Engineering Resilience Into Multi-UAV Systems

Edwin Ordoukhanian

University of Southern California
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Edwin Ordoukhanian, Ph.D. Candidate
Department of Astronautical Engineering
Systems Architecting and Engineering
University of Southern California
ordoukha@usc.edu

Professor Azad M. Madni
Department of Astronautical Engineering
Systems Architecting and Engineering
University of Southern California
Azad.Madni@usc.edu
Outline

- Background
- Current Gaps and Research Questions
- New Approach
- Simulation Results
- Summary
Background

- Multi-UAV Systems have gained interest in recent years
- They operate in open, dynamic environment
  - exposed to many disrupting events
- Need to make decisions continuously during operation
  - during both nominal and off-nominal conditions
- Disrupting events that impact multi-UAV operation can be handled through many alternatives
  - some pre-planning for potential disruptions can be done a priori – however it is not a scalable solution!
Multi-UAV Systems

- A collection of UAVs to carry out specific mission
- Every mission has 4 main phases\(^{[23]}\)
  - deployment, en-route, action-on-objective, re-deployment
- Within every phase, maneuvers fall into 5 patterns\(^{[24]}\)
  - Vertical Take-off and Land; Hover; Straight Path with/without angle; Flying in an arc; Combined Maneuvers
- 3 types of Command and Control \(^{[24]}\)
  - Human-centered
  - Decentralized Control with Human as Supervisor
  - Fully Autonomous
Multi-UAV System Conceptual Framework
Summary of Current Gaps

- Multi-UAV mission execution is currently limited to pre-loaded plans with limited flexibility to known disruptions.

- Safety and risk-based analysis techniques are suitable for single systems (to some degree), but, their application to system-of-systems is limited [19,20]
  - It is rarely the case that one designs constituent systems within SoS from scratch [21,22]
  - Existing systems are usually integrated together under SoS umbrella to satisfy mission requirement.
  - Constituent systems are fully developed systems with some degree of fault tolerance and robustness [21,22]
  - When integrating constituent systems and forming the SoS, the systems engineer can ensure that SoS is robust and can withstand disrupting events, however, anticipating every disruption that can occur is a daunting task [19,20,21,22]
  - It is important to show dynamic adaptability during SoS operation to unexpected events when each system has already some degree of fault-tolerance and robustness.

- There is no method for exploration, comparison, and then selection of appropriate response to disrupting events during multi-UAV operation.
Multi-UAV System Research Areas

- Observation and Monitoring
- Detection and Identification
- Communication and Networking
- Execution and Control
- Decision Making and Planning
Research Focus

- Continuous decision making during nominal and off-nominal conditions to carry out a multi-UAV mission when:
  - each UAV performs set of tasks (T1 ... Tm) within constraints (e.g. limited time and resources)
  - UAVs share information with each other and central authority
  - UAVs have already some level of fault-tolerance and robustness
  - there is a central authority responsible for global decisions with respect to the overall mission – it does not micro-manage each agent
    - central authority has many alternatives to select from to handle a disrupting event (known disruptions, but unexpected)
    - decision about which alternative to select must be made within constraints

- The goal is to select an alternative (given constraints) to handle disrupting events
  - i.e. perform uninterrupted operation within acceptable level of performance and constrains
Research Questions

What is a method that enables exploration, comparison, and selection of appropriate mechanism to achieve dynamic adaptability of multi-UAV system?

- What are the main components of that method?
- How alternatives can be compared to each other?
- How to verify that it works?
Multi-UAV as System-of-System

- Vehicles have operational independence as each system operates to perform its assigned function while also participating in the SoS to carry out the overall mission.
- Vehicle can also have different governance while participating in the SoS.
- Multi-UAV SoS evolves with functions and purposes added, removed, and modified with experience and with changing needs or mission objectives.
- Multi-UAV SoS exhibit emergent behavior as SoS overall functionality do not reside within any single UAV;
  - Multi-UAV SoS behavior cannot be realized by a single UAV.
- UAVs are geographically distributed since primarily exchange information - not mass or energy.
- From DoD classification, Multi-UAV is directed + collaborative.
Multi-UAV System Architecture
Dynamic Adaptation in Multi-UAV Systems

- Ability to operate without interruption within acceptable level of performance and constraints when faced with disrupting events or changing conditions

- Alternatives to handle disrupting events\(^2\):  
  - Human as a Backup: bring human into the loop when the system is unable to handle disruption (humans are good adaptation source)  
    - viewed as the last option for a collection of autonomous systems  
  - Pre-planned Protocols: execute pre-defined plan to handle known disruptions  
  - Physical Redundancy: Another identical system replaces incapacitated system  
    - E.g. deploying a new UAV and integrating it into the system  
  - Functional Redundancy: achieve same functionality by other means  
  - Function re-allocation: re-distribution of overall functionalities (or remaining tasks) among remaining systems upon a disruption  
  - Circumvention: avoid a disrupting event by necessary re-planning  
  - Neutral State: go into a safe mode to prevent further damage  
    - e.g. do nothing - especially important for autonomous system\(^2\)

- How to measure?  
  - Time to restore operation or specific functionality  
  - Adaptation within time constraints
Alternative Evaluation Method

- Enables evaluation, comparison and exploration of alternatives to handle disrupting events
  - without prematurely converging into specific solution

- By Product of the method:
  - Mapping of disrupting events to alternatives under various conditions
  - Generating set of simulation-based heuristics which can be used during system design and mission design
    - See backup for some of the heuristics

- The method consist of:
  - Multiple system operational mode to handle dynamic situations
  - Library of scoring functions and adaptation alternatives
  - Alternative Construction using models and algorithms
  - Evaluation of Adaptation Alternatives
Alternative Evaluation Method

Agent 0 (central authority)

Agent 1

Agent n

Resources

Safety

Mission

Determine Current Operational Mode

Determine Weightings based on priorities

Select Set of Alternatives

Construct Alternative Details

Evaluate Alternatives

Select Alternative

Alternatives

Models

command

feedback
## Multi-UAV System Operational Modes

<table>
<thead>
<tr>
<th>Mission-Dominant Modes</th>
<th>Safety-Dominant Modes</th>
<th>Resource-Dominant Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission-Safety</td>
<td>Safety</td>
<td>Resources</td>
</tr>
<tr>
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<td>Safety-Resources</td>
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<tr>
<td>Mission</td>
<td>Safety –Mission-Resources</td>
<td>Resources-Mission-Safety</td>
</tr>
</tbody>
</table>

*Extended from [3]*

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Evaluating Alternatives

- Utility function must be differentiable and continuous \(^{[2]}\)

- Which categories of variables must be considered?
  - Based on literature [3-24] survey can be group into following categories
    - Mission
      - e.g. time to complete mission, covered area
    - Resources
      - e.g. available vehicles on reserve, batter power, comm. bandwidth
    - Safety
      - e.g. collision, hacking

- Since they are reasonably linearly independent, utility function takes the following form, based on \(^{[3]}\)

\[
Utility = w_1 \text{Mission} + w_2 \text{Resource} + w_3 \text{Safety}
\]
Calculating Weightings

Resources-Mission-Safety

Mission-Safety-Resources

Ratio between \( w_1 \) \& \((w_2 + w_3)\); \( w_2 = w_3 \)
Simulation Results: Modeling Architecture
Simulation Results: Multiple Vehicles

### Mission Profile

<table>
<thead>
<tr>
<th>Number of UAVs on Reserve</th>
<th>1</th>
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</thead>
<tbody>
<tr>
<td>Desired Mission Completion Time</td>
<td>130 s</td>
</tr>
<tr>
<td>Maximum Allowable Time to Complete Mission</td>
<td>200 s</td>
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</table>

### Modes Profile

<table>
<thead>
<tr>
<th>Tactic</th>
<th>Time</th>
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<tbody>
<tr>
<td>Mission-Safety-Resources</td>
<td>T&lt;=55s</td>
</tr>
<tr>
<td>Safety –Mission-Resources</td>
<td>T&gt;55s</td>
</tr>
</tbody>
</table>

### Alternatives Utility

Mission Completed in 155 Seconds

**Vehicle’s Path**

![Vehicle’s Path Diagram](image_url)

**Mission Profile**

- Number of UAVs on Reserve: 1
- Desired Mission Completion Time: 130 s
- Maximum Allowable Time to Complete Mission: 200 s

**Modes Profile**

- Mission-Safety-Resources: T<=55s
- Safety –Mission-Resources: T>55s

**Alternatives Utility**

![Utility Graph](image_url)
Simulation Results: Multiple Vehicles

Mission Profile

<p>| | |</p>
<table>
<thead>
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<tbody>
<tr>
<td>Number of UAVs on Reserve</td>
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<tr>
<td>Desired Mission Completion Time</td>
<td>130 s</td>
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<tr>
<td>Maximum Allowable Time to Complete Mission</td>
<td>200 s</td>
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</table>

Modes Profile

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
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</thead>
<tbody>
<tr>
<td>Resources-Mission-Safety</td>
<td>T&lt;=180</td>
</tr>
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</table>

Alternatives Utility

Vehicle’s Path

Mission Completed in 155 Seconds

Note: Deploy alternative doesn’t get evaluated since there are no available UAVs on reserve
Summary

- Multi-UAV Systems have been of interest in recent years
- There is a gap associated with exploring alternatives for dynamic adaptation of multi-UAV systems when viewed as SoS
- Dynamic adaptation is not only about handling disrupting events, but also handling changing conditions such as addition of tasks
- It is possible to achieve dynamic adaptation of multi-UAV systems by evaluating alternatives real-time
References

Thank You