
# Future C2 Architecture for Distributed Execution: A Case Study of Intelligent Particles

Georgiy Levchuk
Nathan Schurr
Darby Grande
Webb Stacy

Presented at 2009 ICCRTS

Date: 06/16/2009

www.aptima.com
Boston ▪ DC ▪ Dayton

© 2009, Aptima, Inc.

APTIMA
HUMAN-CENTERED
ENGINEERING

# Agenda

- Motivation
- Problem
- Approach
- Results

APTIMA HUMAN-CENTERED ENGINEERING

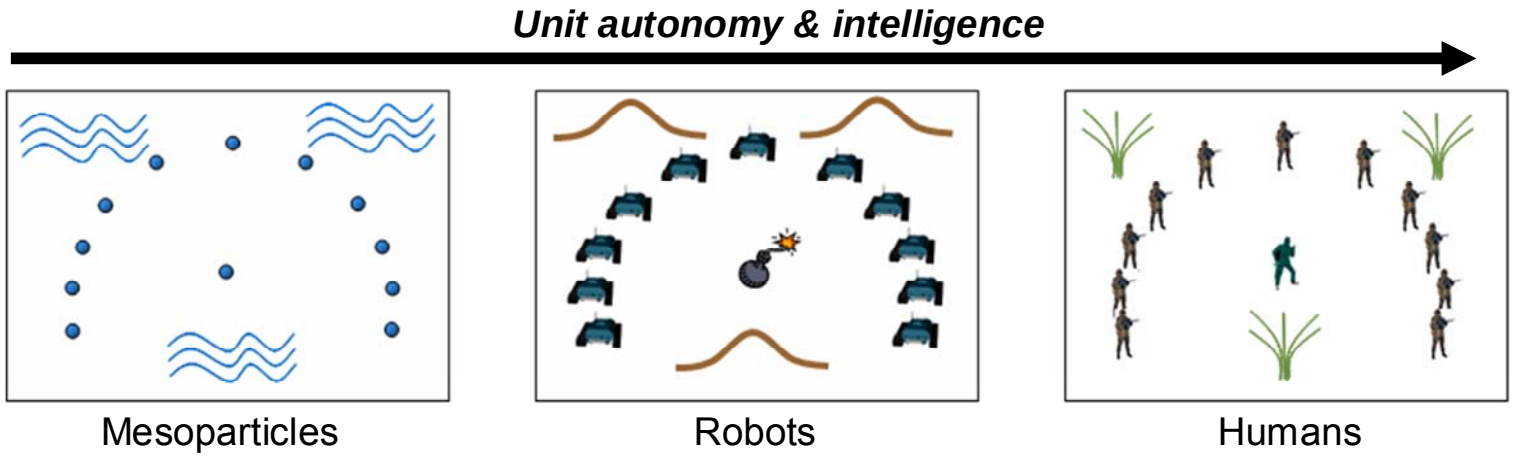
# How to Study Emerging C2 Concepts

- Live experiments
  - Too expensive, impossible to test all architectures
- Virtual (human-in-loop) experiments
  - Hard to create incentives similar to real world
  - Experience interferes with objective performance benefits
- Constructive simulations
  - Questionable validity and generalizability

- Conclusions:
  - Need domains exhibiting all principals and challenges of controlling, coordinating, and synchronizing the operations

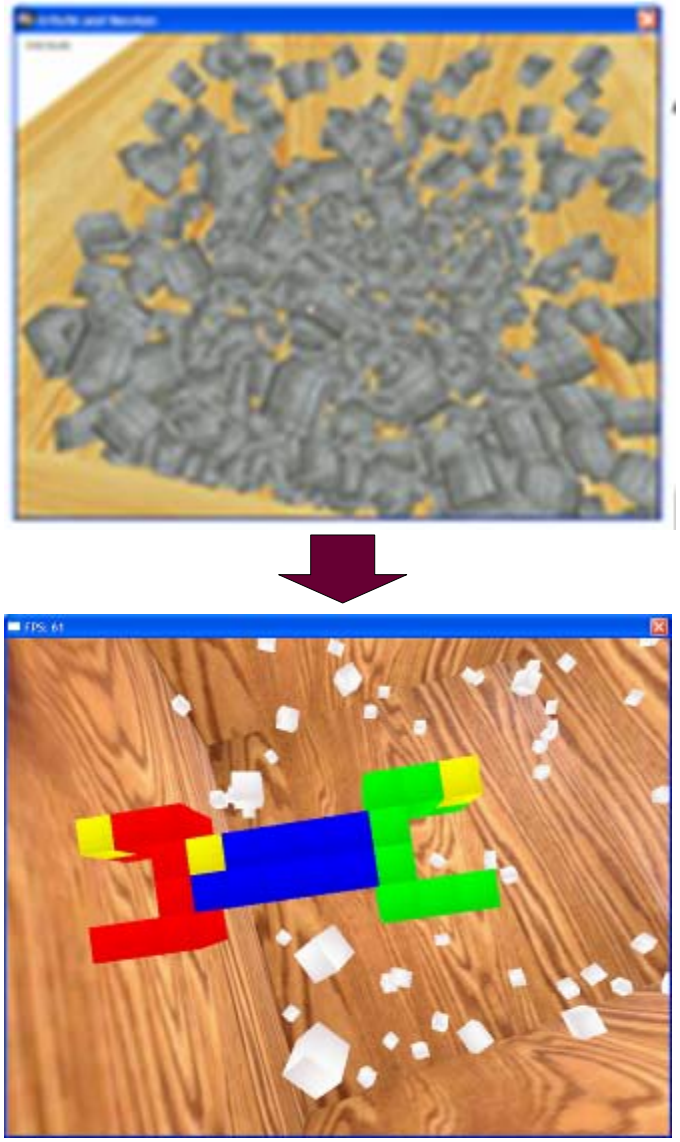
# Domains for C2 Studies

- Appropriate domain for analyzing novel C2 structures and processes is automated control of unmanned heterogeneous vehicles
- In our paper, we describe a case study in a similar domain --- automated assembly of mesoparticles
  - less prone to established constraints
  - is futuristic enough to excite the research community to think of alternative C2 organizations



# C2 Case Study Problem: Domain

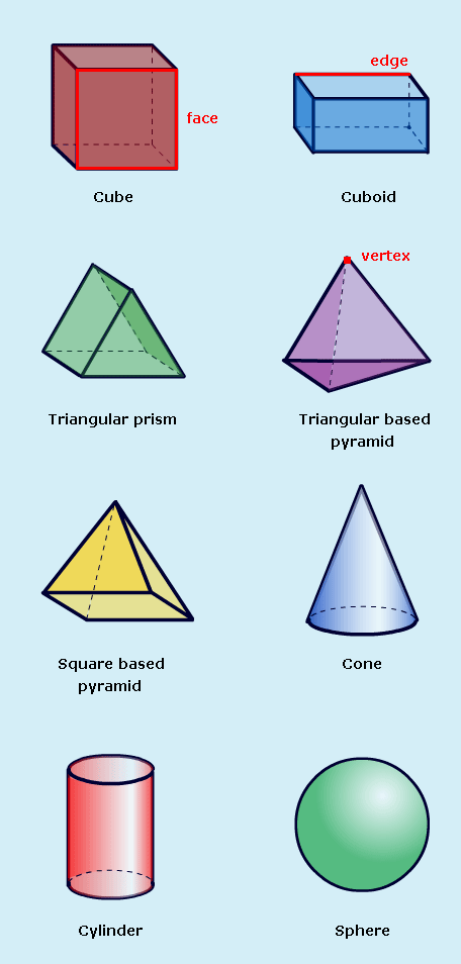
- Given disorganized particle mass…
  - Particles with various intelligence, computation, and motion capabilities



- …obtain particle shape that satisfy required objectives/goals
  - Appearance
  - Physical properties

# Shapes of Interest

- From simple…




- …to complex

*fixed wrench*

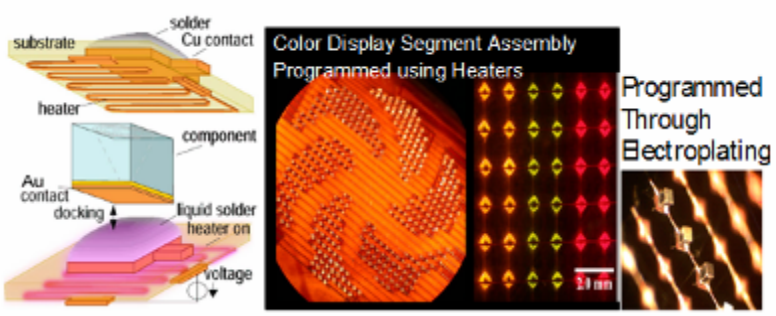
*internal structure*

*adjustable wrench*

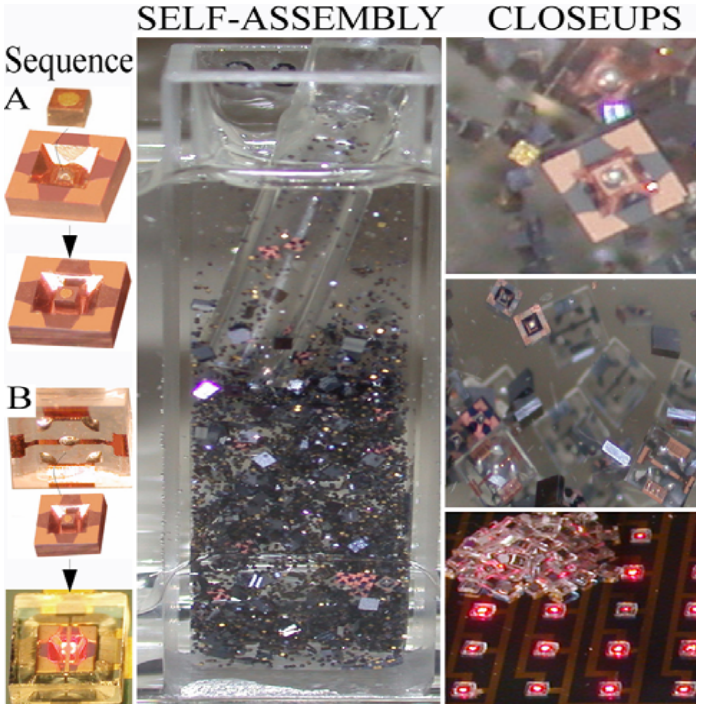
*complex surface*

# Physical Particles and Traditional Assemblies

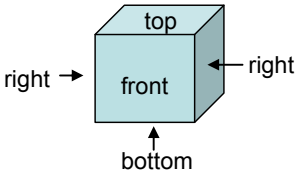
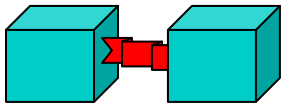
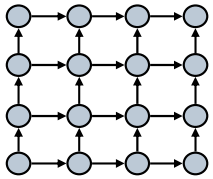
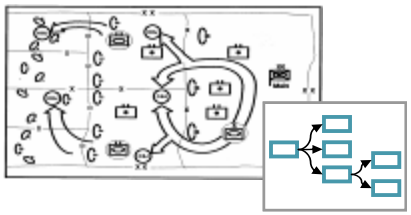
- There are physical meso-particles fitting research goals
  - Communication – wired and wireless
  - Computational power – imprinted circuits
  - Energy and memory storage (limited)




- Traditional assembly planning techniques rely on the skeleton or scaffolding design
  - Appropriate for a predefined fixed set of shapes
  - Cannot design “any shape” – need new scaffolding
  - Cannot handle competition
  - Cannot adapt



# How Assemblies Relate to C2 (1)

| Shape Assembly | | | Military C2 | |
|---|---|---|---|---|
| particles |   | members | soldiers, commanders |  |
| attraction, connection, communication, kinematics |  | actions | (non)kinetics, haptics, communication, kinematics |  |
| Appearance, shape, kinetics properties |  | goals | state of environment, mission objectives, unit positions |  |
| assembly sequencing and role allocation |  | plans | task plans and task-to-resource allocation |  |
| assembly sequencing and role allocation | | execution | distributed, coordinated | |

# How Assemblies Relate to C2 (2)

**Shape Assembly**

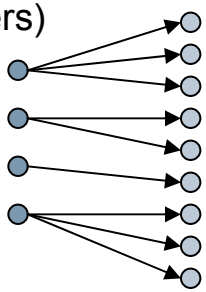
Reactive particles execute connections
Active particles determine what connections need to be executed

organization

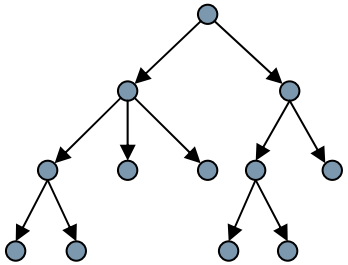
**Military C2**

Units execute tasks
Commanders plan operations and assign tasks

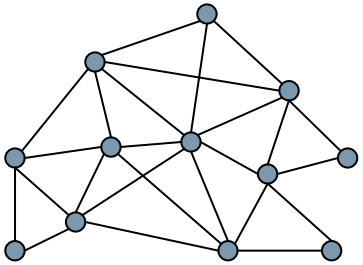
Active (commanders) Reactive (units)



(a) Control Net



(b) Command Net



(c) Communication Net

# How Assemblies Relate to **AGILE** C2?

**Robustness**

- Design, plan, and assemble any shape that can be defined by its physical, structural, and visual properties

**Resilience**

- Recover the shape formation from failures

**Responsiveness**

- Active particles adapt & self-synchronize their individual operations

**Flexibility**

- Develop diverse contingencies for assembly plan

**Innovation**

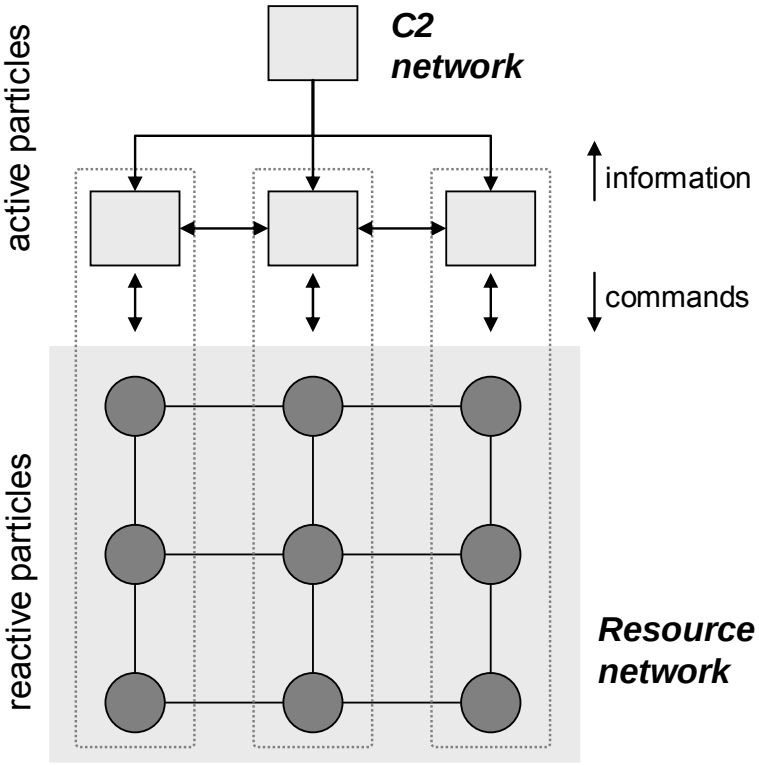
- The changes in assembly instructions can be performed

**Adaptation**

- Adapt the organizational networks, the structure of the shape, the temporal plan of the structure assembly, the roles of active particles, and reactive particles selected to fulfill assembly blocks

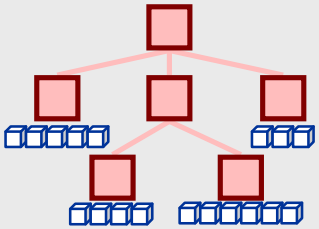
# Questions for Shape Assembly Command and Control

- *What are the coordination challenges of automated shape assembly?*
- *What process and C2 organization is necessary for the automated object assembly planning and execution?*
- *What are important metrics of object formation, and how does the object plan and execution affect them?*



# Automated Assembly Solution

**C2 Organization**

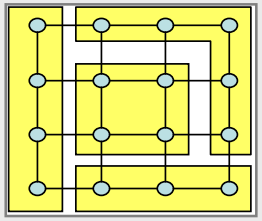


**Target Objectives /Constraints**

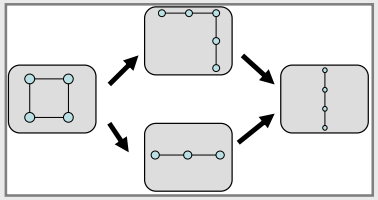
- *Timeliness*
- *Accuracy*
- *Resources*
- *Energy*

**match**

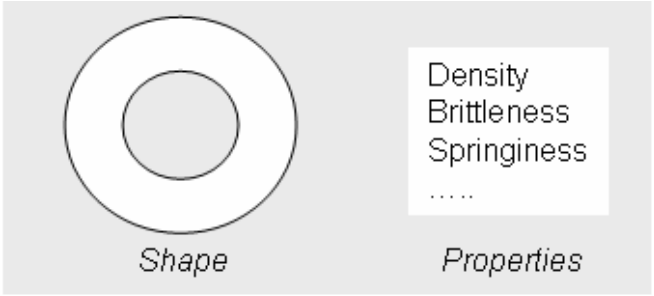
**Shape Decomposition**



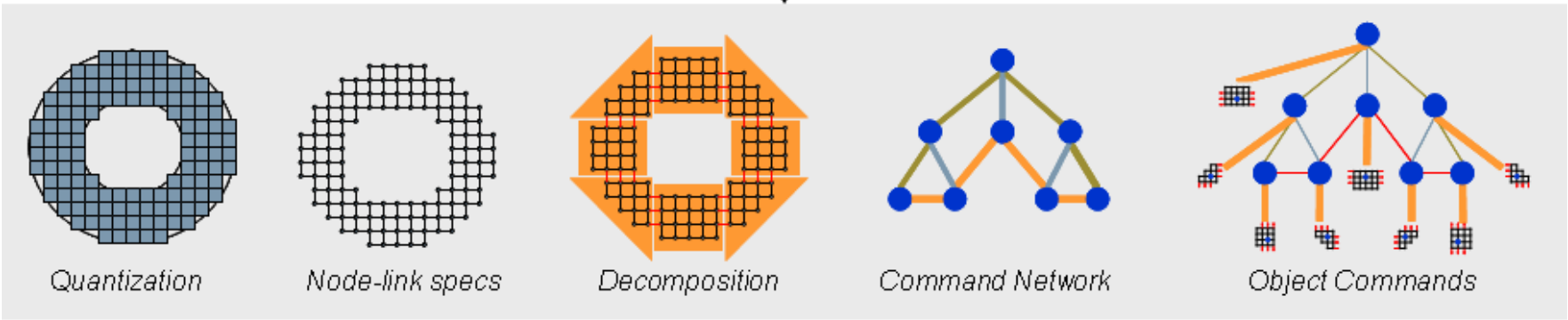
**Shape Plan**



# Shape Assembly Planning

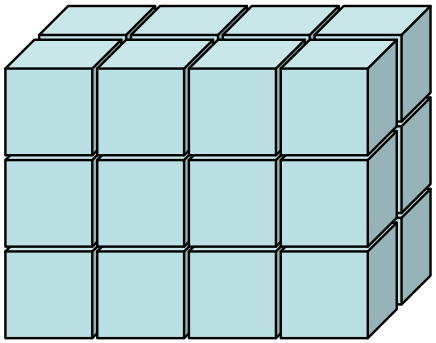



**Object Specifications**

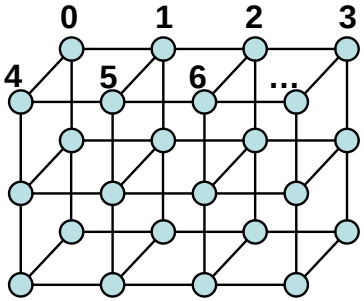



**Object Plan**

# Shape-to-Plan (1)



(a) 3-D Shape

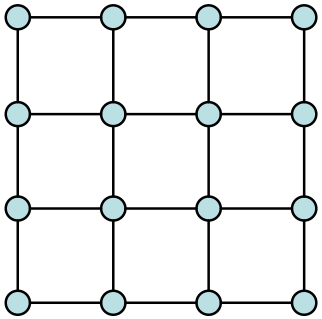



(b) 3-D Graph

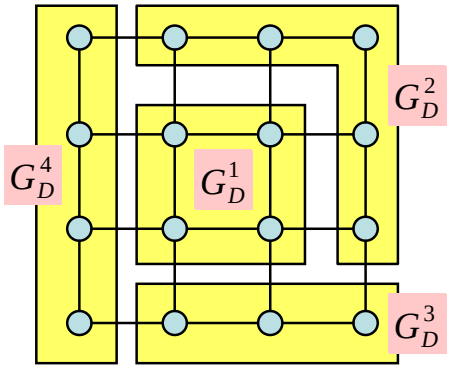
| Link ID | Node From | Node To | Face From | Face To |
|---|---|---|---|---|
| 0 | 0 | 1 | front | rear |
| 1 | 0 | 4 | right | Left |
| 2 | 1 | 2 | front | rear |
| 3 | 1 | 5 | right | Left |
| … | … | … | … | … |

(c) Shape Specification

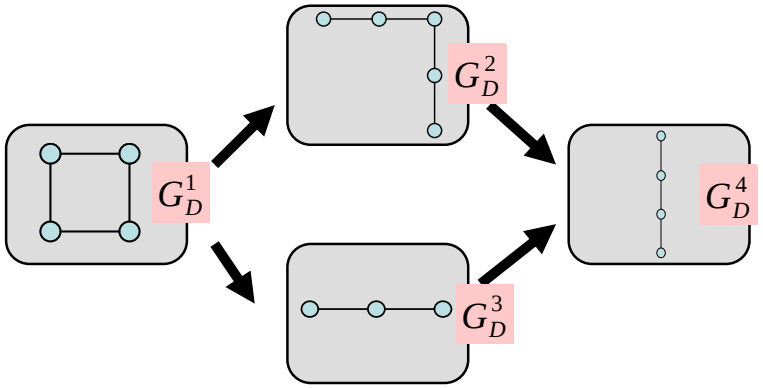
# Shape-to-Plan (2)



(a) Shape Node-Link Spec

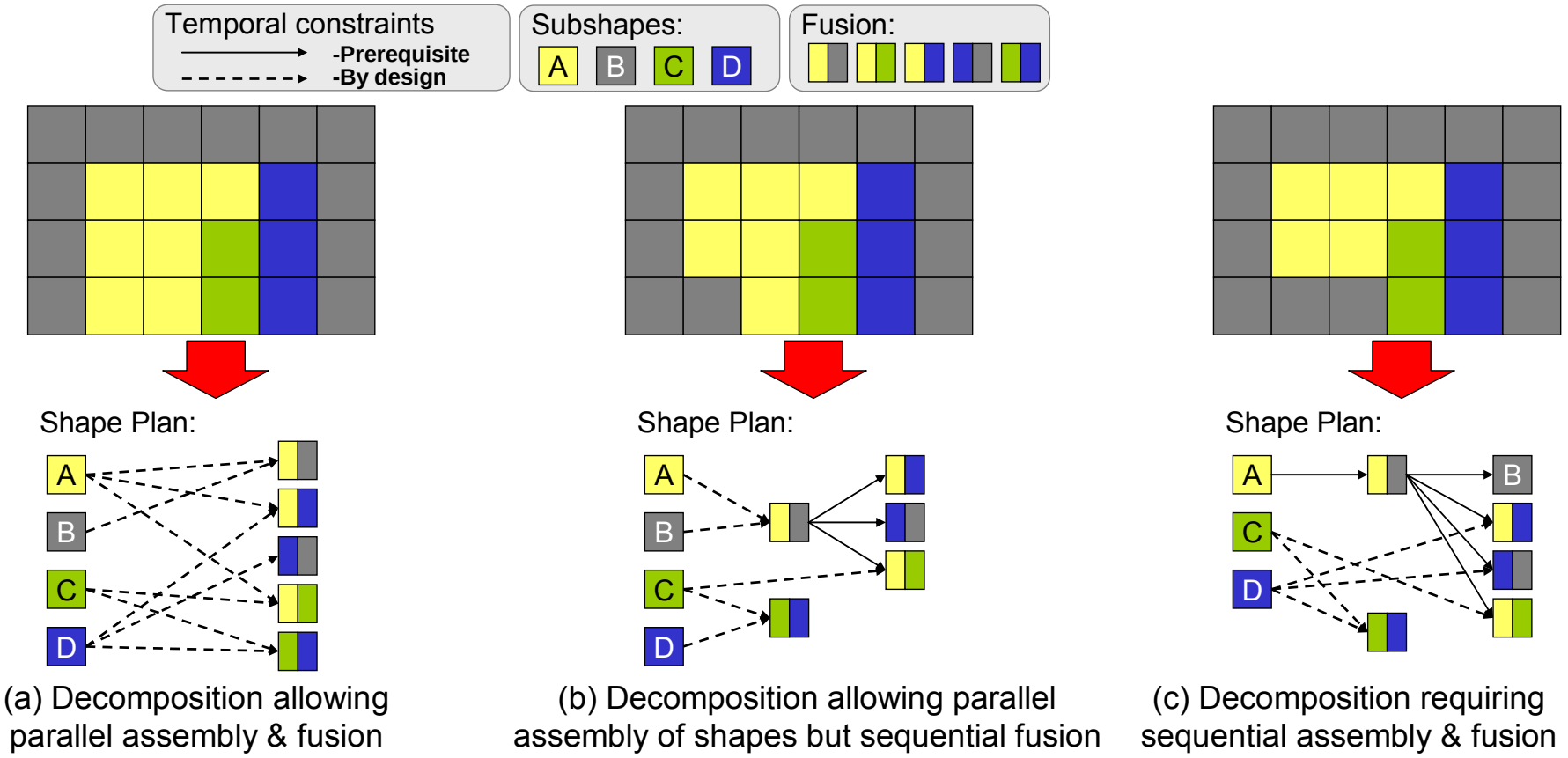



(b) Subshape Decomposition




(c) Shape Plan

# Effect of Shape Decomposition on Plan Design

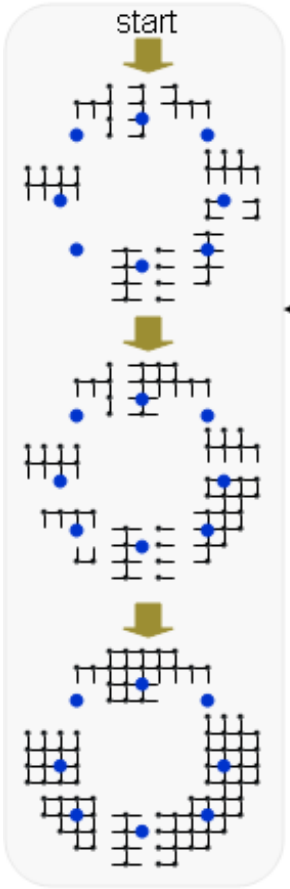



(a) Decomposition allowing parallel assembly & fusion

(b) Decomposition allowing parallel assembly of shapes but sequential fusion

(c) Decomposition requiring sequential assembly & fusion

# Assembly Plan Execution

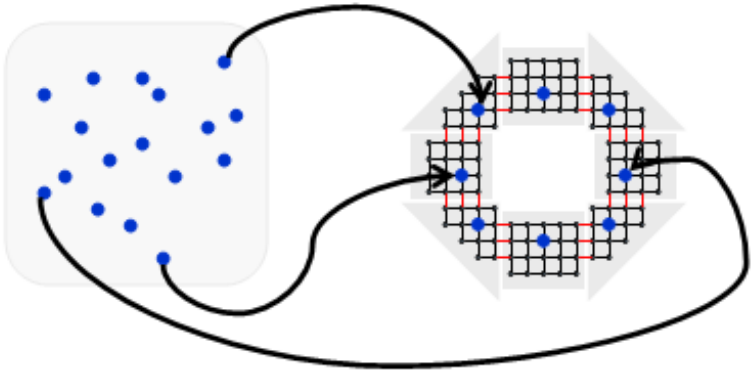


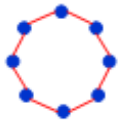

**Execute shape building control**

*Command Net*
*Communication Net*
*Resource control assignment*
*Shape building responsibility*
*Shape fusion responsibility*
*Shape build sequence*

- Joints created/broken
- Executing policy that was developed offline (or leveraging computational reachback)
- Network mapping model
- Observation model for state of local responsive particles
- Observation model for global state of active particles
- Communication between active particles

- **Allocating Active Particles to Roles**
- **C2 Organization Adaptation**
- **Reallocating Active Particles to Roles**

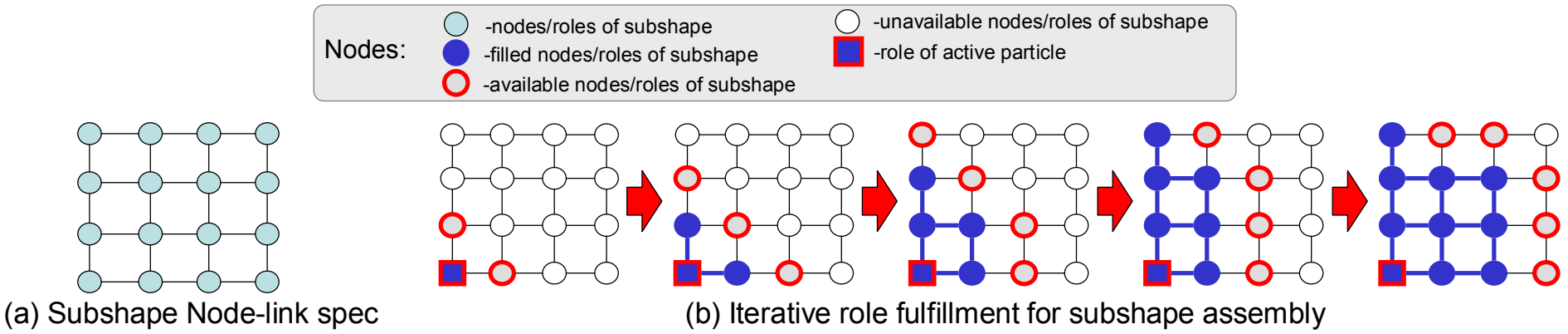




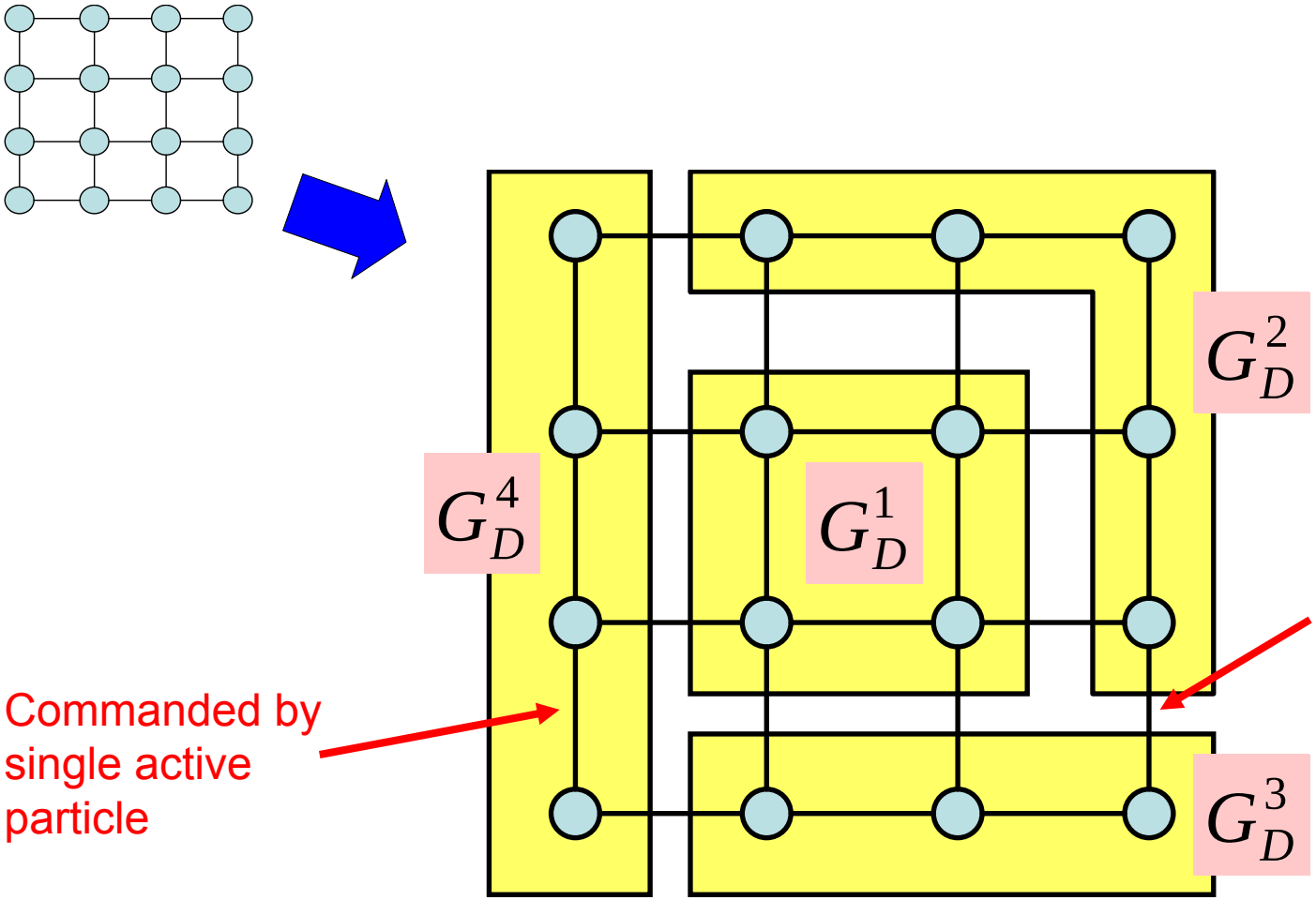
Active Particle Network

- Abstract Model
- Coordination overhead model
- Delay/loss info flow model

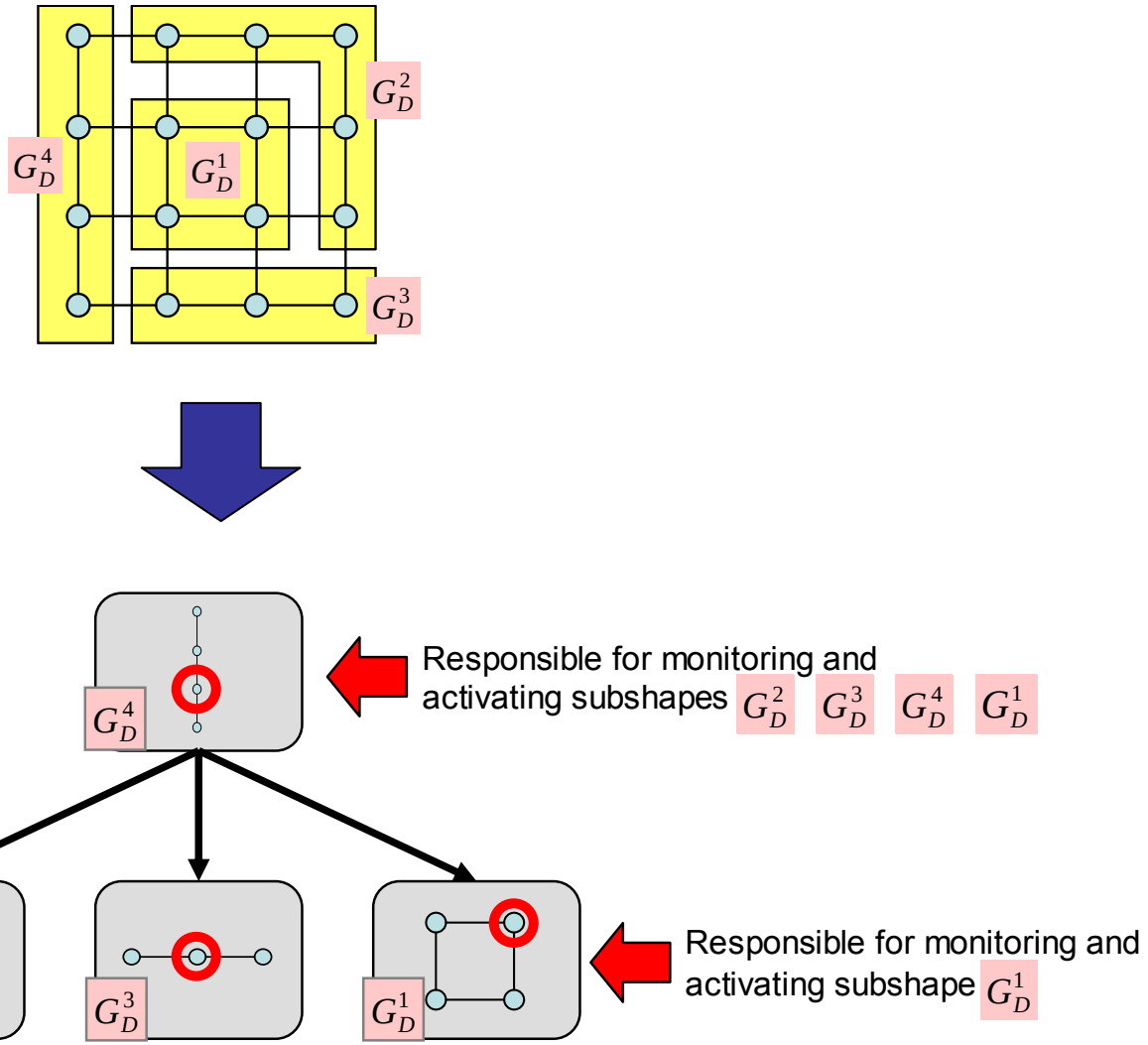
# Operations of Single Active Particle: Example of Iterative Assembly



# Shape Decomposition and its Effect on Particle C2

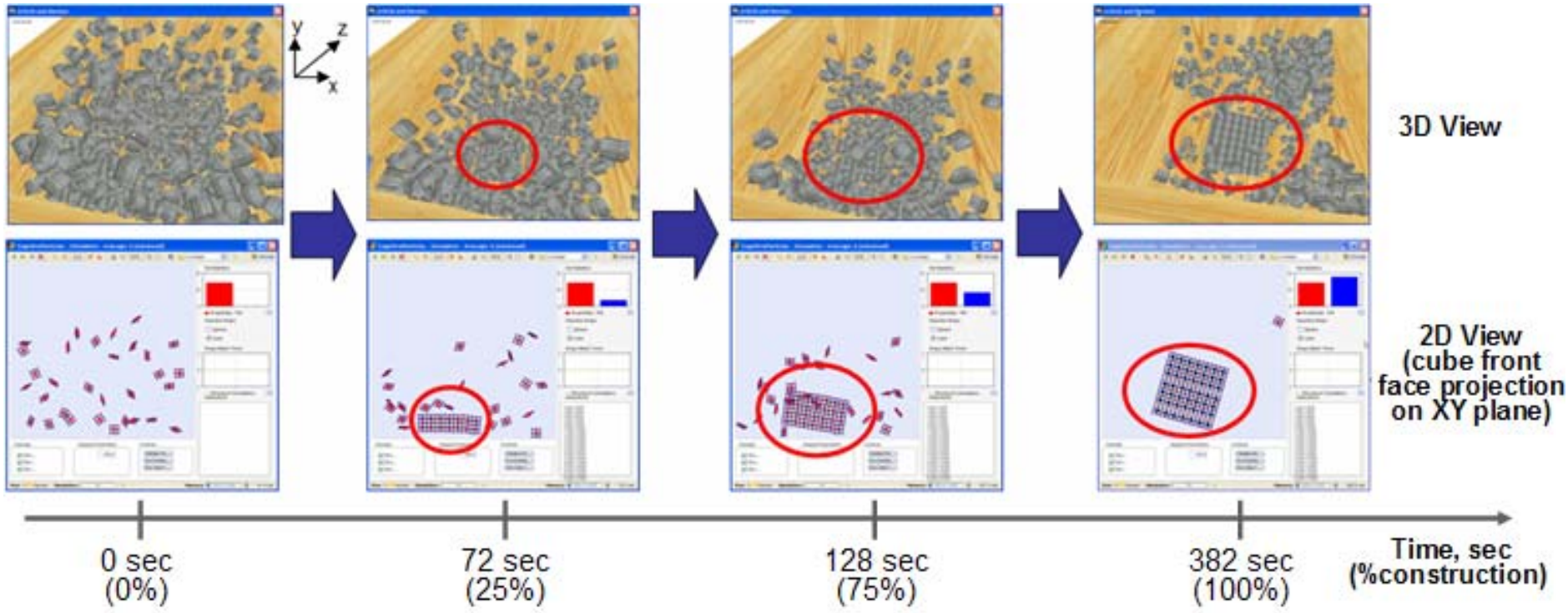


# Subshape-to-Active Particle Allocation and Activation Responsibility Assignment



# Assembly Experiments

- We have conducted several experiments using variety of shapes, assembly plans, and C2 structures
- Example of cube shape assembly in our testbed:



# Measures of Performance & Process

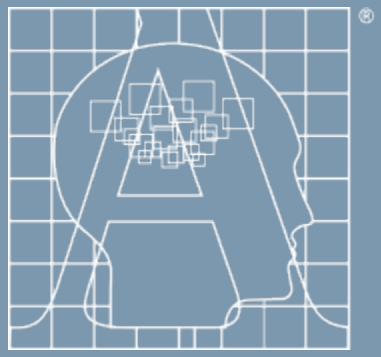
- **Timeliness**
  - Time to complete execution of shape plan
- **Accuracy**
  - Differences between currently assembled object and desired shape plan. In our experiments, we measured the *percentage completion* instead of accuracy, because we have the exact match of the particle ID's to the shape specs when the shape assembly occurs.
- **Resources**
  - Amount of assembly resources which represent the cost of control in terms of manufacturing the required components. We computed this metric as the number of parallel channels of execution, i.e. number of active particles performing commanders' roles in C2 particle organization)
- **Energy**
  - Energy expended by particles to execute the assembly, which represents the cost of control to maintain the execution process

# Lessons Learned

- Increase in the complexity of the mission does not necessitate increased need for all dimensions of agility
  - E.g., parallel execution, while beneficial to speed of the local sub-missions, introduces new resources requirements and complicates coordination when the mission is not easily decomposable into independent operations
- To achieve true mission effectiveness in complex environments with resource constraints, it is often required to limit some agile processes
  - The best C2 design solution is a match between mission requirements, available resources, and C2 organization & processes
  - "**Can** adapt/parallelize execution" does not mean "**should**"
- Benefits to agility
  - Efficient original plan
  - Reallocation of roles
  - Combining accurate situation perception with planning

# Next Steps

- Heterogeneous particles
  - Diversify capabilities, functions and actions of particles
- Shapes that adapt
  - Internal mechanisms for adaptation after assembly is finished
- Competing assemblies
  - Medication fighting viruses?
- Communication between particles and sharing SA
  - Need better mechanisms of sharing observed data between particles
    - Who talks to whom, when, about what



# APTIMA®

HUMAN-CENTERED
ENGINEERING