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A Framework for Integrating the Development of Swarm Unmanned Aerial System (UAS) Doctrine and Design

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Motivation

- Unmanned systems have been rapidly fielded in response to urgent needs from combatant commanders resulting in reduced mission effectiveness and suitability.
  - RQ-4 Globalhawk (2007) – not operationally suitable.
  - MQ-9 Reaper (2008) – found operationally suitable and effective after significant engineering retrofits from the original Predator (2001) and a long-delayed test program.
  - RQ-21A Blackjack (2015) – assessed as neither operationally suitable nor effective.

- Trend likely to continue as UAS technology develops faster than prescribing doctrine.

www.northropgrumman.com

www.af.mil

Reference: DOT&E

Research Purpose

- Develop framework for swarm UAS design that integrates doctrine and technology into system design.
- Develop a common “playbook” from which common swarm tactics and missions can be formulated.
- Identify missions for which swarm UAS are best suited.

Swarming Doctrine

- *Military doctrine* – provides standardized conceptual framework for connecting strategy, operations, and tactics.
  - Influenced by technology, the enemy's capabilities, organizational structure, and geography.
- Swarming origins:
  - British vs. Spanish Armada in 1588, British vs. swarming German U-boat wolf packs in the North Atlantic, Japanese kamikaze attacks against US Navy, Al Qaeda's strikes on multiple US targets on 11 Sept. 2001, and 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.

References: Arquilla 1997, 2000

Swarm Architectures: C2

- *Orchestrated control* - 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.

- *Centralized control* – resembles traditional military command and control (C2).
  - Requires a hub-and-spoke communication architecture that limits autonomous behavior, and allows for single point of failure.

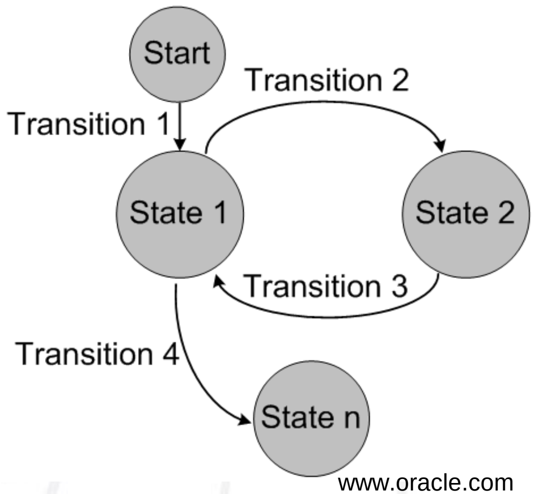
- *Distributed control* - characterized by absence of leader; swarm decisions made via collective consensus among agents.
  - Robust and scalable, but requires communication network that will support potentially increased data traffic, such as wireless, mesh communication networks.

References: Dekker 2008, Chung et al. 2013

Swarm Architectures contd.

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

- Finite State Machines (FSM):
  - Have been shown to be effective 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.



www.oracle.com

References: Dekker 2008, Weiskopf et al., 2002

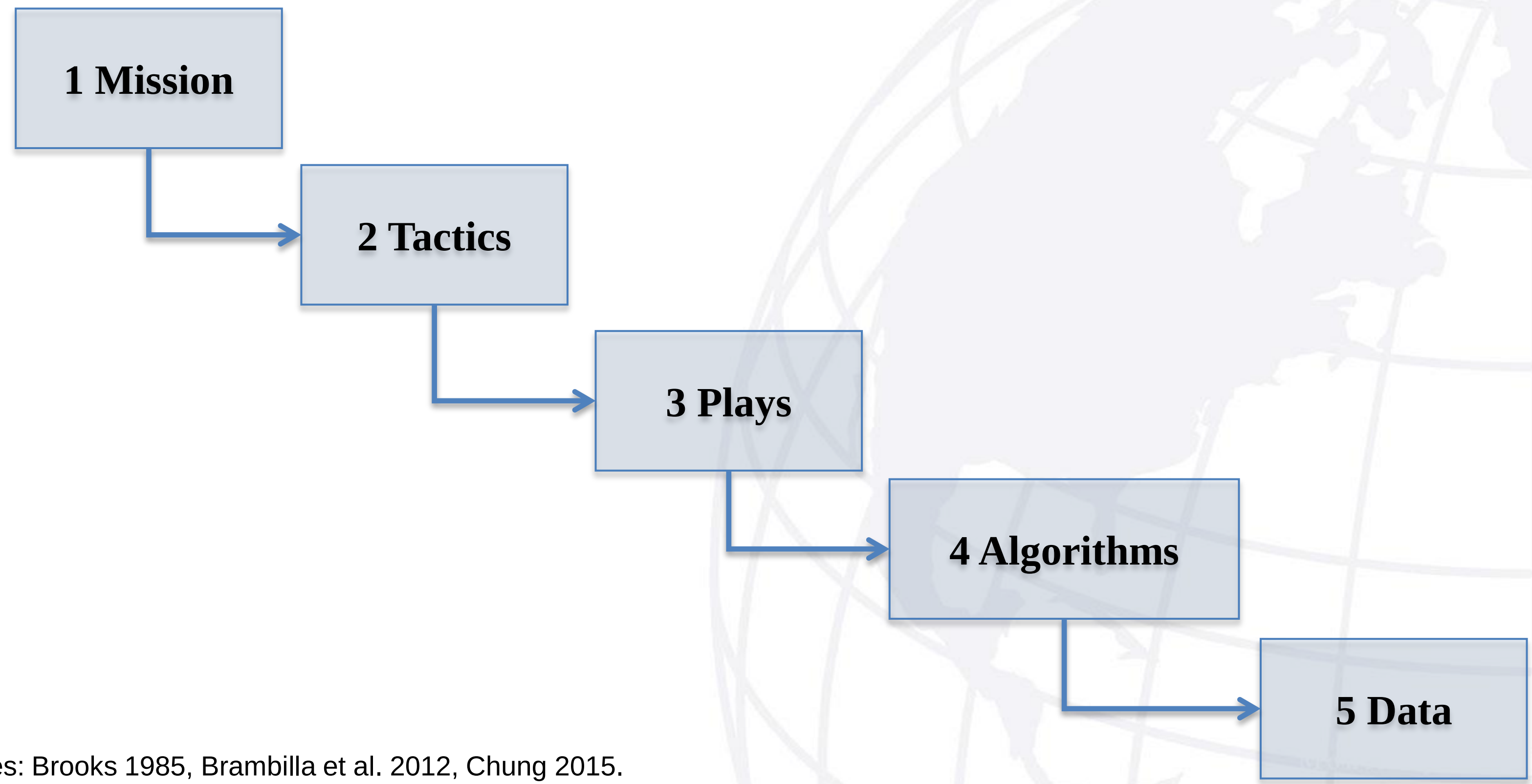
Current Swarm UAS Taxonomies and Design Methods

- Dudek's taxonomy of swarm robotics.
  - Seven design variables.
- Bottom-up, behavior based design – typical for swarm systems.
  - Brooks subsumption architecture – layered FSM approach.
- Top-down design methods – less common for swarm systems.
  - Brambilla's property-driven, four phase method:
    - Phase 1: formally state system requirements by specifying intended properties;
    - Phase 2: create an abstract macroscopic model and model checker to verify properties;
    - Phase 3: use macroscopic model as guide for implementing system;
    - Phase 4: test the system using real robots.

References: Dudek et al. 1993, Brooks 1985, Brambilla et al. 2012.

Proposed Swarm UAS Taxonomy and Design Method

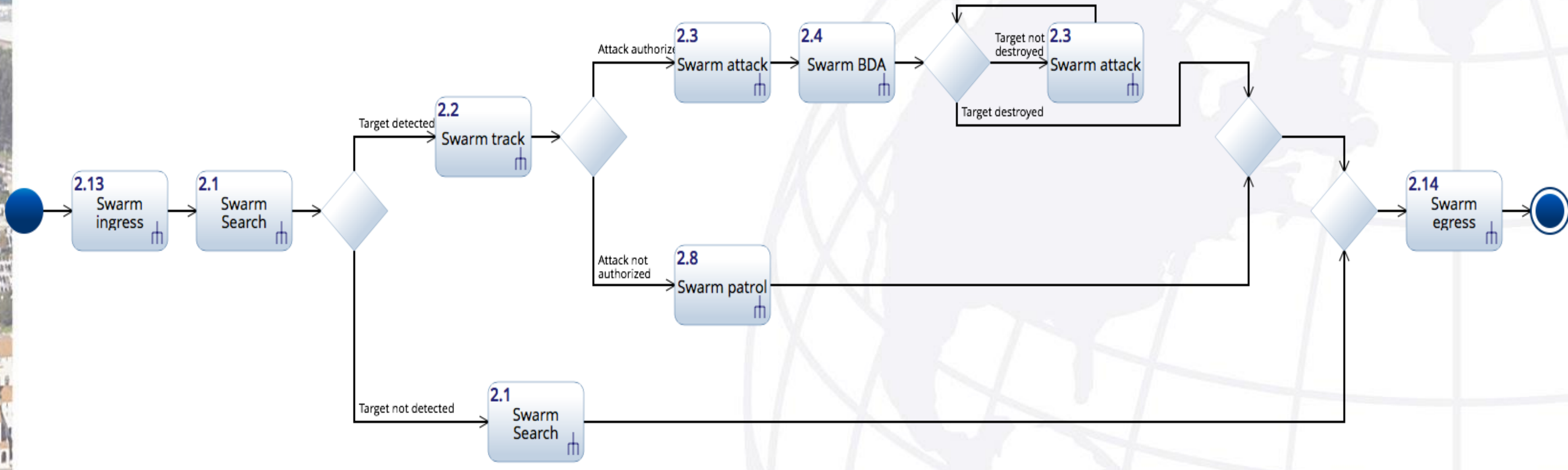
- Top-down, mission-driven design.
- Decentralized C2 architecture.
- Influenced by work of Brooks and Brambilla.



References: Brooks 1985, Brambilla et al. 2012, Chung 2015.

Swarm UAS Mission Example

Swarm UAS Basic Intelligence, Surveillance, Reconnaissance (ISR) Mission at Tactics Level



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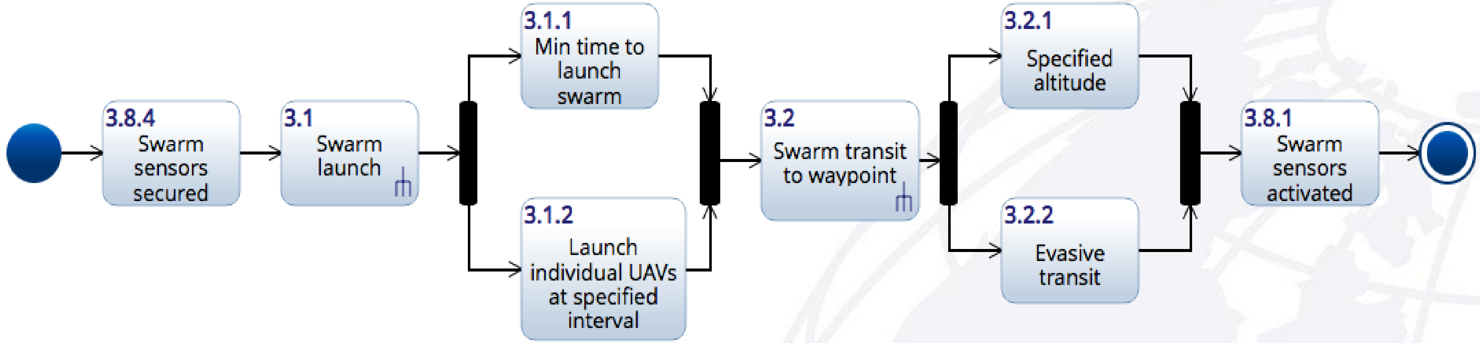
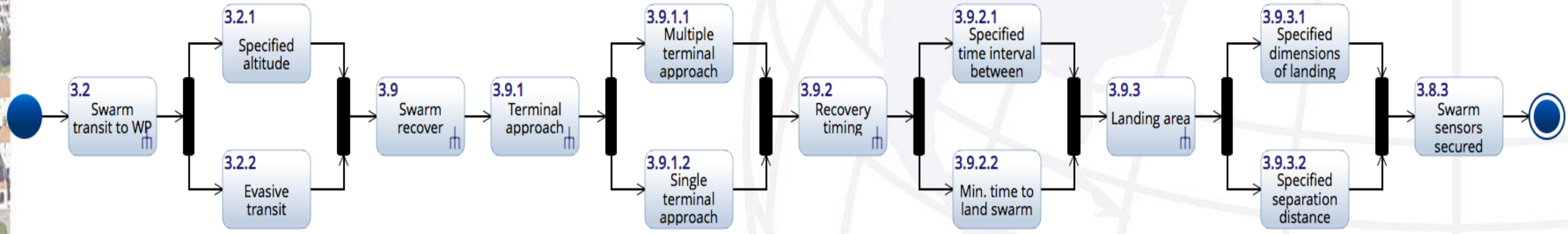
Swarm Tactics Examples

Swarm UAS Ingress Tactic at Play Level



Swarm UAS Egress Tactic at Play Level



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Swarm UAS Mission Architecture Example

State Diagram of Swarm vs. Swarm Mission at Tactics Level

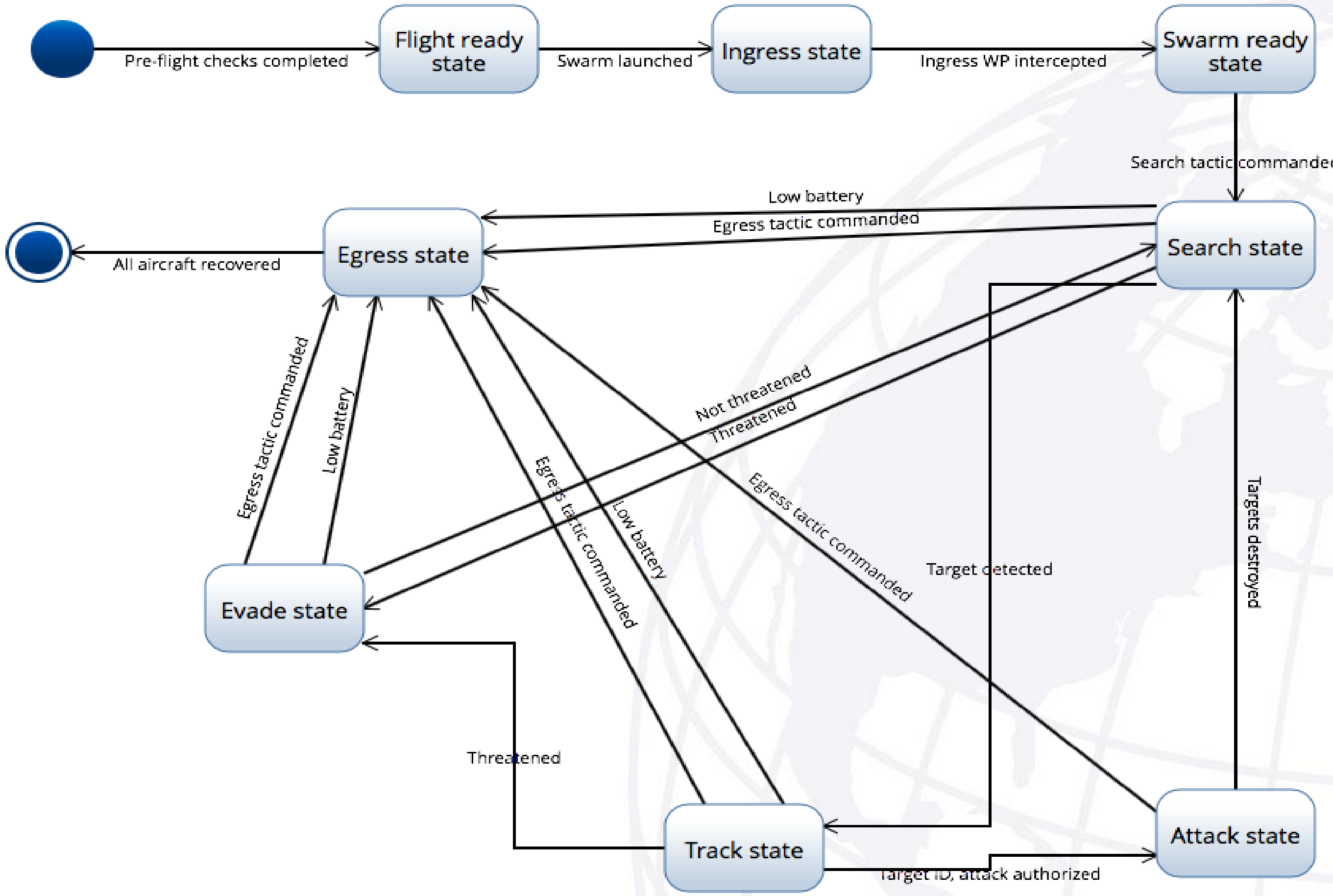

Diagram constructed using *Innoslate*

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Mission Architecture Summary

1 Mission	2 Tactics	3 Plays	4 Algorithms	5 Data
Air Battle: Swarm vs. Swarm	Swarm Ingress	Swarm launch (Min time to launch)	Sorting	Agent state and pose Number of agents Number of launchers
		Swarm transit to WP (Specified altitude)	Flocking	Agent state and pose Number of agents Ingress waypoint
		Swarm sensors activated	Sorting	Agent state and pose Number of agents Sensor range
	Swarm Search	Swarm random pattern	Biologically inspired	Agent state and pose Number of agents Reference positions Search area
	Swarm Track Target	Swarm distributed sensing	Nearest neighbor	Agent state and pose Target pose
	Swarm Attack	Swarm weapon fire	Greedy selection	Agent state and pose Target pose Weapon envelope
	Swarm Evade	Swarm disperse	Physicomimetic	Agent state and pose Number of agents Reference positions
		Swarm join	Physicomimetic	Agent state and pose Number of agents Reference positions
	Swarm Egress	Swarm transit to WP - Specified altitude	Flocking	Agent state and pose Number of agents Egress waypoint
		Swarm recover	Sorting	Agent state and pose Number of agents

Conclusion

- UAS doctrine has been ignored as a specifying design factor in swarm technology.
- Swarm research has focused on developing and varying individual agent behavior until achieving desired collective behavior.
- This research proposes a swarm UAS mission taxonomy designed to support top-down design methodology, using iterative, bottom-up feedback.

Future Work

- Develop model-based systems engineering methods to design swarm UAS architecture from initial doctrine.
- Integrated swarm UAS design framework to support:
  - swarm UAS tactics development,
  - reduction in number of human operators,
  - mission and task-appropriate automation,
  - operationally suitable and effective systems.

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