Mission-based Architecture for Swarm Composability (MASC)

By
CDR Katy Giles, USN
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FHI 360 CONFERENCE CENTER
1825 Connecticut Avenue NW
8th Floor
Washington, DC 20009

www.sercuarc.org
• Background
• Research Focus
• MASC Architecture
• MASC Methodology
• Conclusions and Future Work
Background

What is a swarm system?

“Swarm robotics is the study of how large numbers of relatively simply physically embodied agents can be designed such that a desired collective behavior emerges from the local interaction among agents and between agents and the environment.” ¹

• General attributes:
  – Decentralized control
  – Agent autonomy
  – Large numbers of agents following simple rules

• Relation to systems engineering:
  – Swarm systems are complex adaptive systems
  – Exhibit collective emergent behavior
  – INCOSE complex systems guiding principles²:
    • Identify patterns
    • “Influence & intervene” rather than control
    • “Zoom in and zoom out,” multiple views
  – Cognitively challenging to operate multiple vehicles³,⁴,⁵
    • Air traffic controller research


www.wired.com
www.wikipedia.org
Current

Field

Fleet

Programmer

Operator

Single Vehicle Pilot

Swarm Commander

Future

Motivation
**Problem**

- Informal relationship between swarm mission engineering and swarm systems engineering impedes **architecture reusability**
- Swarm system architecture is dominated by bottom-up, behavior-based design

- Informal
- Operated at single behavior level
- Different action plans for each mission
- Low flexibility
- Micro-management approach

**Proposed Solution**

Transfer typical rule-based decisions from the Swarm Commander to the swarm, freeing the human to make **rules of engagement** related decisions

- Formal
- Reusable common patterns
- Modular
- Intuitive
- Platform agnostic
- Experiential heuristics-based
Intended Benefits of Swarm Architecture

Formalize relationship between swarm mission engineering and swarm systems engineering to promote architecture reusability

- Intuitiveness
- Modularity
- Composability
- Mission Doctrine Integration
Mission-based Architecture for Swarm Composability

Operational Architecture

Solution Architecture

Research focus
• **Swarm mission** describes the overall task and purpose delineating actions assigned to the UAV swarm
  
  — Examples: intelligence, surveillance, reconnaissance (ISR), humanitarian assistance/disaster relief (HADR), search and rescue (SAR), and counter drug operations

• Research focuses on three basic missions:
• *Swarm phase* describes a distinct time period within the mission

• There are five operational phases in a swarm mission ($M$):
  – Preflight ($P_1$)
  – Ingress ($P_2$)
  – OnStation ($P_3$)
  – Egress ($P_4$)
  – Postflight ($P_5$)
Swarm Tactic and Swarm Play

- **Swarm tactic**: employment and ordered arrangement of agents in relation to one another for the purpose of performing a specific task
  - Each tactic composed of one or more swarm sensor and maneuver plays
  - Designed to be used in multiple missions
  - Examples: search, divide, evade, and attack

- **Swarm play**: maneuvers and behaviors of swarm as a collective of agents with specific triggers and temporal constraints
  - Each play composed of one or more swarm algorithms
  - Designed to be used in multiple missions
  - Examples: launch, transit, split, join, or bit, and sensors EMCON

Diagram of part of simulation developed in Innoslate™

EMCON
Swarm Algorithm

- Three general categories\(^1\):
  - Reactive: sense and act, pheromone-based, and other biologically inspired algorithms
    - Reynold’s “Boids” flocking, bee colony, ant colony
  - Deliberative: require information trading and solution deliberations
    - Sorting, consensus, greedy selection, physicomimetic
  - Evolutionary: genetic algorithms and other fitness-based optimization functions

- **Swarm algorithms**: step-by-step procedures used by the controlling software to solve a recurrent task

References: \(^1\)Senanayake et al. 2015, Mitchell 2009
1. Develop mission scenario

2. Depict swarm behavior at tactics level

3. Develop mission simulation beginning at phase level

4. Check for logical errors

5. Review implementation with stakeholder

6. Revise tactics

7. Swarm doctrine & swarm system requirements
Consider this scenario....

- Multi-national maritime interdiction operation
- UAV swarm supports boarding team with surveillance, communication relay
- Swarm provides real-time, close range sensor collection

Adapted from: Okon 2012
MIO Mission Tactics Level as FSM
MIO Mission
Activity Diagram Simulation

MIO Mission at tactics level using MASC framework

Diagram of part of simulation developed in Innoslate™
Data were collected from 15 subject matter expert naval aviators and naval flight officers.

Participants read the fictional MIO scenario, constructed a **UAV swarm mission plan**, and answered a survey

- Group 1 used tactics
- Group 2 used only plays, no knowledge of tactics

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Conclusions

**Modular**

<table>
<thead>
<tr>
<th>Tactic</th>
<th>SvS</th>
<th>MIO</th>
<th>MIO HSR</th>
<th>HADR</th>
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<td>Evasive search</td>
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**Intuitive**

“Seemed to work well and I was able to perform the task in a timely manner.”

“Playbook provided all the necessary support for this mission type”

“The structure of mission phases supports the mission execution”

**Composable**

**Integrates mission doctrine**

“Playbook provided all the necessary support for this mission type”

“The structure of mission phases supports the mission execution”

3 mission areas, one playbook
Future Work

• Support improved graphical user interface for UAV swarm operations
• Incorporate system and operational failure modes into simulation
• Develop swarm system evaluation measures of performance
Drone problems....

People in the park keep flying drones near me, so I've built a system to shoot them down. Cool! Oh yeah, there's one now. Time for a test! 

Okay, locking on... wait, it just crashed. Damn.

Here comes another one! Aim for... nope, it got stuck in a tree.

Three hours later... finally, two more just-no, one crashed and the other is hurtling sideways toward the lake. Will you people learn to fly these things?!

https://xkcd.com/1846/


References contd.

Background - Enabling Technology

• Swarm technology – inspired by biology:
  — Swarm systems are robust, flexible, scalable
  — Emergent behavior arises from interactions between agents

• Enabling technologies for UAV swarms:
  — Improved communication networks including meshed ad-hoc networks
  — Cost-effective miniaturized electronics: GPS, video cameras, radio receivers, autopilot processors
  — Automation - must shift from operators to monitors and supervisors
Background- Swarm C2 Architectures

- **Orchestrated** - one agent selected as temporary leader based on specified factors (e.g., location, state, mission scenario)
  - Architecture is somewhat robust, but not scalable to large or geographically dispersed swarms, and places significant processing burden on one agent

- **Hierarchical** – resembles traditional military command and control (C2)
  - Simplifies data flow, but not robust and inflexible when dealing with dynamic situations that require rapid reactions from agents

- **Distributed** - characterized by absence of leader; swarm decisions made via collective consensus among agents
  - Robust and scalable, but requires communication network that will support potentially increased data traffic, such as wireless, mesh communication networks

- **Emergent swarming** - describes relationships which occur in ant, termite, and bee colonies in which there is no management
  - Agents have no leader, have low situational awareness, and follow simple rules based on local information (i.e. sharing pheremone signals)
  - Have potential to become more relevant as genetic algorithms are further developed

References: Dekker 2008, Chung et al. 2013
Background- Architecting a Swarm

- Hybrid C2 architectures can be used to maximize strengths of each:
  - US Navy’s Cooperative Engagement Capability (CEC) anti-air warfare system utilizes a distributed architecture for situational awareness data and an orchestrated architecture for target selection

- Finite State Machines (FSM):
  - Used in modeling multi-vehicle autonomous, unmanned system architectures
  - Applicable to military swarm systems performing high risk missions
  - Probabilistic FSMs can be used to allow for bounded behavior variability

- Petri Nets:
  - Effective in visualizing and analyzing systems in which there are multiple, independent activities occurring at same time

Problem Space Examination - Swarm System Design

Before

Fleet Needs

- Carrier Strike Group in pre-deployment training
- Fleet visiting U.S. ports
- Exercises with allies in the North Sea
- Operations in the Eastern Med
- Counter-Piracy operations in the MidEast
- Expeditionary Strike Group Trans-Atlantic crossing
- Counter-narcotics missions in the Caribbean

Behaviors & Algorithms

Research focus

Operational Architecture

Solution Architecture

After

Fleet Needs

- Aircraft carrier supporting Operation Enduring Freedom
- Maritime Partnership exercises with allies in Africa
- Navy Hospital Ship Conducting Humanitarian Operations
- Forcible Entry to the Western Pacific

Navy Outreach

Reference: DARPA OFFSET BAA, 2017

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SSRR 2017
• Military doctrine
  o “Fundamental principles by which the military forces or elements thereof guide their action in support of national objectives” (JP 1-02)
  o Influenced by technology, the enemy’s capabilities, organizational structure, and geography
  o Applies at every level of warfare (strategic, operational, tactical)

• Military tactics
  • Handling of forces in battle
  • “The sum of the art and science of the actual application of combat power” (Arthur Cebrowski, VADM USN, ret)
  • “…the choice of tactics will also be governed by scouting effectiveness and weapons range” (Hughes)
  • Tactical doctrine organizes the playbook

“Fire effectively first!” –Wayne Hughes, CAPT USN (ret)
Background- Swarming Doctrine

• Swarming origins:
  — British vs. Spanish Armada in 1588
  — British vs. swarming German U-boat wolf packs in N. Atlantic
    Japanese kamikaze attacks against US Navy
  — Al Qaeda's strikes on multiple US targets on 11 Sept. 2001
  — Typical NGO operations

• What will modern swarming doctrine look like?
  — Transition from “few and large” forces to “many and small” units
  — Centralized strategy
  — Widely distributed, smaller units executing pulse-like tactics
  — Distributed Lethality?

References: Arquilla 1997, 2000
Background - Current Doctrine vs. Swarming Doctrine

**Traditional Command Structure**
- Hierarchical
- Carrier strike group, amphibious strike group

**Swarming Command Structure?**
- Widely distributed, small units, multi-axis, convergent attacks
- Disperse and amass
- Historical: German U-boats, Japanese kamikaze, Al Qaeda

Transition from “few and large” forces to “many and small” -Dr. Arquilla

References: Edwards 2010, Arquilla 2000
Research Objectives

Common conceptual architecture-level patterns for mission-suitable swarm systems across a range of missions

A modular, mission-oriented playbook from which standard swarm tactics and missions can be formulated
Research Approach

Problem Space Examination
- Review swarm system literature
- Study current UAV swarm operations
- Identify research opportunities

Solution Generation
Develop:
- Swarm architecture
- Mission scenarios
- Operational activity models
- Logic checking models

Solution Evaluation
- Logic checks
- Evaluate system behavior
- Elicit feedback from HSR
- Evaluate for intuitiveness, modularity, and integration of mission doctrine

Implication of Solution
- Document architecture and methodology
- Demonstrate reusability of tactics and plays across missions
- Demonstrate composability at each level

Reference: Cross 1989
Related Work

• Dudek’s swarm robotics taxonomy (Dudek et al., 1993)

• Bottom-up, behavior-based design
  – Agent-based modeling (Bonabeau 2002, Munoz 2011)
  – Brooks Subsumption architecture (Brooks 1985)
  – Petri Nets (Levis & Wagenhals 2000, Palamara 2008)

• Top-down design methods
  – DeLoach et al.’s Multi-agent Systems Engineering methodology (DeLoach et al. 2001)
  – Brambilla’s property-driven, four phase method (Brambilla et al., 2012)

• Playbooks
  – RoboCup soccer (Browning et al. 2004)
  – McLurkin’s library of behaviors for swarm robots (McLurkin 2004)
  – Smart Information Flow Technology (SIFT) Playbook-enhanced Variable Autonomy Control System (PVACS) (Goldman 2005)
  – DARPA OFFSET program - human-swarm teaming and swarm autonomy within an urban gaming environment (DARPA TTO 2017)
Solution Generation -
Heuristics for Model Building

• Applied as guidelines to Innoslate models and simulation:

  • Every activity not designated a context activity should have at least one parent
    \( (\forall a_1 \in A)[\neg context(a_1) \rightarrow (\exists a_2 \in A) \text{decomposes}(a_1, a_2)] \)

  • No activity shall have exactly one child
    \( (\forall a_1 \in A) (\forall a_2 \in A) [\text{decomposed by}(a_1, a_2) \rightarrow \left(\exists a_3 \in A\right) \text{decomposedby}(a_1, a_3) \land (a_2 \neq a_3)] \)

  • No activity shall be decomposed by itself
    \( (\forall a \in A)[\neg \text{decomposedby}(a, a)] \)

    • Every activity shall have at least one input or trigger
      \( (\forall a \in A) (\exists r \in R) [\text{input}(r, a) \lor \text{trigger}(r, a)] \)

    • No performer shall have more than seven children
      \( (\forall p_1 \in P) [(\forall p_2 \in P) |\text{decomposedby}(p_1, p_2)| \leq 7] \)

Source: Rodano & Giammarco 2013
Finite state machines are concise way to depict swarm behavior

- Specify each tactic as a state
- Sub-swarms operate in one state at a time

A finite state machine (or automaton) $M$, can be defined by a 5-tuple:\(^1\):

$$(\mathcal{E}, \mathcal{S}, s_0, F, \delta)$$

wherein:

- $\mathcal{E}$ is the set of inputs to $M$
- $\mathcal{S}$ is the set of states, including tactics, of $M$
- $s_0 \in \mathcal{S}$ is the initial state of $M$ (preflight completed and flight ready)
- $F \subseteq \mathcal{S}$ is the final state of $M$ (all UAVs recovered)
- $\delta : \mathcal{S} \times \mathcal{E} \rightarrow \mathcal{S}$ is the transition function (mappings of inputs to original states which result in state change)

- FSM has modelling implications in Innoslate and Monterey Phoenix
  - Innoslate FSM do not interface with simulation
  - MP does not permit implicit or explicit recursion in grammar rules\(^2\)

References: \(^1\)Wright 2005, \(^2\)Auguston 2017
# Solution Evaluation - Modularity of Plays Across Missions

<table>
<thead>
<tr>
<th>Play</th>
<th>SvS</th>
<th>MIO</th>
<th>MIO HSR</th>
<th>HADR</th>
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<tr>
<td>Launch</td>
<td>B</td>
<td>B</td>
<td>8</td>
<td>B</td>
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<tr>
<td>Transit to WP</td>
<td>B</td>
<td>B</td>
<td>8</td>
<td>B</td>
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<tr>
<td>Orbit</td>
<td>B</td>
<td>7</td>
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<tr>
<td>Racetrack</td>
<td>B</td>
<td>4</td>
<td></td>
<td>B</td>
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<tr>
<td>Split (logic based)</td>
<td>B</td>
<td>7</td>
<td></td>
<td>B</td>
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<tr>
<td>Join</td>
<td>B</td>
<td>B</td>
<td>8</td>
<td>B</td>
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<tr>
<td>Disperse</td>
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<td>B</td>
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<td>Transmit video</td>
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B = selected for baseline mission case study (Innoslate model)

# = number of HSR participants who selected play
### Solution Generation & Evaluation – MIO Mission Composition

<table>
<thead>
<tr>
<th>Tactic ID</th>
<th>Tactic Name</th>
<th>Play ID</th>
<th>Play Name</th>
<th>Algorithm ID</th>
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Solution Generation & Evaluation – SvS Mission as FSM

FSM applied to field experimentation scenario

Modified with additional MASC swarm tactics
Solution Evaluation – SvS Mission Innoslate Simulation

SvS Mission at Tactics Level using MASC Framework

Diagram of part of simulation developed in Innoslate™
Solution Evaluation – SvS Mission as FSM in Monterey Phoenix

Reference: 1 Auguston 2017
## Solution Evaluation - Modularity of Tactics Across Mission

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*B = selected for baseline mission case study (Innoslate model)

# = number of HSR participants who selected tactic
Solution Evaluation - Composability

Mission

Phase

Tactic

Algorithm
Research Scope & Assumptions

- Not developing new swarm behavior algorithms
- Not developing collision avoidance algorithms
- Not focusing on logistical activities
- Not including system failures or failsafe modes in models
- Not addressing operational failures in models
- Not developing game-like prototype (yet)

- Subset of US Navy Missions
- DoD category 1-2 fixed-wing, homogeneous UAVs
- Swarm Operations Team: Swarm Commander, Swarm Health Monitor, Ground Crew
- System operates under distributed control using mesh ad-hoc network
- Sub-swarm is lowest level unit for tactics employment
- Each sub-swarm executes 1 tactic at a given time
- Tactics are focused on inflight mission phases
1. Develop mission scenario

2. Depict swarm behavior at tactics level

3. Develop mission simulation beginning at phase level

4. Check for logical errors

5. Review implementation with stakeholder

6. Revise tactics

7. Swarm doctrine & swarm system requirements