Transferring Insights from Complex Biological Systems to the Exploitation of Netted Sensors in Command and Control Enterprises

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FUTURE RESEARCH

Biologically Inspired Methods for Agile Command and Control (BIO C2)

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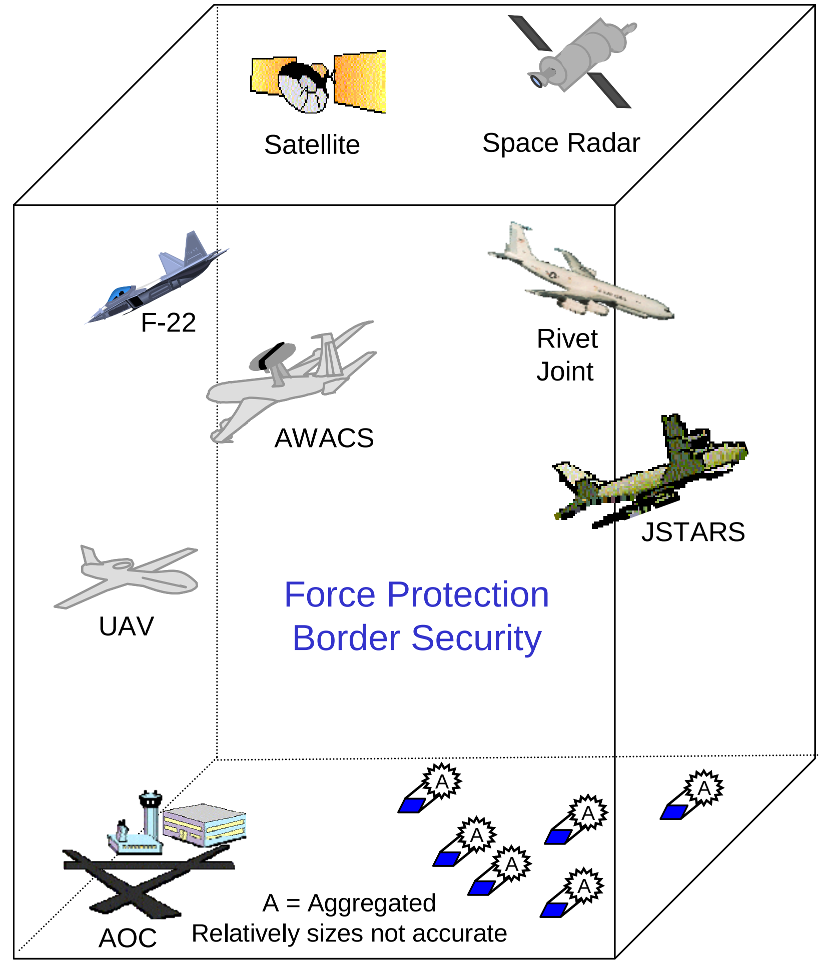
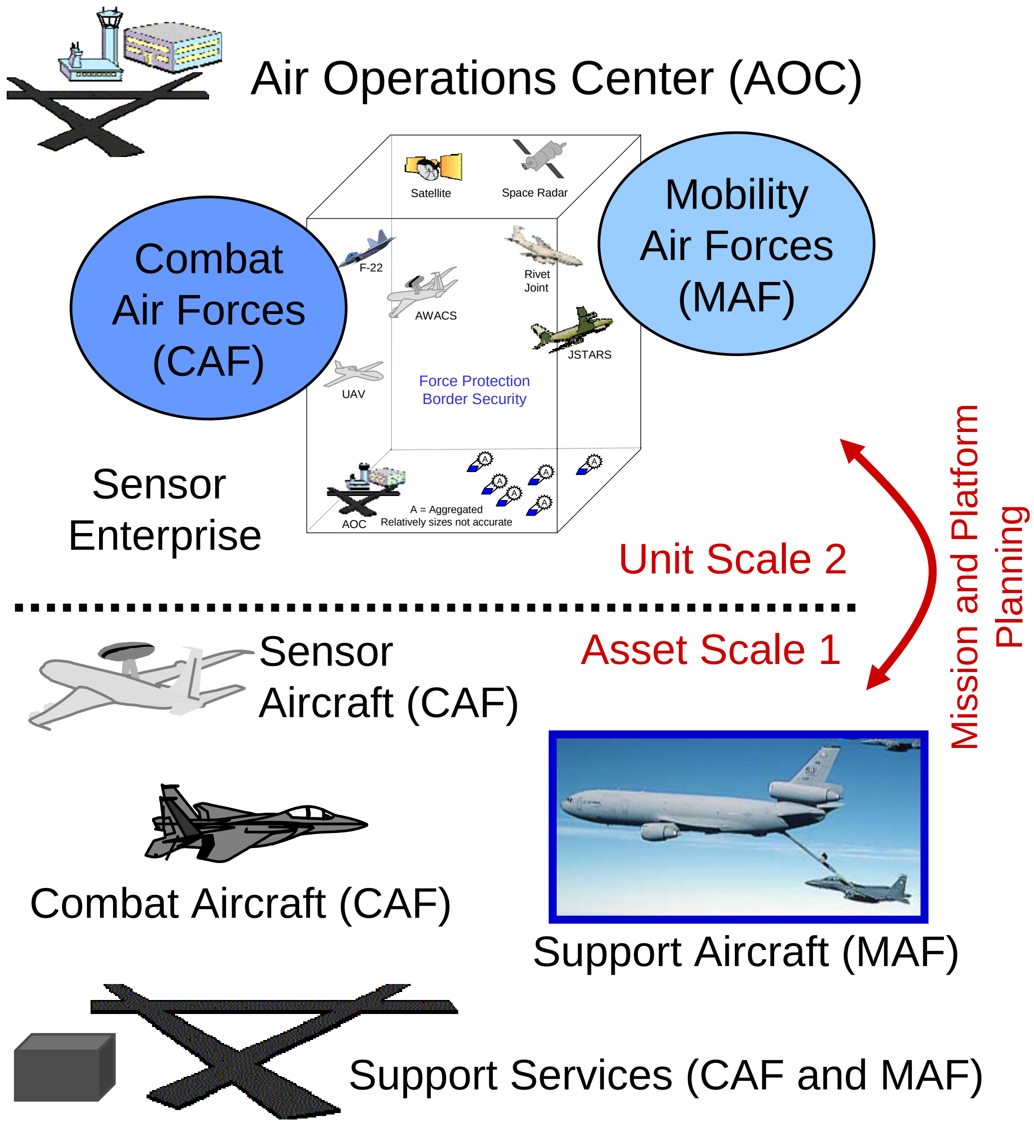
Problem Formulation

- **In a dynamic, complex threat environment, agile responses from Command and Control are needed — especially for cross-scale interaction**
- **Biologically inspired methods based on individual behavior to population response dynamics will be explored for coupling scales**
- **Sensor Enterprise Proof-of-Concept:**
  - The Sensor Enterprise Scales
  - Air Operation Center (AOC) Scales
  - Develop agent-based models to investigate biologically inspired methods for coupling / exploitation
- **Map threats in the Sensor Enterprise to optimal scale coupling method for agile response capability**
- **Extension to other domains (disaster response, distributed operations)**



"Sensor Enterprise"

Scales in the Air Operations Center



- **Multiple scales in AOC**
  - The Asset Scale (TCT Scale 1)
  - The Unit Scale (ATO Scale 2)
- **The Asset scale includes:**
  - National Assets
  - Combat Air Forces - CAF (e.g. F-15, AWACS, etc.)
  - Mobility Air Forces – MAF (e.g. KC-10, KC-135, etc.)
- **The Unit scale includes the controlling organizations**
- **The ATO and TCT have distinct cycle times**

ATO - Air Tasking Order
TCT - Time Critical Targeting

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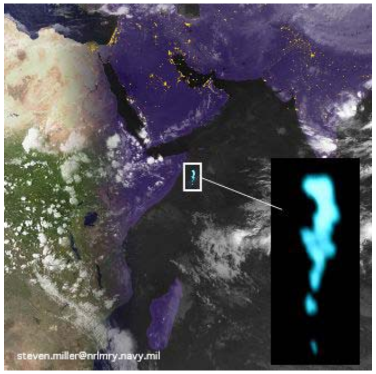
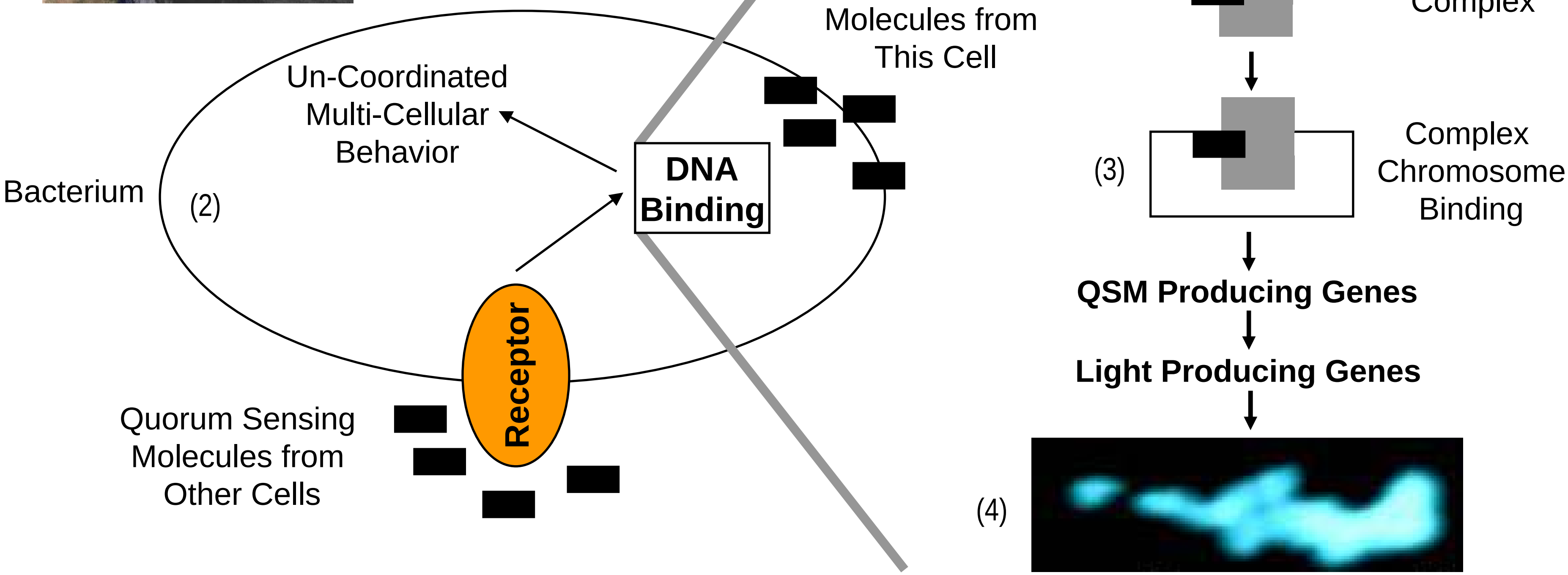
Technical Idea - Example: Multiple Scale Biological Inspired Methods for Command and Control



Bacterial "Milky Sea"
Distributed cell-to-cell communication or quorum sensing, and coordinated light production (1)



Bacteria / Microalgae Bloom

1) Haddock, S. and Case, J. 2006. University of California at Santa Barbara.
2) Camilli and Bassler. 2006. Science 311:1113-1116.
3) Ward et al. 2001. IMA Journal of Mathematics Applied in Medicine and Biology 18:263-292.
4) Miller et al. 2005. Proceedings of the National Academy of Sciences 102(40):14181-14184.

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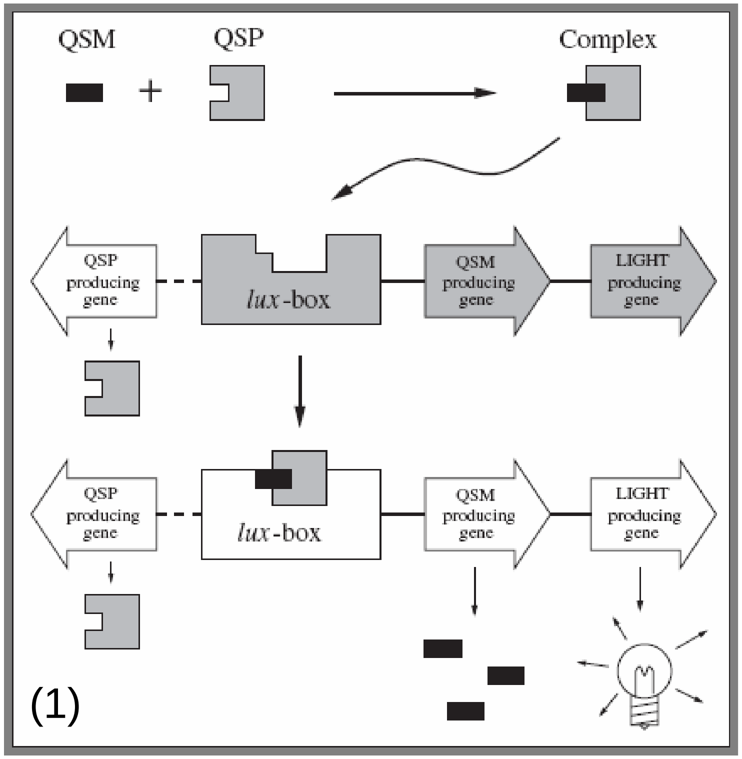
Mathematical Description of Quorum Sensing and Extension to Netted Sensors



(1)

1. Population Model: Differential Equations (Deterministic)

Up-Regulated (N_u) and Down-Regulated (N_d) States:

$$\frac{dN_u}{dt} = r(\gamma - 1)N_u F(N_d + N_u) + \alpha G(A)N_d - \beta N_u$$

$$\frac{dN_d}{dt} = r(N_d + (2-\gamma)N_u)F(N_d + N_u) - \alpha G(A)N_d + \beta N_u$$

Cell Division *Growth Rate* *Complex Formation*

α – *Formation Rate of Up-Regulated State*

β – *Breakdown Rate or Dissociation of the Complex*

Concentration of Extra-Cellular QS Molecule (A):

$$\frac{dA}{dt} = K_u N_u + K_d N_d - \alpha G(A)N_d - \lambda A$$

Disappearance Rate

Up- and Down-Regulated Rate *QSM Complexed*

2. Extended to Sensor Mote Field (3):

$N_u + N_d = N_T$ = constant

$$P = \frac{N_u}{N_T}$$

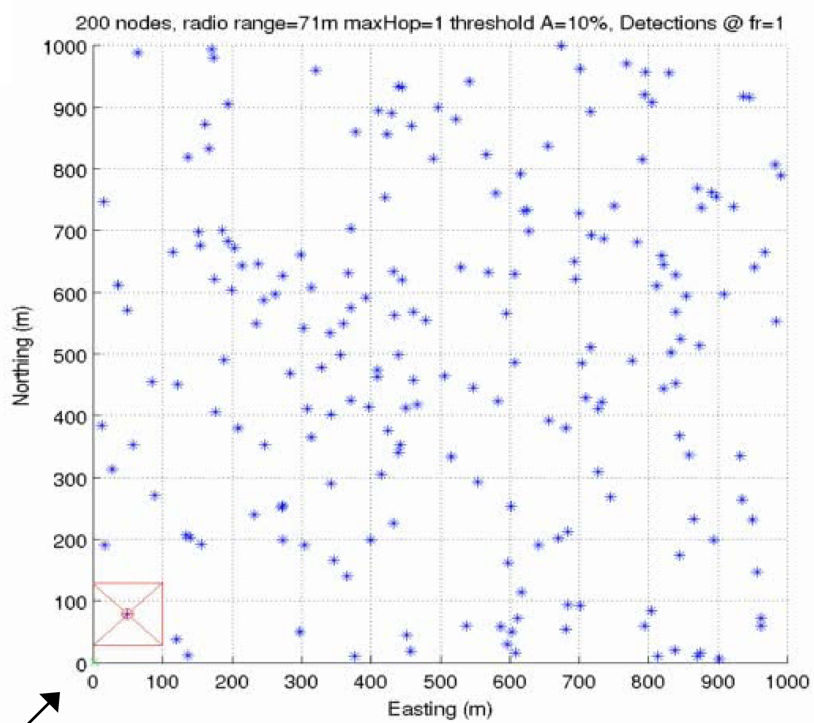
D = Probability of Hit on Single Sensor

$$\frac{dP}{dt} = \alpha A(1-P) - \beta P + \varphi DP$$

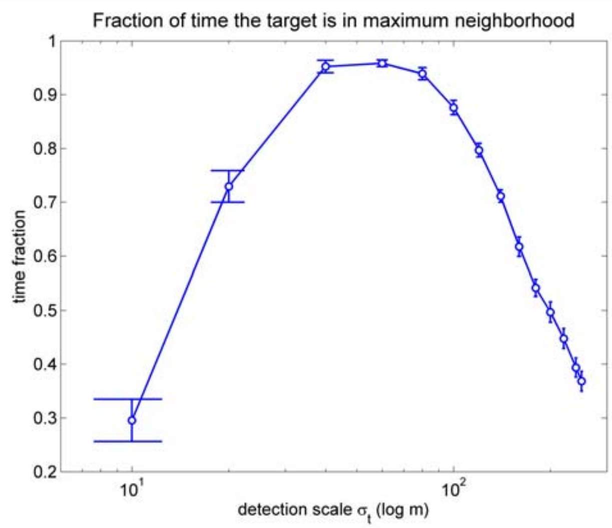
$$\frac{dA}{dt} = K_u P + K_d(1-P) - \alpha A(1-P) - \lambda A$$

1) Ward et al. 2001. *IMA Journal of Mathematics Applied in Medicine and Biology* 18:263-292.

Application to Acoustic Sensor Mote Field



MITRE Motelab Testbed



3. Probability of Sensor Detection (P_d)

$$P_d = \tfrac{1}{2}\exp\left(-\frac{\| x_s - x_t \|^2}{2\sigma_t^2}\right)$$

4. Quorum Sensing Concentration or Shared Information

$$A_k(t) = \tfrac{1}{2} A_k(t-1) + \tfrac{1}{2N_k} \sum_{m \in neighborhood\, k} u_m(t-1)$$

$$P\left(u_k(t)^- = 1 \mid u_k(t-1) = 1, A_k(t)\right) = 1 - \beta$$

$$P\left(u_k(t)^- = 0 \mid u_k(t-1) = 1, A_k(t)\right) = \beta$$

$$P\left(u_k(t)^- = 1 \mid u_k(t-1) = 0, A_k(t)\right) = \alpha A_k(t)$$

$$P\left(u_k(t)^- = 0 \mid u_k(t-1) = 0, A_k(t)\right) = 1 - \alpha A_k(t)$$

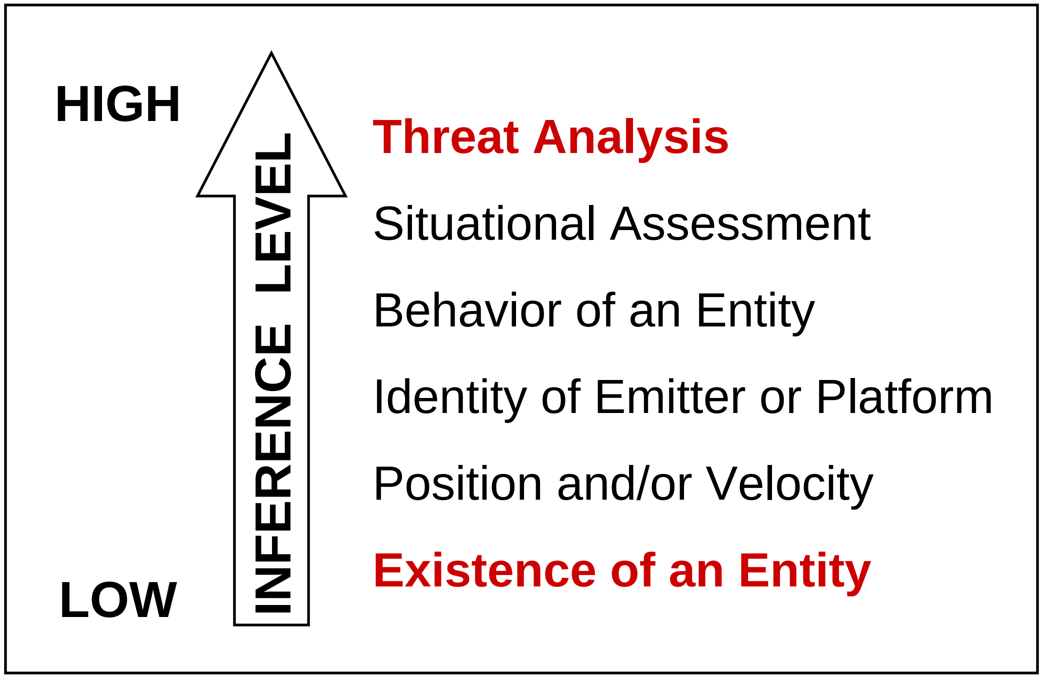
$$u_k(t) = \max(u_k(t)^-, h_k(t)).$$

State Changes:

α – QS Parameter

β – Forgetting Rate

Relationship to JDL Fusion Levels



JDL Data Fusion Level 3

Joint Directors of Laboratories (JDL)
Data Fusion Working Group

JDL Data Fusion Level 1

Biologically inspired methods can be applied to all fusion levels

Proof-of-Concept: Application to the mote sensor field (fusion level 1)

Research: Application to the Sensor Enterprise (fusion level 3)

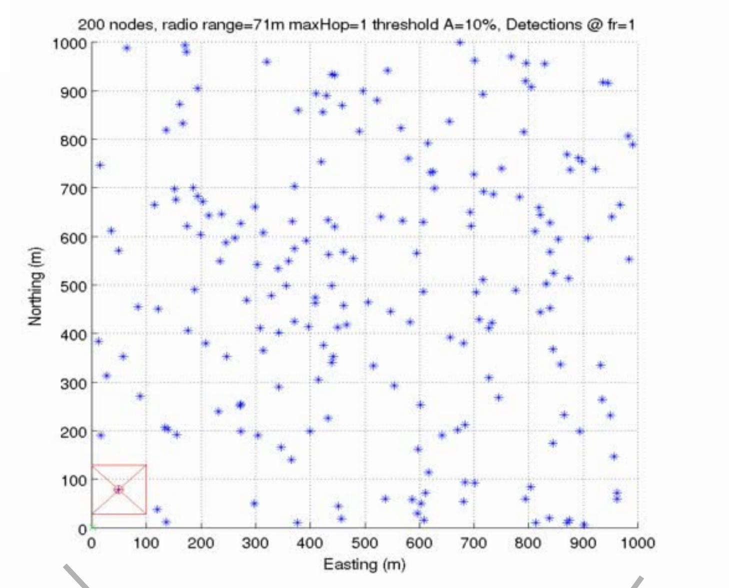
Hall and Ilinas. 1997. An Introduction to multisensor data fusion. Proceedings of the IEEE 85(1):6-23.

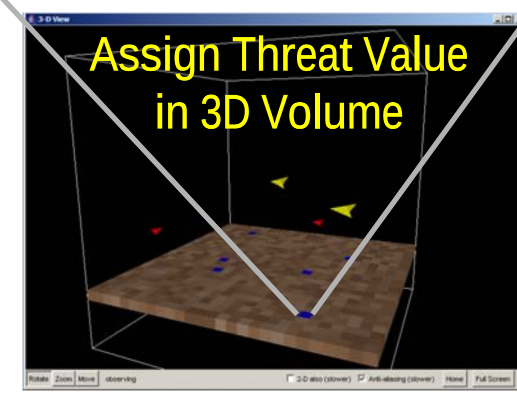
Technical Proof-of-Concept

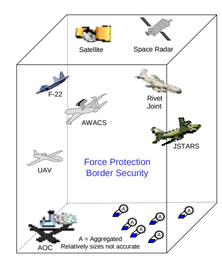
- **Bacterial quorum sensing molecule (QSM) algorithm**
  - Based on the non-linear dynamics observed at the population scale
  - Calculate the QSM level or information sharing level at each acoustic node
  - Neighboring nodes make use of this QSM level to calculate their level
- **Can be applied to all JDL levels / Moving Target Indicator Exploitation**
  - **Proof-of-Concept:** Mote field scale
  - **Future Work:** Sensor Enterprise scale
  - Measure performance with standard engineering tools
  - Validation with specific test cases / applications
- **Agent-Based Modeling (ABM)**
  - The threat value for different parts of the environment can be determined (uncoordinated collaboration)
  - The QSM can be viewed as a token of information being passed around (coordinated collaboration)
  - Map threats to optimal coupling / exploitation method

Detect Threats in Mote Field

MITRE Motelab Testbed







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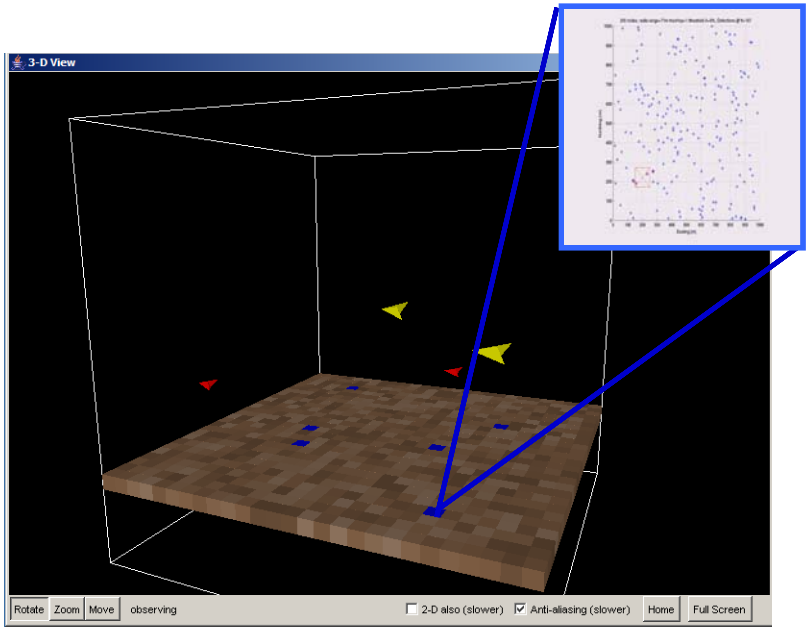
Scenario for Force Protection and Border Security

Uncoordinated Collaboration

- **Agent-Based Modeling Scenario for Border Security**
  - **Protect ground bases (blue squares)**
  - JSTARS/space radar detects moving target on the ground and assigns a **"threat value"** to the area where detected
  - A UAV responds to this **"threat value"** and changes its field of view, obtaining video of the target—the **"threat value"** is further increased
  - In response to the high **"threat value,"** AWACS attempts to provide radio frequency emitter data for the target (Electrical Support Measures, ESM)
  - In response to the high **"threat value,"** the aggregated (A) motes field provides increased power for the acoustic sensors, which can distinguish small targets from large targets
- **Probabilistic models with appropriate structure for each asset**



Transition Opportunities

- **Sensor Networks, Air Operations Center Netcentric Enabled Command and Control**
- **Disaster Response (e.g. DHS)**
  - Simulation environment to experiment with “marking” and “reading” the environment
  - Facilitate single scale “communication” (e.g. first responders)
  - Facilitate cross-scale “communication” (e.g. local and state/federal representatives)

Uncoordinated Collaboration

(1)

Four Quorum Sensing-like Molecules?

1) The Federal Response to Hurricane Katrina Lessons Learned. February 2006.

State-of-the-Art: Biologically Inspired Methods

- "Big challenges for future computing systems have **elegant analogies and solutions in biology**, such as the development and evolution of complex systems, resilience and fault tolerance, and adaptation and learning." Towards 2020 Science
- "These different strategies of change are not independent but operate at different time scales and either at the individual or population level. We propose and interdisciplinary exploration of adaptation, learning, self-organization, evolution, and other **emergent functionalities of living systems for the design of new computing models**, algorithms, and software programming paradigms." ERCIM News: Emergent Computing

- Signal Processing / Speech Recognition
- Evolutionary Computation (e.g. search algorithms)
  - Genetic Programming (e.g. evolving code)
  - Genetic Algorithms (e.g. mutation for variation)
  - Evolutionary Programming (e.g. evolving code with mutation)
- Neural Networks (e.g. estimation / pattern recognition)
- SWARM Intelligence (e.g. robustness)
- **Cross scale-interaction or coupling**

- "**Integrating artificial life simulation with synthetic biology**" a session at the *International Conference on the Simulation and Synthesis of Living Systems* conference, better known as *Artificial Life X*. ALIFE X, June 3-7, 2006

Emmott, S. Towards 2020 Science. 2006. Microsoft Corporation.
Plexousakis, D. 2006. Bits, Atoms and Genes Beyond the Horizon. ERCIM News: Emergent Computing 64.
Mateus Rocha, L. et al. (Eds). 2006. Artificial Life X. The MIT Press.

Promising Biological Strategies

- Stem Cell Differentiation
- T-Cell Pathogen Recognition and Reaction (1)
- Cell Pattern Formation (2)
- Cell Division
- Reaction/Diffusion Behavior (skin patterns)
- Apoptosis or programmed cell suicide (3, 4)

Digital (on/off, threshold)

- Stem Cells → muscle
- Immune system response (1)
- Bacterial nitrogen fixation
- Bacterial virulence (5)
- Biofilm production (6)

Analog (proportional, amplified)

- Pulsed response to a steady input (e.g. bacterial enzyme production, 7)
- Chemical concentration gradients cause cell differentiation (2)

1) Parham. 2006. Nature 441:215-216.
2) Basu et al. 2005. Nature 434:1130-1134.
3) You et al. 2004. Nature 428:868-871.
4) Sterritt and Henchey. 2005. FAABS 2004 262-270.
5) Anguige et al. 2004. Mathematical Biosciences 192:39-83.
6) Chopp et al. 2002. Journal of Industrial Microbiology & Biotechnology 29:339-346.
7) Basu et al. 2004. Proceedings of the National Academy of Sciences 101(17):6355-6360;
Weiss. 2006. Synthetic Biology: From Bacteria to Stem Cells. MITRE Technology Program Speaker Series.

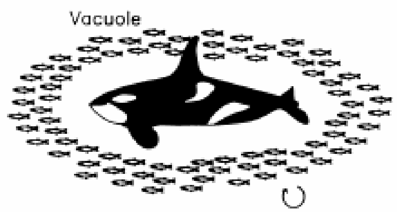
Strategic Relevance

Uncoordinated Collaboration

Direction value (1)

$$= L^{-2} * \left(\sum_{dx=-2}^{dx=-1} \sum_{dy=-2}^{dy=-1} \text{Cell value} (x + dx, y + dy) / \max(dx, dy) \right)$$

(1)



(2)

- **Corporate Thrust on Enterprise System Engineering**
- **Corporate Thrust on Biotechnology / Biosecurity**
- **Agile functionality for conventional & asymmetric threat (3)**

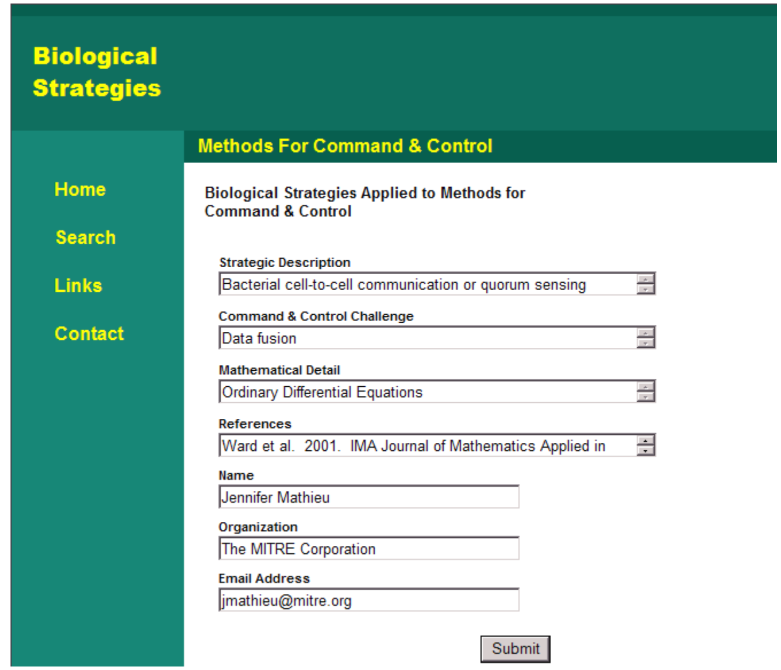
1) Vabo and Nottestad. 1997. Fisheries Oceanography 6(3): 155-171.
2) Charles Maxwell Underwater Video Services. 2002. Sardine run. Permission for non-profit use of movie granted.
3) Cabana, K. A., et al. 2006. Agile Functionality for Decision Superiority. MITRE Product No. MP05B0000043.

Impacts

- **Map threats or disaster-related challenges to optimal scale coupling / exploitation method**
  - Uncoordinated Collaboration (e.g. biologically inspired)
  - Coordinated Collaboration (e.g. passing tokens)
  - Hybrid Approach
    - Uncoordinated
    - Coordinated / Peer-to-Peer
    - Hierarchical

Distributed (Uncoordinated; Coordinated / Peer-to-Peer)

http://sepo1.mitre.org:8080/bstrategies



- **Technique will be beneficial for many multiple scale Enterprise challenges (e.g. disaster response, distributed operations, and data sharing)**
- **Searchable Web interface for biological strategies applied to Command and Control challenges**

References

- Anguige et al. 2004. Mathematical modelling of therapies targeted at bacterial quorum sensing. Mathematical Biosciences 192:39-83.
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- Miller et al. 2005. Detection of a bioluminescent milky sea from space. Proceedings of the National Academy of Sciences 102(40):14181-14184.
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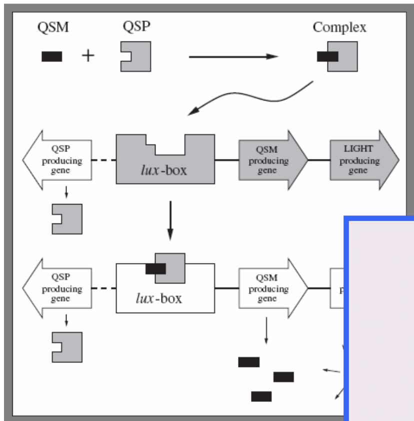
Summary of Technical Approach



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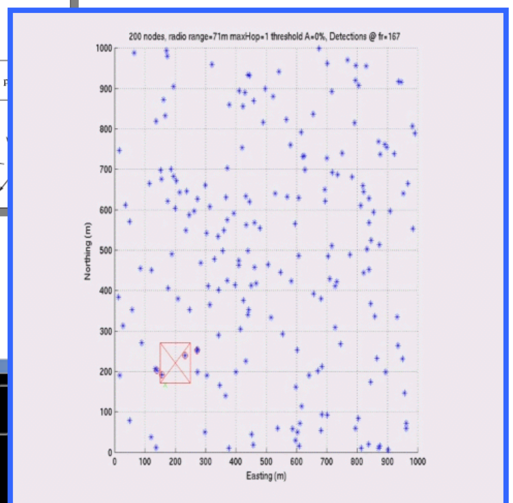

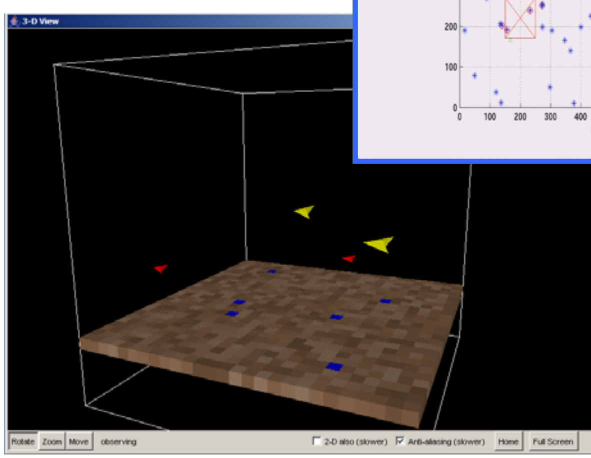

- **Biologically Strategy**
  <u>Example</u>
  Bacterial Quorum Sensing
- **QSM Algorithm**
  <u>Proof-of-Concept</u>
  Mote Sensor Field
- **Agent-Based Modeling**
  <u>Future Work</u>
  Sensor Enterprise
  Disaster Response

1) Ward et al. 2001. *IMA Journal of Mathematics Applied in Medicine and Biology* 18:263-292.