A New Methodology for Design and Evaluation of Heterarchical Structures

Georgiy M. Levchuk\textsuperscript{1}
Feili Yu\textsuperscript{2}
Yuri Levchuk\textsuperscript{1}
Krishna R. Pattipati\textsuperscript{2}

\textsuperscript{1}Aptima, Inc.
\textsuperscript{2}University of Connecticut

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# A New Methodology for Design and Evaluation of Heterarchical Structures (Briefing Charts)

**Performing Organization Name(s) and Address(es):** Aptima Inc, 12 Gill Street, Woburn, MA, 01801

**Sponsoring/Monitoring Agency Name(s) and Address(es):**

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**Supplementary Notes:** The original document contains color images.
Basic Notions

- **Mission**
  - Events, activities, tasks to be executed

- **Organization**
  - **Agents**
    - Limited workload capacity
    - Heterogeneity in effectiveness of observation, command, information fusion, task execution
  - **Structure**
    - Access to and transfer of resources
    - Access to and transfer of information
    - Generation and transfer of command
    - Structures have capacity constraints
  - **Strategy**
    - Observation (who sees what)
    - Information routing and fusion (who communicates to whom)
    - Command execution and transfer (who commands whom)
    - Task allocation and execution (who executes what)

- **Resources**
Formalization

What problem are we addressing?
- Design of organizational structures / networks and strategies

What is the structure/network in our context?
- Collection of items and rules/constraints of their interactions
- Collection of nodes, links, channels

What is the strategy?
- Policy/procedures/rules/guidance to execute a mission

What is an issue?
- Interactions between mission, structure, and strategy
Overview

- Why study heterarchies?
- Types of Structures and Design Challenges
- Research evolution
- Problem identification & constraints
- Process chain
- Agent process graph
- Multi-layer network structure
- Solution approach
- Simulation examples
Why Study Heterarchies?

- New technologies – additional friendly flexibility to exploit (FORCEnet concept)
- Need to study the enemy (e.g., terrorist networks)
- Need to study the environment (e.g., customer networks, social interactive environments, supply-demand chains, “informal” relationships within hierarchies)
- Heterarchical relationships are “richer”, and contain principles and mechanisms that have potential to render superior performance
- Thus need to study these relationships in order to:
  - determine how to influence other organizations
  - see if concomitant design principles can be imbedded into control structures of organizations to enhance performance
Types of Structures

Command
- Execution ordering
- send commands

Control
- Execution capabilities
- resource ownership structure

Communication
- Info propagation
- send information

Information
- Knowledge/SA
- info/event access structure
Design Challenges

**Challenge 1:** Identification of interactions between agents
- Use template interaction message library
- Use rule-based reasoning in synthetic environment

**Challenge 2:** Interaction constraints and agent effectiveness
- Study restrictions in information access and flow, workload capacity, processing speed, command flow, etc.
- Study feasibility of structures in military domain

**Challenge 3:** Complexity & influence of (sub)structures and strategies on each other
- Model how flow is treated in the organization (transfer, consumption, generation, etc.)
- Inter- and intra-agent networks

**Modeling approaches:**
- Use flow model: cost and capacity constraints
- Non-linear function of cost for flow transfer links
- Multi-commodity & non-splittable flow modeling
- Heuristic algorithms to maintain network robustness
- Local / distributed decision making
Research Evolution

**Overhead-based** design

- **Given:** communication requirements
- **Find:** a hierarchy
- **Objective:** minimize communication overhead

Cons:
- No effect of overhead
- No network constraints

**Schedule-based** design

- **Given:** agent network
- **Find:** a task assignment and schedule
- **Objective:** minimize mission time
  - Based on task information flow and inter-agent communication

Cons:
- Global controller
- No network design
- Limited routing; no info split

**Routing-based** design

- **Given:** communication requirements
- **Find:** a network and info routing
- **Objective:** minimize average delay
  - Based on information routing & queuing model

Cons:
- No strategy (assignment)-structure allocation
- No multi-structure design

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Design Evolution
What is Missing?

- Strategy-structure-mission interaction/influence

- **Strategy**: how and what is done

- **Structure**: by what means a strategy is accomplished

- **Mission**: what needs to be accomplished
Problem Identification

Agents
- Observe events
- Receive/transfer/fuse info
- Generate/receive/transfer command
- Receive/transfer/process tasks

Links/Channels
- Transfer information
- Direct command
- Access observations

Model agent operations as flow processing
- Flow of information, command orders, resources, requests for synchronization, exceptions, etc.

Flow

Agent

Resend
Use
Reject
Transform
What Are We Doing?

- Observation
- Monitoring
- Event
- Processing
- Task
- Execution
Getting the Right Info to Right People

Monitoring → Event

Observation

Execution → Task

Processing
Direct Info Access

Monitoring Event
Observation
Monitoring

Execution
Processing
Task
Command as a Resolution

Monitoring Event

Observation

Execution

Processing Task

Execution

Processing Task

Processing Task
Constraints

Agents:
- Workload capacity
  - Limit amount of operational and cognitive load
  - Include load of observations, communication, decision-making, task execution
- Operation efficiency
  - Different expertise for observation, command, task processing, transfer
  - Based on agent expertise
    - Multiple types of expertise assessed; grading each
    - Multi-type expertise capability ⇒ generalists
    - Single-type expertise capability ⇒ specialists

Links/channels:
- Cost of maintenance
- Use simple linear function of flow amount
Problem Specifics

- Flow chain:

  start → observe → command → execute → end

  event → information → task(s)

- Agent process graph:

  Command is generated

  Tasks are selected for execution

splitting allowed
Capacity and Mission Gain

Capacity
- Identifies the threshold of volume
- At agent process nodes & links: agents constraints
- At links/channels: structure constraints

Mission Gain
- **Positive** – *task execution gain*: from the efficiency/accuracy of agents to observe, conduct decision making, execute tasks, communicate
- **Negative** – *transfer cost*: info/tasking through network
  - Network maintenance
  - Information loss
  - Interpretation loss
  - Noisy transmission
Joint Graph

Event-agent assignment

E1  E2  E3  ...

[Diagram of a joint graph with nodes labeled A1, A2, A3 and arrows connecting them.]

Buffers:
O - Observation
I - Information
C - Command
P - Process
Example of Hybrid Structure

Information Network

Command Network

Final Architecture
Multi-Layer Organization

Event is observed

![Diagram of Multi-Layer Organization]

**Information Network**

**Command Network**

Decision making generates command
Solution Approach

- **Step 1:** Define mission
  - Events volume and expertise requirements
- **Step 2:** Define organization
  - Agent expertise
- **Step 3:** Define agents’ process graphs
  - Agent capacities, processing gain
- **Step 4:** Define structure constraints
  - Link/channel capacities for different-type networks
- **Step 5:** Expand the aggregate network
  - Replace node capacity and gain constraints with link capacities and cost
- **Step 6:** Apply minimum cost maximum flow algorithm
Output

- **Structure:** specification of load for sub-networks
  - Can use to design network bandwidth and architecture

- **Strategy:** specification of who does what
  - Observation, fusion, communication, transfer, execution
Sample Results

- Increase the accumulated mission execution effectiveness (gain) while decreasing the communication overhead, cost and volume
- Optimal network allows better access to efficient nodes
Future Directions

- Consider network robustness constraints
- Implement *multi-commodity* problem formulation
  - Currently we implemented single-type events
- Consider problem of *unsplittable* or partially splittable flows
  - An item can only be transferred through *single path*, without splitting
- Consider flow *transfer* and generation
  - Flow volume change
- Consider error propagation
- Consider local autonomous agent strategy based on partial information
Conclusions

Accomplishments:
- Developed methodology to design inter-dependent organizational sub-structures (command, observation, communication, information)
- Utilize the benefits and constraints of hierarchical, heterarchical, and hybrid structures
- Integrated structure-strategy optimization

Applications:
- Will provide innovative strategy and structure solutions for various levels and nodes of the FORCEnet