



Command and Control of Teams of Autonomous Units

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Autonomy and Command and Control (C2): Definitions for Our Purposes

Autonomy: Mobile robots, including autonomous vehicles, can be characterized by three tasks they perform – sense the environment around them; make a decision based on a predefined task and the environment it senses; and finally act in order to perform the predefined task by adapting to its environment [IEEE-Robotics 101].

- A mobile robot is comprised of sensors, autonomy algorithms and actuators
- Autonomy is therefore the decision making based on the task and the robot's model of the environment.
- Cooperative Autonomy is the ability of a group of AUS to collaboratively make task assignments and interpret and execute the intent of the system operator [Brizzolara 2011]



Autonomy and C2: Definitions for Our Purposes

"Command is the doctrinal assignment of authority". One must possess a measure of command in order to exert control, which is defined as "...guiding the operation". Control of forces can be described through the following contributions that a commander may make to an operation [ADM Willard 2002]

- ▼ Maintain alignment: The commander must ensure that all decisions remain aligned with the operation's mission and the commander's intent.
- ▼ Provide situational awareness: The commander must assess the status of plan execution constantly, utilizing a common operational picture (COP).
- ▼ Advance the plan: The commander must monitor the status of plan execution against the plan's timeline.
- ▼ Comply with procedure: The commander oversees compliance with warfighting procedures to avoid mistakes (e.g., blue-on-blue engagements or collateral damage) and achieve efficiencies.
- ▼ Counter the enemy: The commander must be responsive to emerging intelligence, surveillance, and reconnaissance information that differ significantly from expectations.
- ▼ Adjust apportionment: Changes to asset availability or changes to requirements and priorities may require reapportionment of assets.

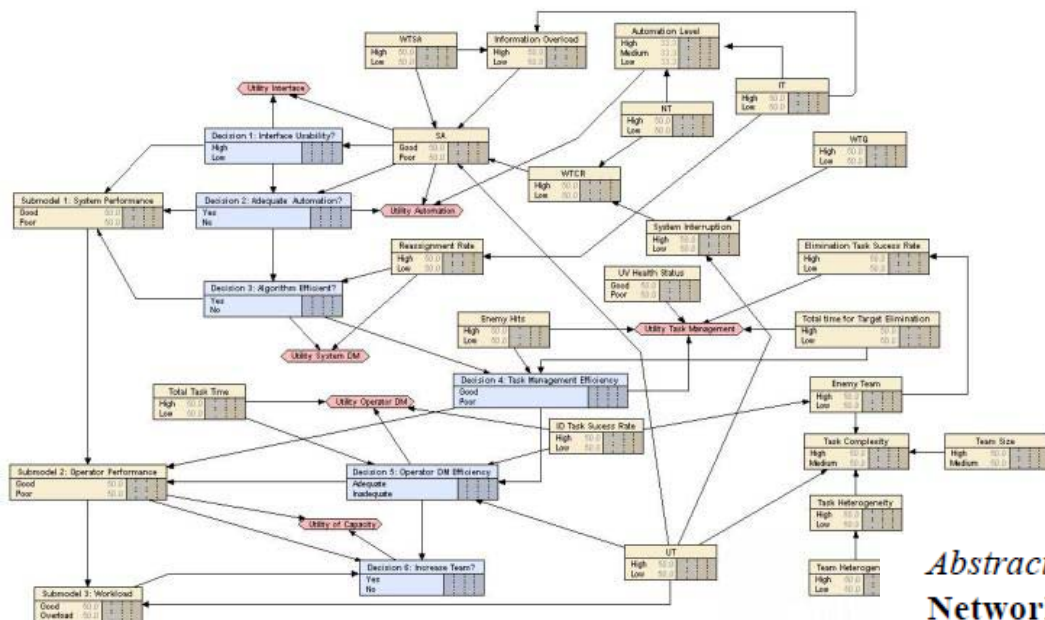
Requirements for C2 of AUS

- ▼ Communicate task and commander's intent to AUS. Commander must have confidence that AUS can accomplish mission and that all tasks and constraints are understood.
 - Vocabulary of tactics
 - Adapt to new tactics and constraints efficiently and effectively
 - Seamlessly adjust to team composition and geometry
- ▼ Maintain SA at appropriate level of abstraction
 - Ability to control multiple AUS in dynamic team arrangements
 - Recognize the difference between correct and aberrant behaviors relative to tasks and constraints provided. When must new tasking be given.
 - Recognize opportunities and requirements for changes to resource apportionment.

Sparse Supervisory Control

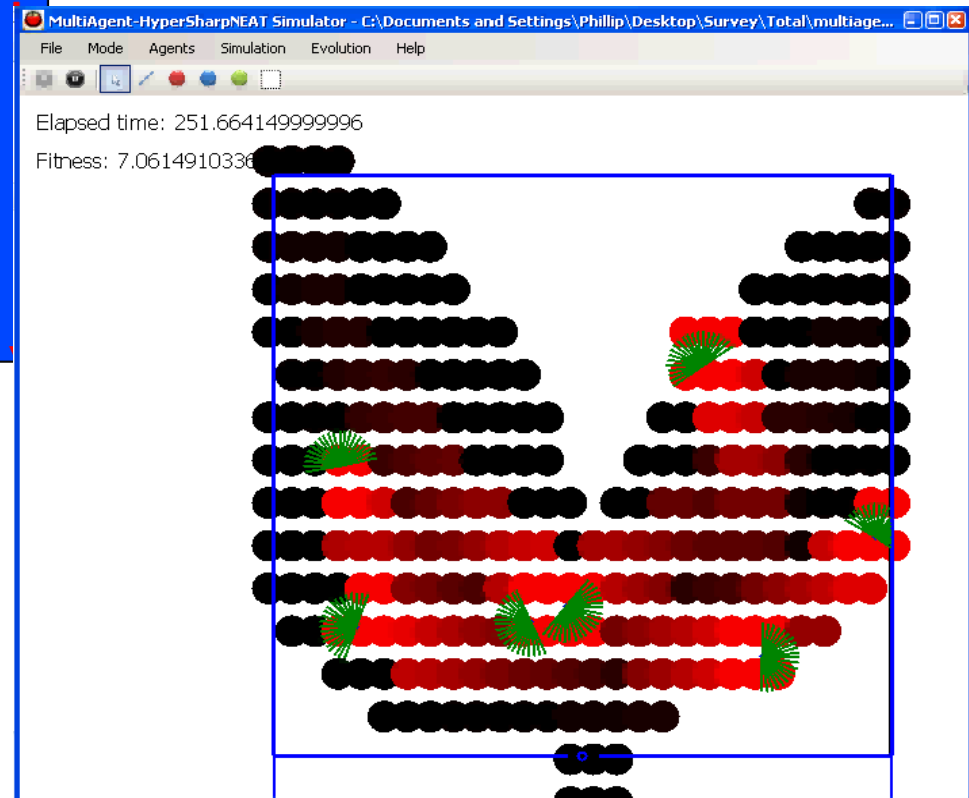
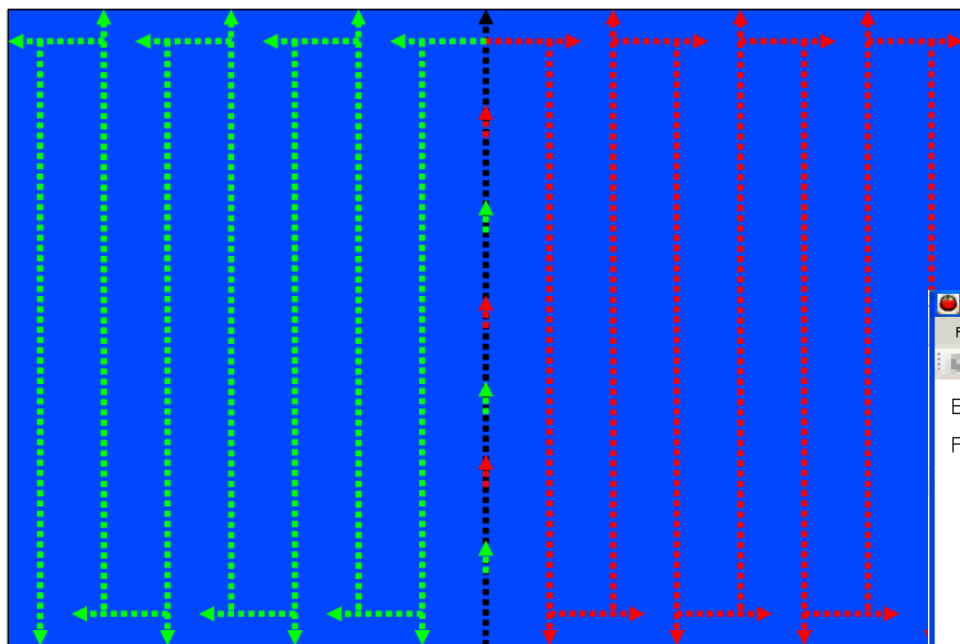
- 1 human operator controlling many (20-30+) AUS
→ 'inverting' the ratio
- Operator role now becoming *supervisory*:
 - issue orders & supervise: versus manually direct, navigate, survey, investigate, etc.
 - occasionally intervene: approve/disapprove of actions, change action/goals
 - In general; monitoring the actions of the AUS, stepping in when necessary
- Situation awareness important for both operator and AUS
- Human recognition of proper or aberrant behavior by the AUS

Situational Awareness and Operator Load

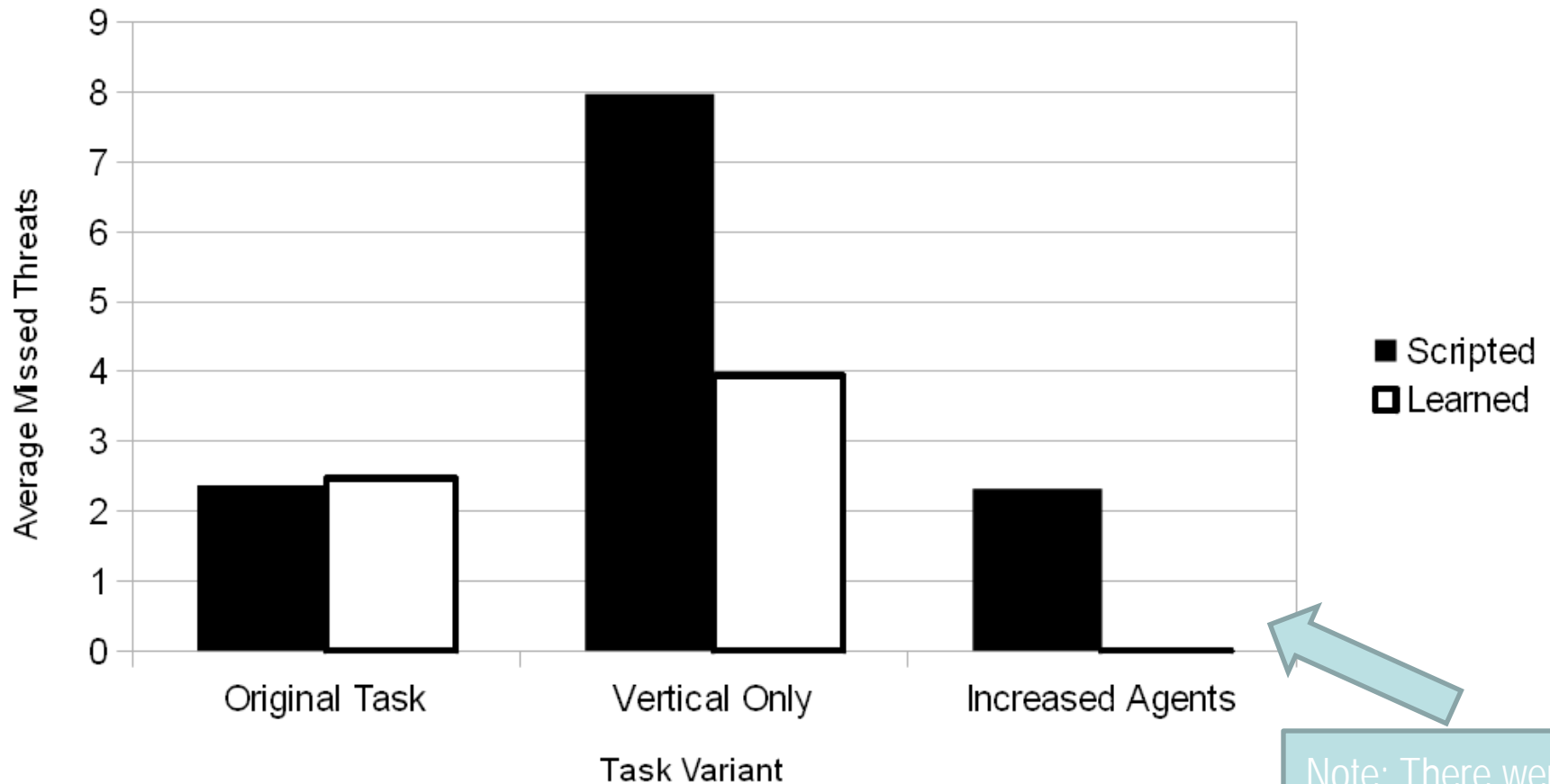


Abstract—The Department of Defense's future vision for Network Centric Operations (NCO) will increase combat power by networking relevant entities across the battlefield. This will result in highly complex mission scenarios in which the operator's workload will be easily overloaded if the system is not designed to support the mission requirements. New technologies for these complex command and control environments are currently being developed. Evaluating the adequacy of a particular technology for specific mission requirements is critical for military decision makers. This paper will introduce a new approach to model operator and system performance.

Scripted Tactics vs Multi-Agent HyperNEAT

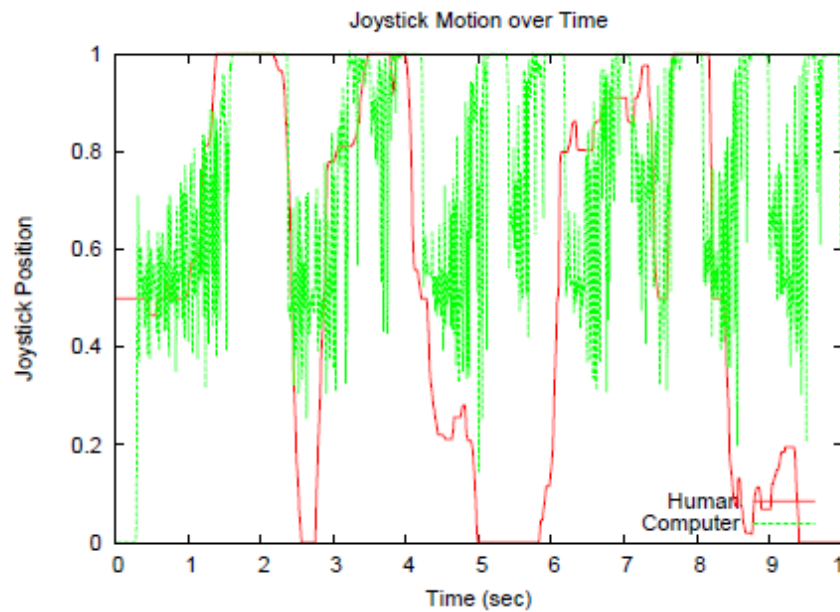


Experiments with HyperNEAT

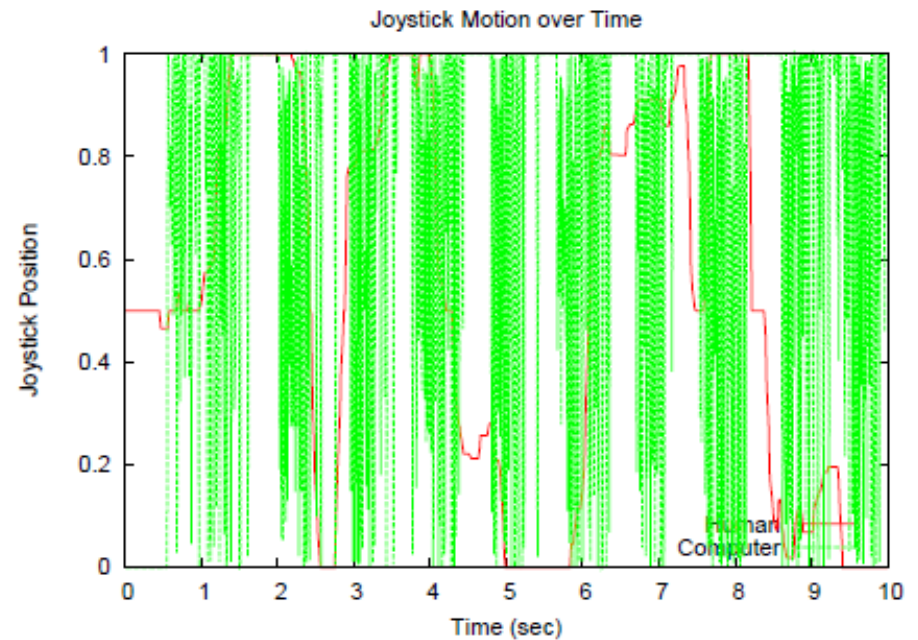


Note: There were 0 missed threats for this case.

Human Recognition of Behavior

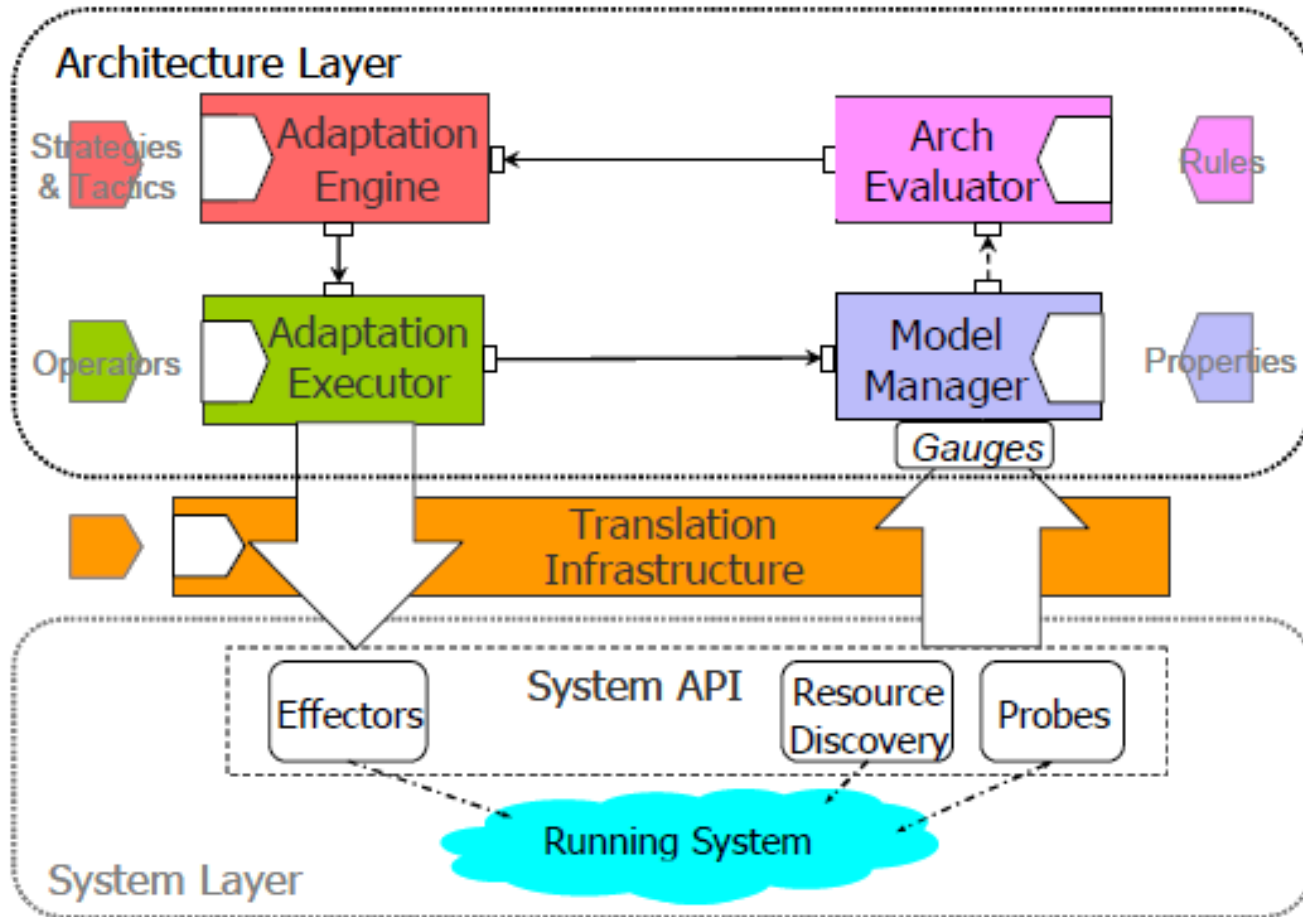


Observational + Experiential



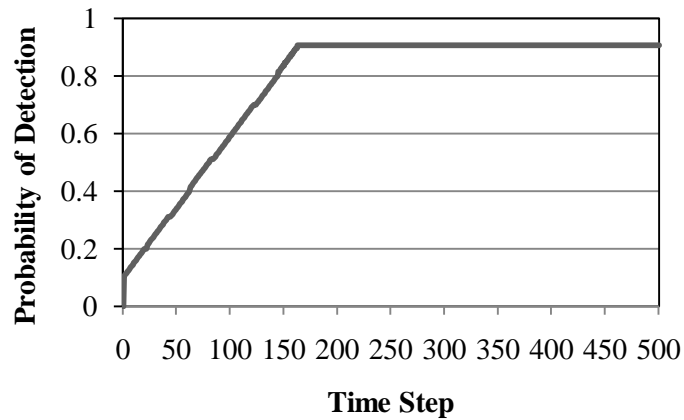
Experiential Only

AUS C2 Enhanced by Rainbow



Cheng, Garlan, and Schmerl, "Making Self-Adaptation an Engineering Reality", In Self-Star Properties in Complex Information Systems, Springer-Verlag, 2005

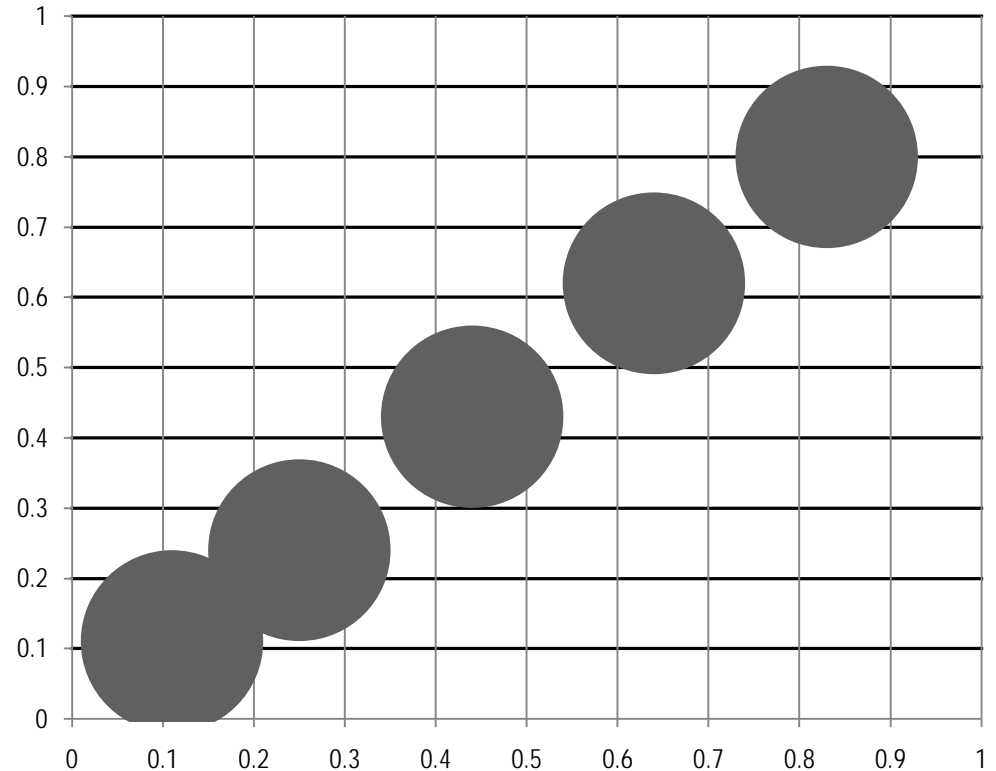
Emergent Behavior Using Rainbow



```

strategy BruteDetection
[styleApplies as cViolation] {
  t0: (overlapExists) -> move();
  t0a: (default) -> done;
}
t1: (cViolation as ! overlapExists) -> enlistAUS() {
  t1a: (overlapExists) -> move();
}

tactic enlistAUS () {
  condition {
    // Probability of detection is below a threshold
    ModelAlt.probabilityDetection(M.components) < M.MIN_PDTECT;
    // there should be enough available AUS
    ModelAlt.availableServices(T.AUST) >= 1;
  }
  action {
    set aus - Set.randomSubset(ModelAlt.findServices(T.AUST), 1);
    for (T.AUST freeAUS : aus) {
      S.activateAUS(freeAUS);
    }
  }
  effect {
    // Probability of detection rising should result
    ModelAlt.probabilityDetection(M.components) >= M.PDTECT;
  }
}
  
```



Implications for Cyber-Physical Systems

- ▼ Large Complex CPS result in “Human On-the-Loop” rather than “in-the-loop”.
 - Sparse Supervisory Control
 - Command and Control
- ▼ We are likely to require the use of machine learning.
 - Adaptation == under-specification
 - Trust comes from experimentation and observation. Is that enough in a safety critical application.
 - How will techniques of proving properties of composed systems of black-boxes work when the boxes adapt and affect each other.
- ▼ Observation of machine optimized policies.
 - AUS teams are composed and will exhibit cooperative autonomy
 - Commanders need to understand when to step in