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

Georgiy Levchuk
Nathan Schurr
Darby Grande
Webb Stacy

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Motivation
Problem
Approach
Results
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…
  - Cube
  - Cuboid
  - Triangular prism
  - Triangular based pyramid
  - Square based pyramid
  - Cone
  - Cylinder
  - Sphere

- …to complex
  - Fixed wrench
  - Internal structure
  - Adjustable wrench
  - Complex surface

Motivation | Problem | Approach | Results
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**
- particles
- attraction, connection, communication, kinematics
- Appearance, shape, kinetics properties
- assembly sequencing and role allocation

**Military C2**
- members: soldiers, commanders
- actions: (non)kinetics, haptics, communication, kinematics
- goals: state of environment, mission objectives, unit positions
- plans: task plans and task-to-resource allocation
- execution: distributed, coordinated

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

Units execute tasks
Commanders plan operations and assign tasks

(a) Control Net  (b) Command Net  (c) Communication Net

Motivation
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
- 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

Shape Plan

Shape Decomposition

match
Shape Assembly Planning

Object Specifications

- Shape
- Density
- Brittleness
- Springiness

Object Plan

- Quantization
- Node-link specs
- Decomposition
- Command Network
- Object Commands

Motivation

Problem

Approach

Results
Shape-to-Plan (1)

(a) 3-D Shape  (b) 3-D Graph  (c) Shape Specification

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Motivation

Problem

Approach

Results
Effect of Shape Decomposition on Plan Design

Temporal constraints
-Prerequisite
-By design

Subshapes:
A  B  C  D

Fusion:

(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

**Motivation**

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

**Problem**

- Execute shape building control

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

**Approach**

- 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

**Results**

- Active Particle Network
  - Abstract Model
  - Coordination overhead model
  - Delay/loss info flow model
Operations of Single Active Particle: Example of Iterative Assembly

(a) Subshape Node-link spec
(b) Iterative role fulfillment for subshape assembly

Nodes:
- nodes/roles of subshape
- filled nodes/roles of subshape
- available nodes/roles of subshape
- unavailable nodes/roles of subshape
- role of active particle
Shape Decomposition and its Effect on Particle C2

Motivation

Commanded by single active particle

Requires coordination of two active particles

$G_D^1$, $G_D^2$, $G_D^3$, $G_D^4$
Subshape-to-Active Particle Allocation and Activation Responsibility Assignment

Motivation

Responsible for monitoring and activating subshapes $G_D^2$, $G_D^3$, $G_D^4$, $G_D^1$

Responsible for monitoring and activating subshape $G_D^1$
Assembly Experiments

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

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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