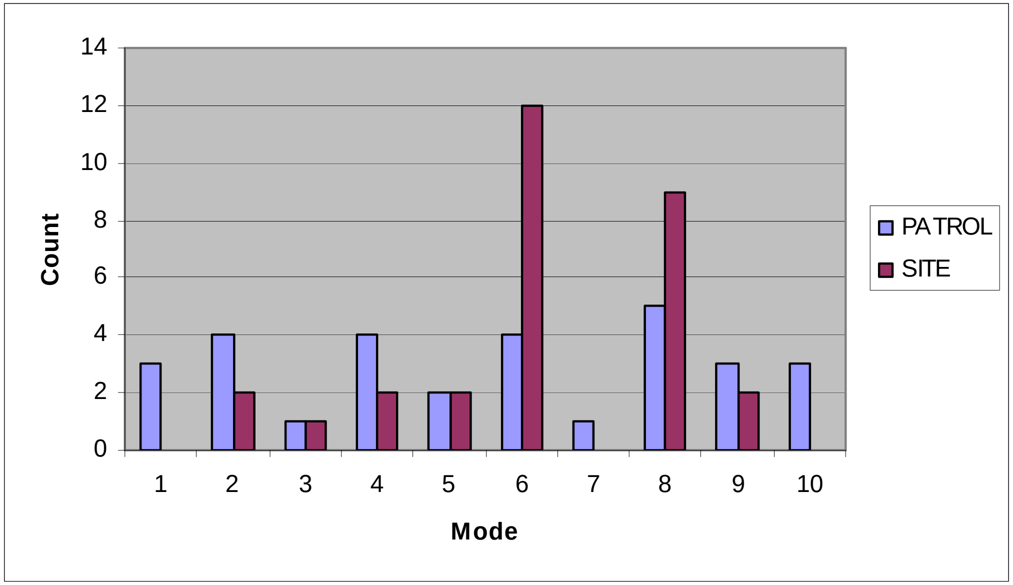
- Developing schemes capable of harnessing the complexity and self-organization of warfare
- Two key factors:
  - awareness of and response of modeled entities to complexity
  - optimization of combatant behaviour in response to this awareness
- The complexity of the analyzed systems quantified using a set of complex systems measures of effectiveness (CMOEs)



- <u>ABMs</u>:
  - convenient environment for exploring such lines of interest
  - represent emergent behaviour in a battle scenario
  - provide controls to vary and optimize the behaviour of combatants [a]

Symmetropy as a Decision Factor

- PATROL members to be identified and eliminated by the indirect fire (IF)
- Determination based on the pre-defined encounter-type signature recognition
- Symmetropy used as the CMOE of choice
- Describes changes in spatial entropic heterogeneity of the enemy force



- Symmetropy modes:
  - defined as dominant combinations of the basic symmetries
  - are a reflection of commonly encountered patterns in the symmetropy matrix
  - labeled consecutively as Mode 1, Mode 2, etc.,
  - distinct signatures observed for SITE and PATROL encounters (Modes 6 and 8)
  - conservative approach – IF used until Mode 6 appeared

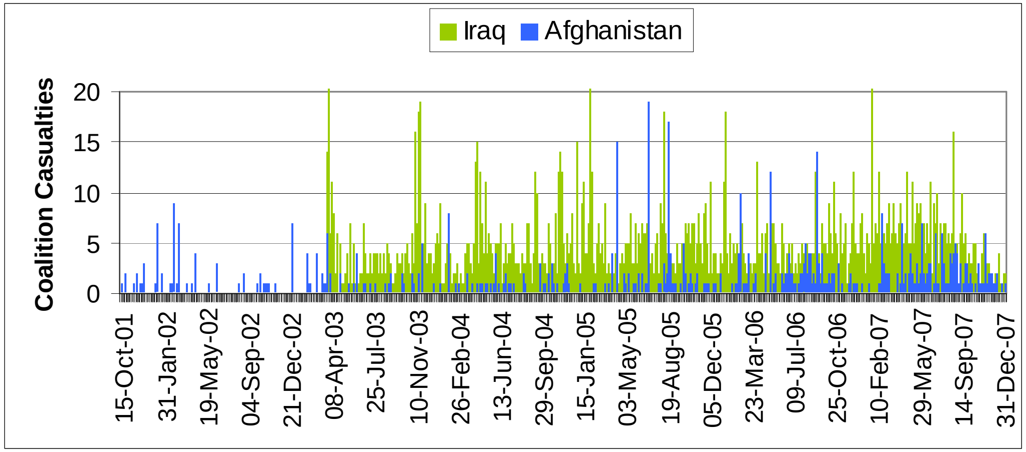
Symmetropy as a Decision Factor

- 35% (47 of 133) of the BLUE force's opportunities to detect and classify the RED site defenders were successful
  - in line with expectations
  - false positives occurred in 3.3% of cases (16 of 485)
  - mission was completed in all runs
  - if no CMOEs, the site defenders were destroyed by IF almost always
  - if the decision to use IF random, the performance was poorer
- CMOE successful in improving mission success for a real-time combat scenario
  - in spite of the sparseness of available data
  - CMOE used in a precursory-like fashion, hinting at the nature of an imminent near-future change in the system dynamics
  - suitable CMOEs might differ from scenario to scenario
- Tracking CMOEs in conflicts seems to have potential for enhancing awareness about the underlying complex system dynamics

Other Use of CMOEs

- Main purpose of CMOEs:
  - Assess complexity in combat models
  - Provide insights into the modeled behaviour
  - Provide quantities for theoretical models
- Application to real systems:
  - Analysis of time series (point processes)
  - Correlations, intermittency, scaling properties
  - Understanding of the informational content of “real” data

Intermittency of COIN



- Look at real conflicts:
  - Afghanistan, Iraq: likely in a near-critical (critical) state
  - Different nature of the two conflicts (correlations in fatality numbers)
  - Exploring relationship between intermittency and criticality in conflict data
  - Is there a difference in the intermittency of fatality numbers for the two conflicts?

Fatalities in Afghanistan

- Previously shown:
  - Afghanistan conflict is discharge event system:
  - fatalities are anti-correlated
  - fatalities obey power law
- Intermittency:
  - co-dimension is $C_2 = 0.36$
  - medium intermittency of fatalities
  - suggesting that the overall system is likely anti-persistent (increase at a given time means decrease for the future)
- Fano factor:
  - calculated value was $\alpha = 0.61$
  - close to expected theoretical value of $\alpha = 1 - C_2 = 0.64$
  - Results consistent with Fractal Point Processes

Fatalities in Iraq

- Previously shown:
  - fatalities are correlated, obey power law
  - Iraq conflict is self-organized criticality
- Intermittency:
  - co-dimension is $C_2 = 0.10$
  - low intermittency of fatalities
  - the overall system may be persistent
- Fano factor:
  - calculated value was $\alpha = 0.38$
  - Far from expected theoretical value of $\alpha = 1 – C_2 = 0.90$
  - Hurst coefficient $H = 0.69$, close to previously estimated value ($H \sim 0.8$)
  - Results consistent with Fractal Rate Point Processes

Point Processes and Warfare

- Example shown – fatalities as a point process
- Yield a significant qualitative difference between the numbers in Afghanistan and Iraq
- Consistent with both conflicts exhibiting characteristics of fractal processes
- Consistent with the IW conflicts being near-critical systems
- Other quantities could be used as well
  - Significant incidents
  - Reconstruction projects
- Correlations between different quantities?
- Characterization of transitions in conflict dynamics?

Summary

- Agent-based models are a viable alternative to interactive wargames for irregular warfare
  - Use as supplement: high fidelity games, efficiency of modeling
  - Use as stand-alone models: explore complexity of combat
- Need for new evaluation means to capture the system dynamics
  - End state-focused, attrition-based assessment is inadequate
- Complexity-Based Measures of Effectiveness (CMOEs)
  - not strictly dependent on attrition
  - able to capture the dynamics of the battlefield including dispersion and re-aggregation of forces
  - provide a means of classifying some combat systems
- Combination of the two provides means to
  - gaining deeper insights into complex nature of combat
  - exploring the harnessing of complexity to optimize the entities' response to the battlefield situations.

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