Resilience Concepts for UAV Swarms

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Background

- Unmanned Aerial Vehicles (UAVs) are seeing increasingly greater use in both defense and civilian operations
- Often multiple UAVs are deployed to satisfy the needs of the mission
- UAV swarms can be homogenous or heterogeneous
- Member of the swarm need to collaborate to carryout their mission
- Flexible allocation of requirements tasking to individual vehicles is an essential aspect of swarm resilience

UAV Swarm

- No single vehicle responsible for entire operation
- Component systems (i.e. UAV) can be incrementally integrated and tested, and ultimately, deployed in operational environment
- Comprises standalone systems (i.e. UAVs) brought together to satisfy mission capability requirements
- Dynamically assembled to perform a particular mission
- Can be reorganized to perform other missions
- Collaboration among UAVs provides significant operational advantages through improved situational awareness
- Can have a leader and subordinates, or multiple agents commanded by ground station

UAV Swarm
(cont'd)

- Component systems can be based on different technologies
  - requires resolving technology and semantic incompatibilities
- Evolve with functions and purposes added, removed, and modified with experience and/or with changing needs
- Exhibits complex adaptive system's characteristics
  - **Heterogeneity**, diversity in interactions
  - **Randomness,** patterns or predictability in interactions
  - **Modularity,** clustering or grouping in interactions

Resilient UAV Swarm Operation

- UAV swarms operating in open environments are susceptible to disruptions
- Uncertainties and unexpected factors in the environment can disrupt systems operation and adversely impact overall system performance
- Ability to maintain acceptable levels of performance through flexibility and adaptability in the face of disruptions is called **resilience**
- Designing a resilient multi-UAV system requires in-depth trade-off studies that spans both SoS and individual system level

Typology of Disruptions
(Madni and Jackson, 2009)

- **External,** associated with environmental obstacles and incidents; often random and with unknown severity and duration
- **Systemic,** happens when internal component's functionality, capability or capacity causes performance degradation; easily detectable in technological systems
- **Human-triggered** are associated with human operators inside or outside of the system boundary
- Disruptions can be **predictable** or **random**

Modeling Disruptions

- **Predictable** disruptions are modeled in terms of time of occurrence, location of occurrence, and triggering event
- **Random** disruptions are described using probability distributions
- Disruptions severity is typically a function of **context** and **duration**
  - **context** reflects the system's state and current operational use
  - **duration** determines whether a disruptive event is temporary or an indication of a trend

Applicable Resilience Definitions

- Maintain acceptable level of service (performance) in the face of interruptions in system's normal operation
- Serve effectively in a variety of missions with multiple alternative through rapid reconfiguration or timely replacement despite uncertainties about individual system performance
- Anticipate, resist, absorb, respond to, adapt to, and recover from both natural and man-made disruptions

Applicable Resilience Concepts

- **Loose coupling** between component systems to assure ease of change in interactions among component system
- **Human Backup** if a component system fails
- **Preplanned protocols** if communication between UAVs or between UAVs and ground station fails
- **Physical Redundancy** to have another UAV take over when one UAV fails, or have another subsystem in a UAV take over when one subsystem fails
- **Functional Redundancy,** achieve same functionality by other means
- **Function re-allocation** to re-distribute tasks among remaining UAVs upon the loss of an UAV (disruption)
- **Drift correction** to initiate counter measures before onset of disruptions

Learning From Disruption

- UAV swam can learn from disruptions by capturing disruption type, operational context, and actions taken for recovery
  - accumulates “experience” during operation
  - improves in recovery from future disruptions the longer it operates

Resilience Methods: Overview

- **Identification of Levers:** Early identification of potential disruptions in the operational context allows identifying key areas of resilience
- **Trade-offs and Risk Analyses:** tied to mission context and underlying physics
- **State Estimation:** determination of current state and path to desired end state, or neutral state
- **Tradespace Exploration:** to uncover hidden interactions among UAVs, and to understand how change propagates
  - allows incorporating measures such as adding resources, adding margins, and increasing capacity to counteract

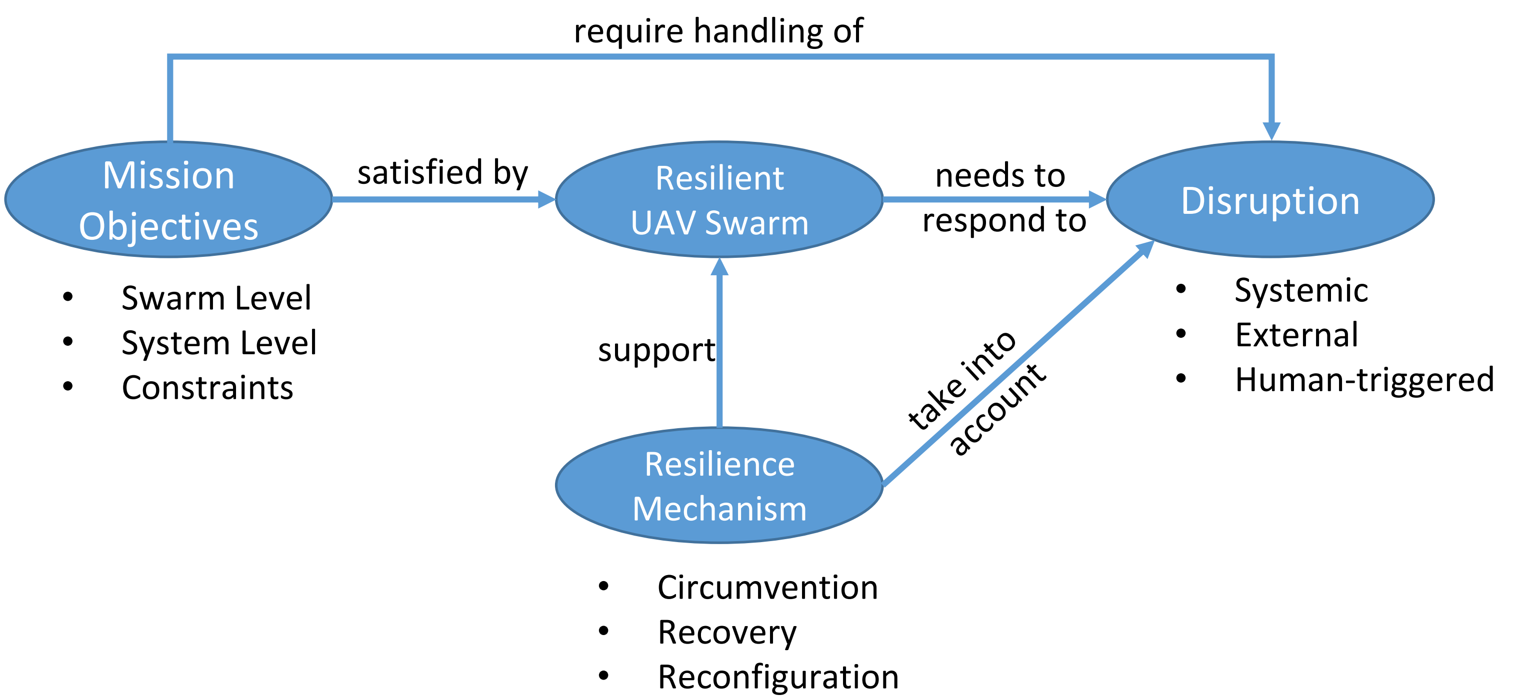
Resilient UAV Swarm Characteristics

- Localized Capacity
  - if an UAV is damaged, remaining UAVs should be able to take over the functions of the incapacitated UAV
- Collision avoidance
  - SoS, as well as, UAVs are able to detect and avoid obstacles
- Re-configuration and maneuverability of the entire system-of-system
  - presence of some obstacles may not be known due to uncertainties in operational environment
- Extending capacity and capability to deal with disruption

Exemplar Metrics

- **Flow Rate,** accurate and timely data flow
  - successful operation heavily depends on effective, reliable, and secure communication between UAVs
  - state awareness depends on data flow
  - shared semantics is key to successfully and effectively transmitting the data among UAVs
- **Response time,** round-trip time between sending a command to the swarm and receiving a response
  - task distribution algorithm, individual system's capabilities, and communication bandwidth and protocols impact response time
- **Recovery time,** time it takes between detecting a failure and restoring operation

Conceptual Framework for Resilient UAV Swarm



Challenges in Introducing Resilience

- Design of resilient UAV swarm significantly impacts both cost and development schedule
- Not cost-effective to design a UAV swarm that deals with infrequent, inconsequential disruptions – need to prioritize and address the most consequential
- Likelihood of conflicts among requirement increases with an increase in the number of UAVs in the swarm
- As complexity increases, system becomes more vulnerable and less reliable – minimize structural complexity (elegance)
- Heterogeneity of UAVs impacts resilience mechanisms design

Challenges in Introducing Resilience (cont'd)

- Multiple resilience mechanisms can be implemented to deal with disruptions - need to ensure that resilience mechanisms are compatible and affordable
- Defining right metric to measure effectiveness of a resilience mechanism – need to evaluate metric relevance through sims
- Oftentimes achieving resilience in one area can make the system fragile in other area(s) – need to perform trade studies
- Difficult to back track events to identify main source(s) of disruption in a dynamic environment
- V & V of a resilient UAV swarm is likely to be time-consuming and costly – can exploit agent-based simulation technology
- Situational (state) awareness in UAV swarm is challenging due to non-determinism – need to employ probabilistic models

Summary

- UAV swarms operate in open and uncertain environments, thus susceptible to disruptions (i.e., external, systemic, human-triggered)
- UAV swarm offer a new mission capability through on-demand composition of needed component systems
- Resilience can be viewed as a combination of flexibility (dealing with expected change) and adaptability (dealing with unexpected change)
- Mission/operational context must be accounted for when designing a resilient UAV swarm operational capability

Summary (cont'd)

- Design of resilient UAV swarm needs to address:
  - system-level
  - swarm level
  - human-system level
- Major challenges:
  - system heterogeneity and complexity
  - non-deterministic and adaptive behavior
  - system verification and validation
  - online real-time trade-offs to determine best course of action while maintaining situational (state) awareness in face of disruptions

Way ahead

- Model UAV swarm scenarios
- Identify disruptions
- Develop resilience mechanisms to respond to disruptions
- Create prototype simulation and demonstrate resilience in UAV swarm
- Document and publish findings in key conference
  - AIAA Science and Technology
  - AIAA Space
  - INCOSE International Symposium

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Thank You