Engineering Resilience Into Multi-UAV Systems

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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

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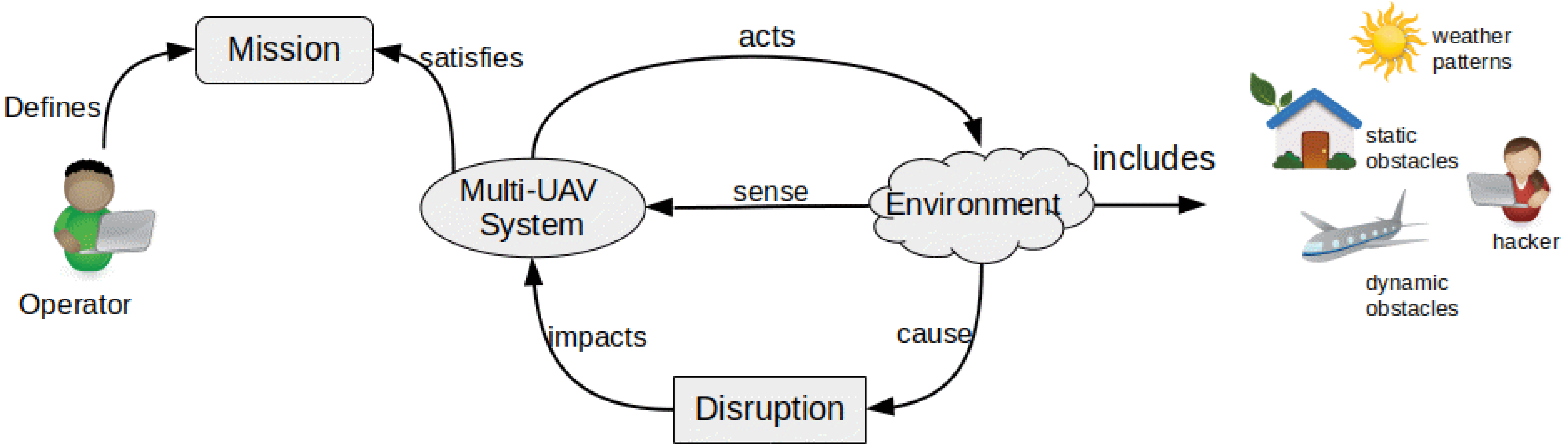
Multi-UAV System Conceptual Framework



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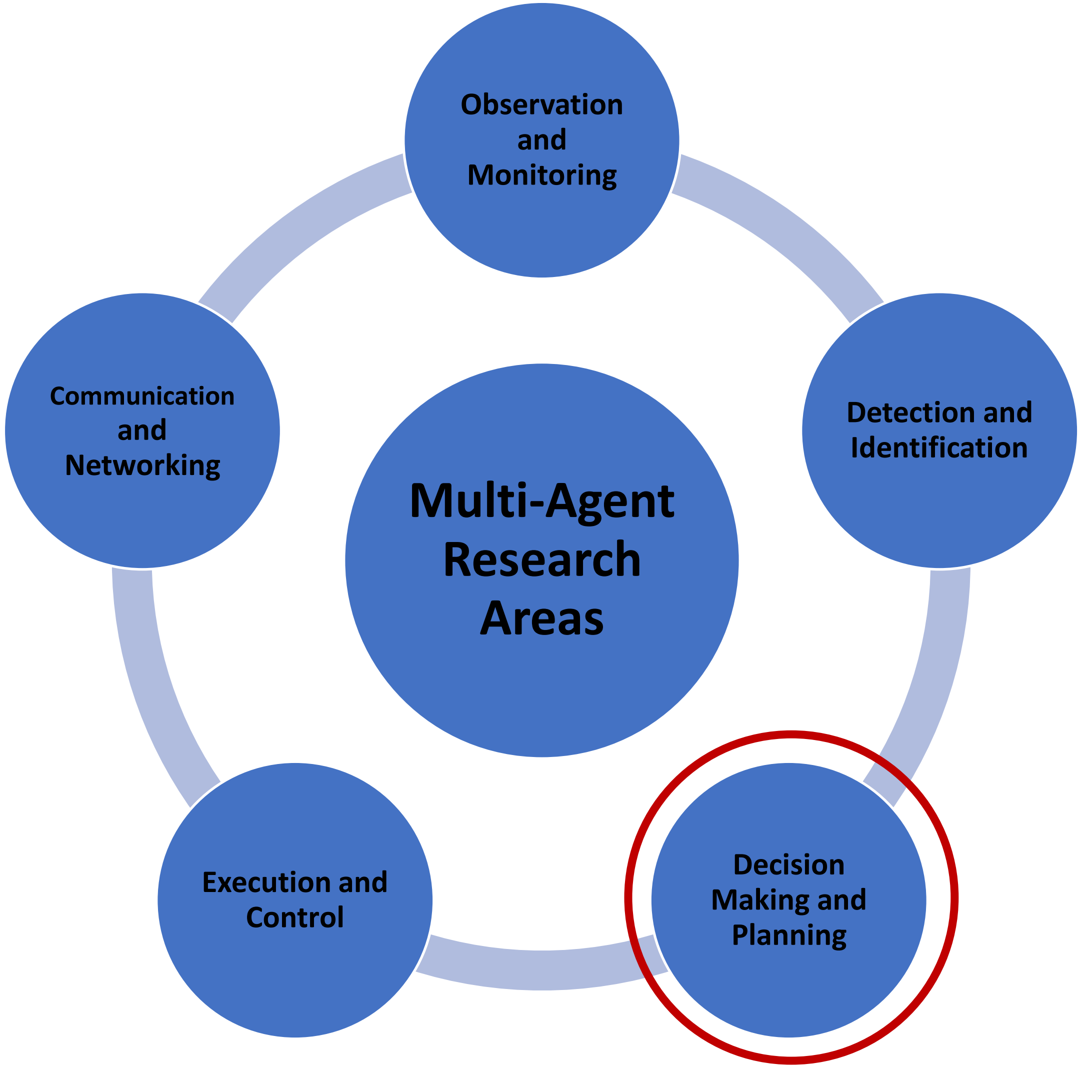
Summary of Current Gaps

- 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



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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

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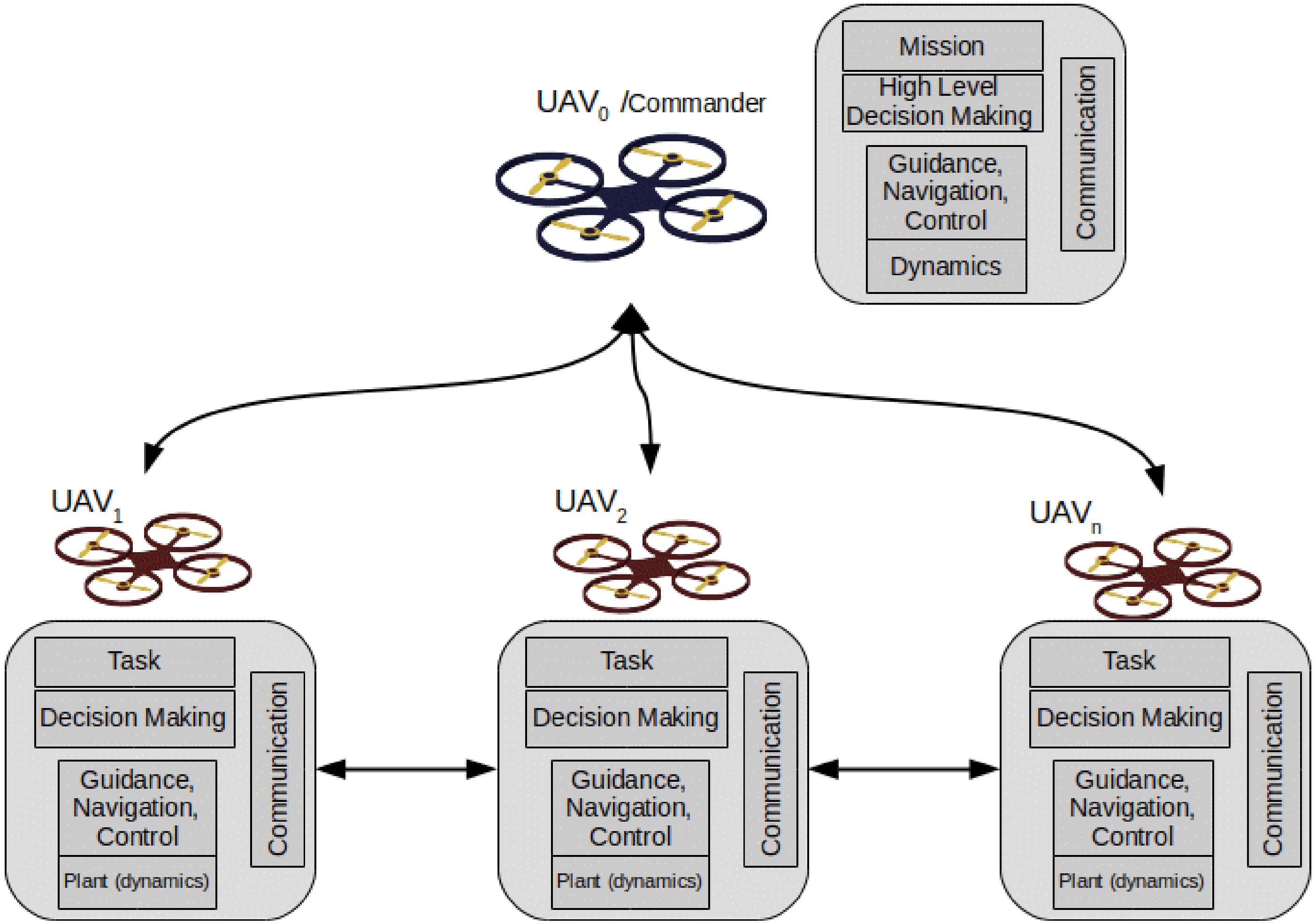
Research Questions

- 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



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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[25]:
  - 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

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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

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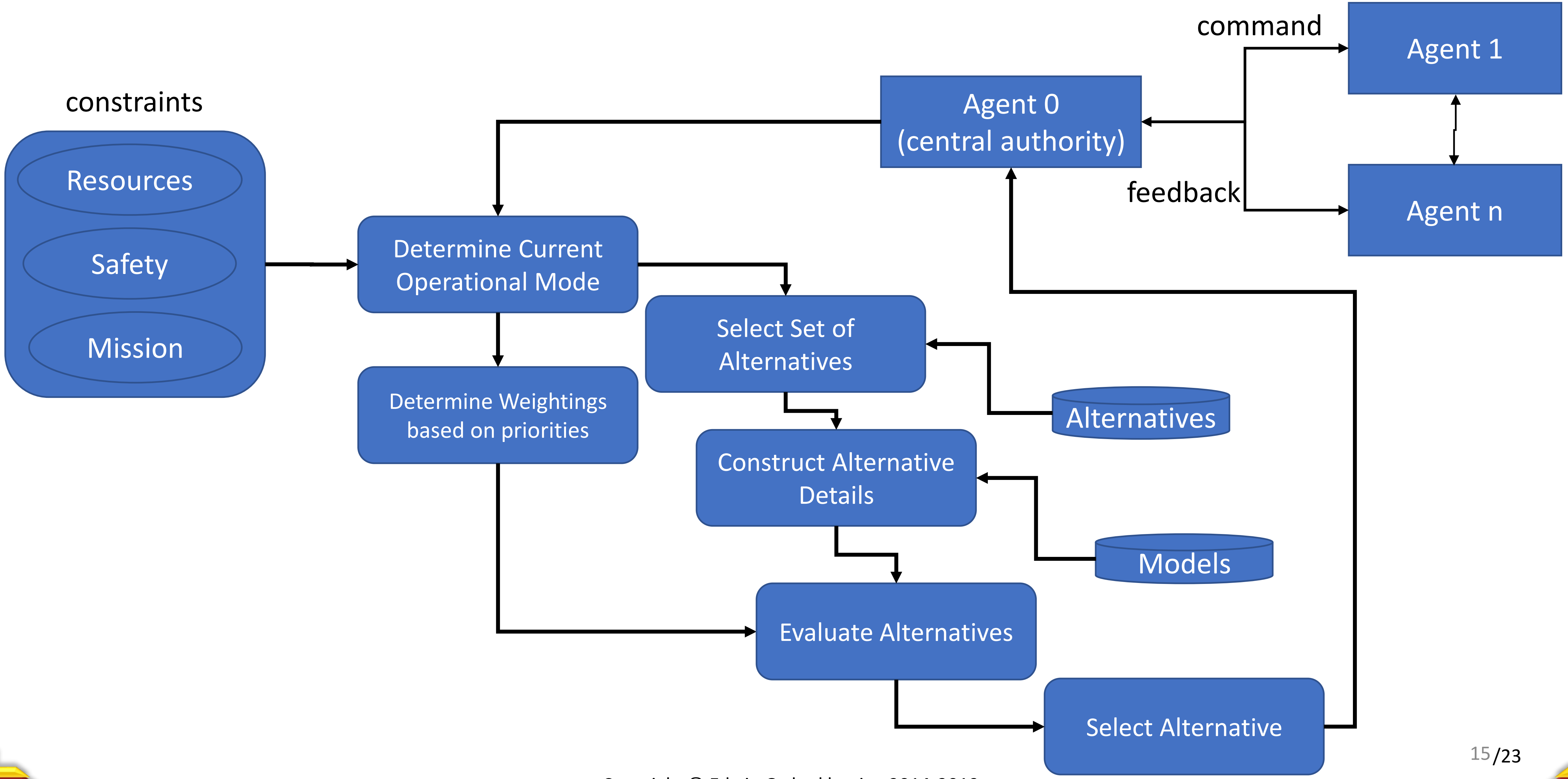
Alternative Evaluation Method



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Multi-UAV System Operational Modes

	M	S	R
Mission-Safety	1	2	-
Mission-Safety-Resources	1	2	3
Mission-Resources-Safety	1	3	2
Mission-Resources	1	-	2
Mission	1	-	-

Mission Dominant Modes

	M	S	R
Safety	-	1	-
Safety-Resources	-	1	2
Safety-Resources-Mission	3	1	2
Safety-Mission	2	1	-
Safety –Mission-Resources	2	1	3

Safety Dominant Modes

	M	S	R
Resources	-	-	1
Resources-Safety	-	2	1
Resources-Mission	2	-	1
Resources-Safety-Mission	3	2	1
Resources-Mission-Safety	2	3	1

Resource Dominant Modes

Extended from [3]

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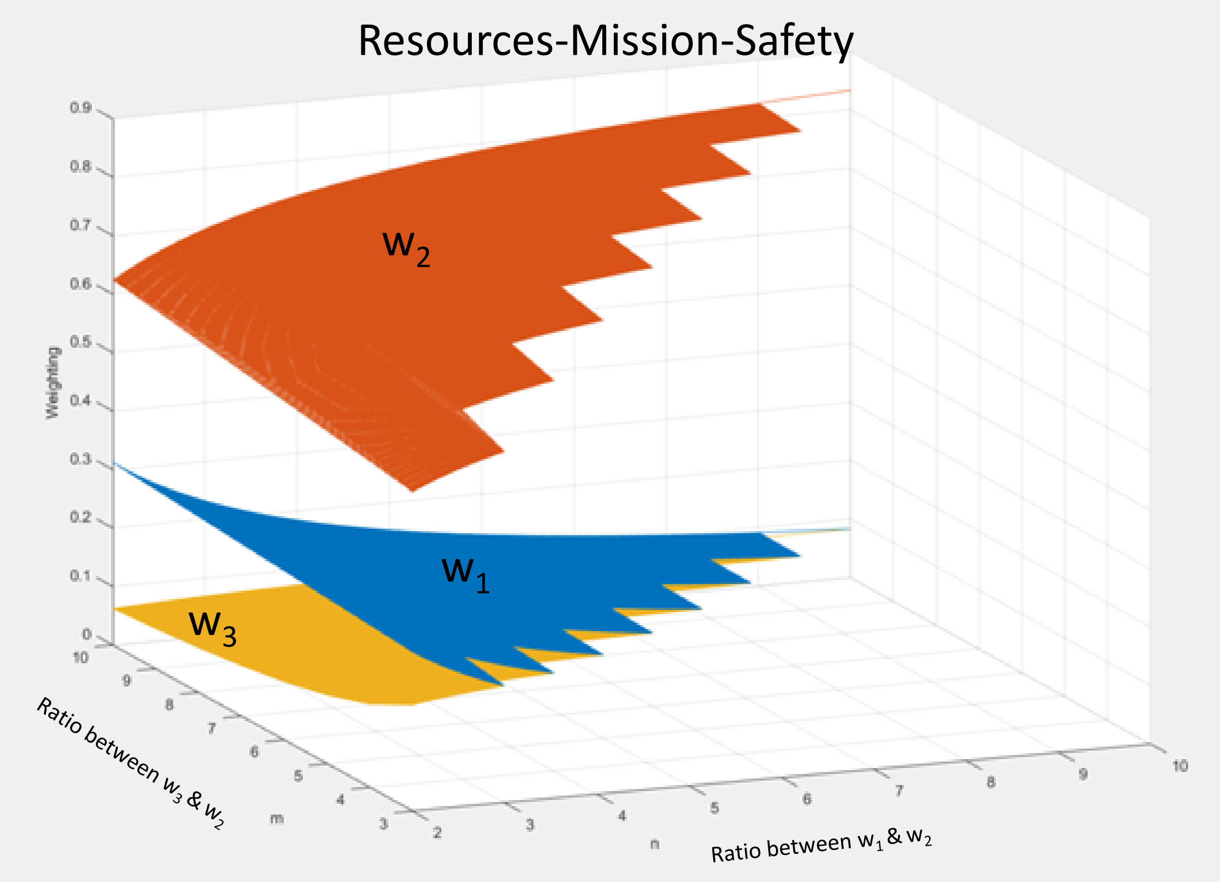
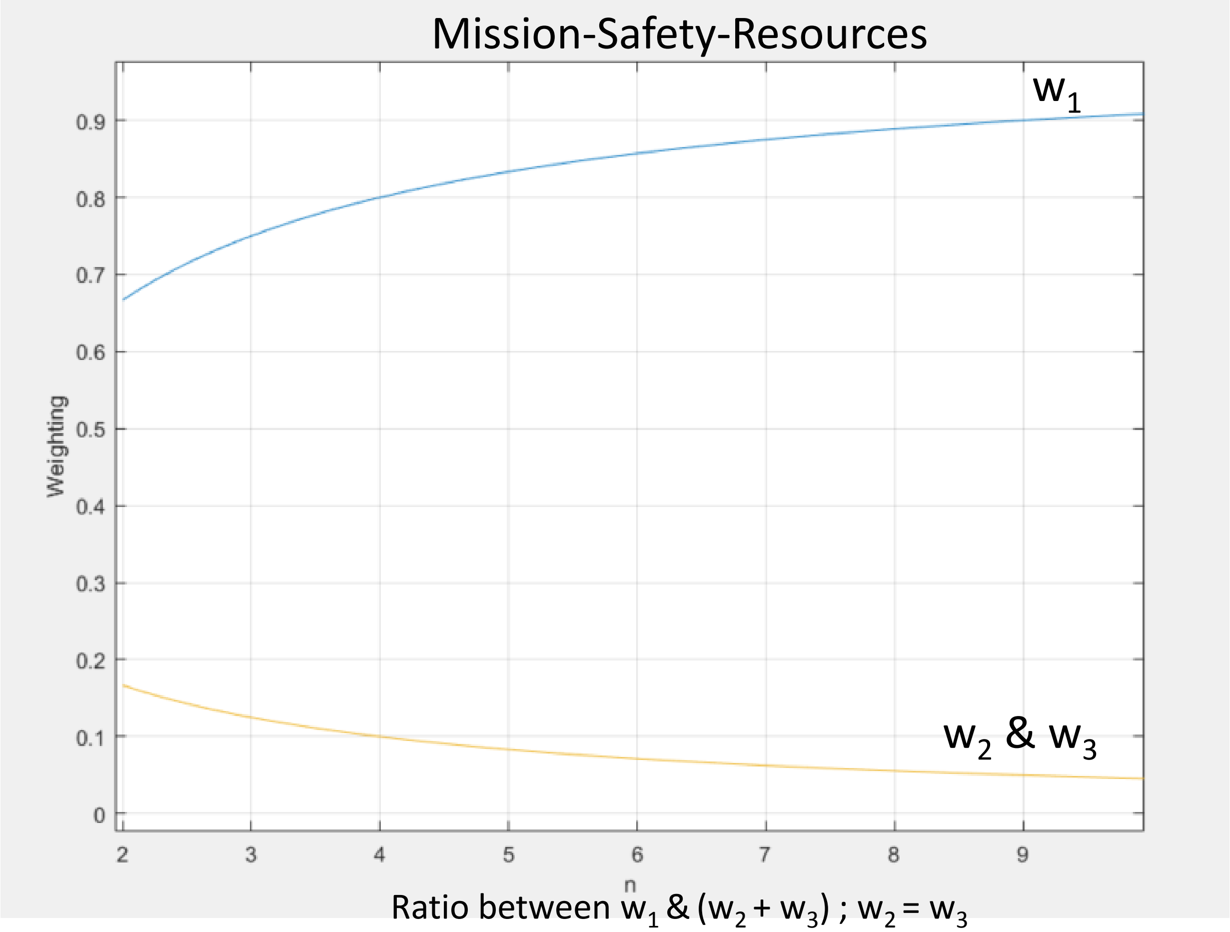
Evaluating Alternatives

- 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]

$$Utility = w_1 Mission + w_2 Resource + w_3 Safety$$

Calculating Weightings





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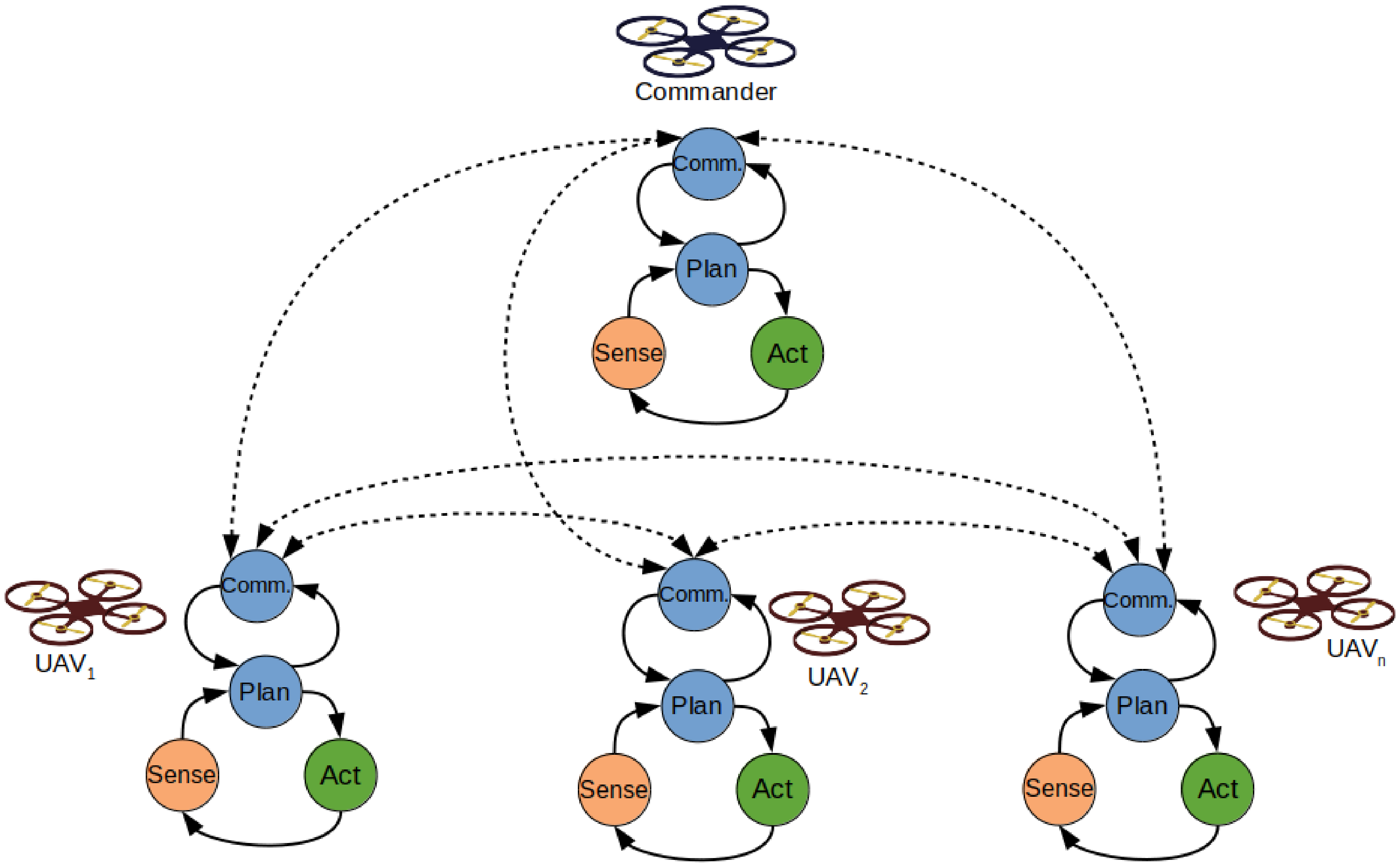
Simulation Results: Modeling Architecture



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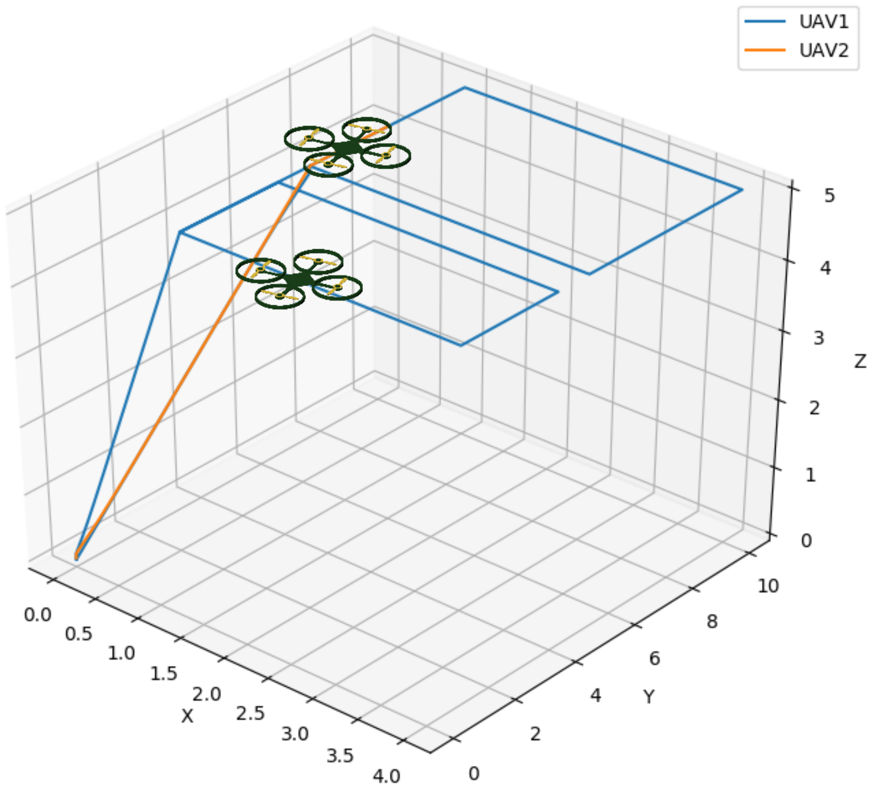
Simulation Results: Multiple Vehicles



Vehicle's Path

Mission Completed in 155 Seconds

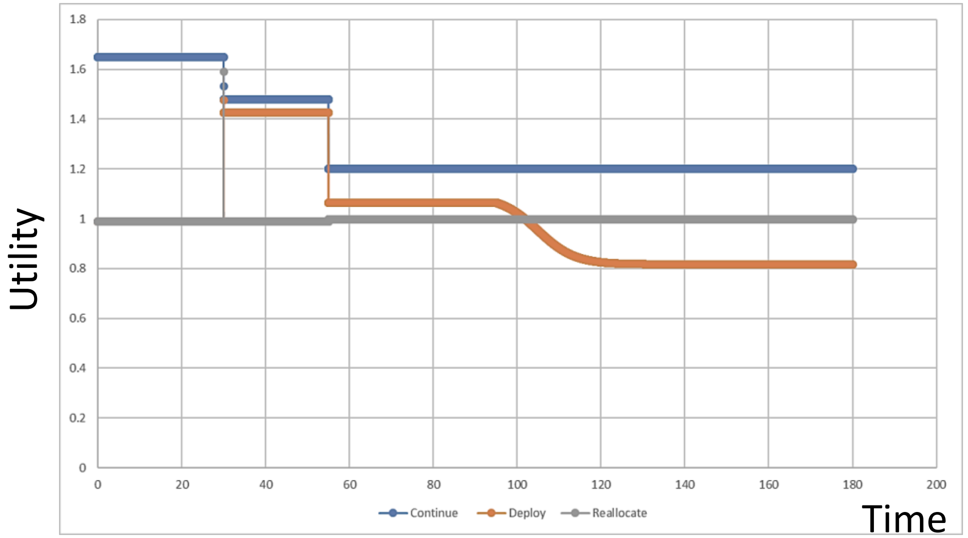
Mission Profile

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

Modes Profile

Tactic	Time
Mission-Safety-Resources	T<=55s
Safety –Mission-Resources	T>55s

Alternatives Utility



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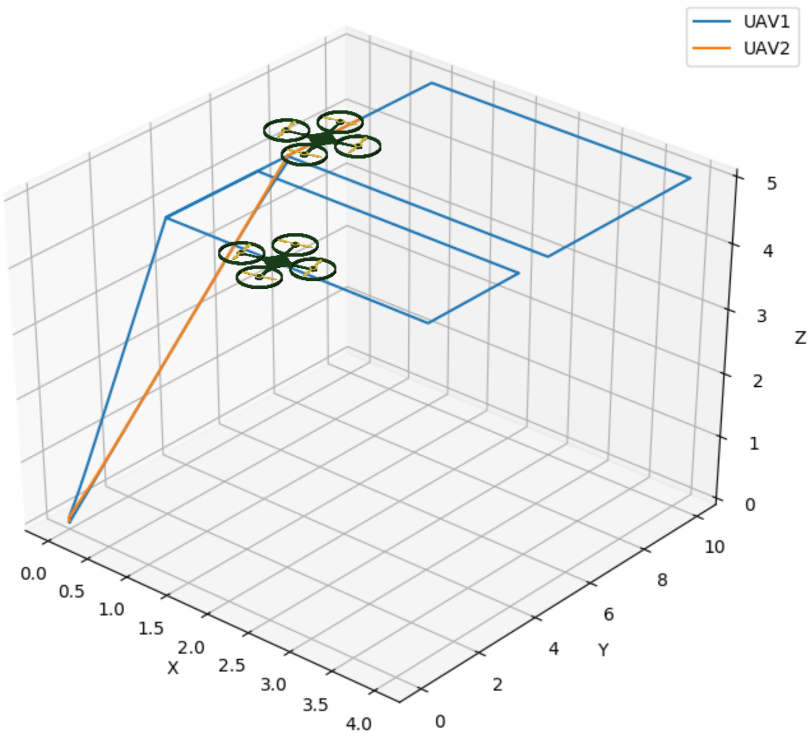
Simulation Results: Multiple Vehicles

Mission Profile

Number of UAVs on Reserve	0
Desired Mission Completion Time	130 s
Maximum Allowable Time to Complete Mission	200 s

Modes Profile

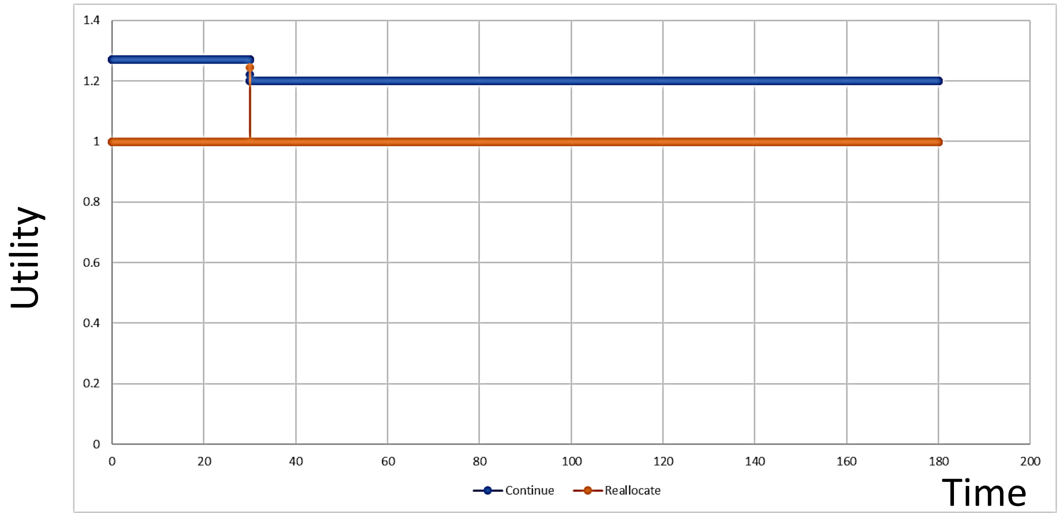
Mode	Time
Resources-Mission-Safety	T<=180



Vehicle's Path

Mission Completed in 155 Seconds

Alternatives Utility



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

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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

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Thank You