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The mission execution capability of multi-UAV system-of-system today is *limited* to the plans loaded before the mission *without adequate flexibility* to respond to *known* and *unknown* disruptions including:

- system failures (within UAV, within UAV SoS network)
- environmental disruptions (e.g. jamming, loss of communication, loss of observability due to extreme weather)
Research Objectives

- Investigate most appropriate formulation of multi-UAV problem to study resilience of individual UAV and multi-UAV SoS
- Develop a methodological framework to explore impact of candidate resilience mechanisms into individual UAV and SoS
- Identify methods to conduct trade-off analysis in choosing most appropriate resilience mechanism(s)

*mechanisms include algorithms, rules or heuristics that are data-driven or pattern-based*
Research Hypothesis

- By framing the multi-UAV problem as a system-of-system problem the key advantage is the flexibility afforded to study different interaction protocols and conduct trade-offs in terms of both resource allocation and function allocation to the different members in the SoS.
  - these capabilities will enable the investigation of resilience and resilience mechanisms within SoS
- If resilience mechanisms are chosen systematically while conducting trade-offs among them, it will lead to safe and faster recovery from disruptions while maintaining acceptable level of performance
  - defining and measuring resilience and resilience mechanism largely depends on the problem domain and mission context
  - Mechanisms can be in conflict, hence trade-off analysis is necessary

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Multi-UAV Operations

- High demand for Unmanned Aerial Vehicles(s)
  - military reconnaissance; surveillance; science data collection
- Designing and operating single vehicle that meets all requirements is **costly** and **labor-intensive**
- UAVs can experience down time
  - internal failure; scheduled maintenance; refueling
  - disruptions in single-vehicle operation puts mission success and completion at risk
- Multi-UAV operation enables allocation of mission requirements to different vehicles
  - flexibility in allocating requirements to multiple vehicles - reduces design complexity
  - flexibility in allocating functionalities to different vehicles - increases overall mission performance
Multi-UAV as SoS

- Vehicles have **operational independence** as each system operates to perform its assigned function while also participating in the SoS put together 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
Applicable Resilience Definitions in Multi-UAV Context

- 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
- Anticipate, resist, absorb, respond to, adapt to, and recover from both natural and man-made disruptions
- 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; relatively easy to detect in technological systems
  - **Human-triggered** are associated with human operators inside or outside of the system boundary
  - Disruptions can be **predictable** or **random**
Applicable Resilience Concepts

- **Loose coupling** between component systems to assure ease of change in interactions among component system
- **Human Backup** if communication between UAVs is lost, or a malfunction in system function occurs
- **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

Resilient Behavior of Multi-UAV SoS

- Localized Capacity
  - if an UAV is damaged, remaining UAVs should be able to take over the functions of the incapacitated UAV
    - e.g. functional re-allocation, functional redundancy

- Collision avoidance
  - SoS, as well as, UAVs are able to detect and avoid obstacles
    - presence of some obstacles may not be known in operational environment
    - re-configuration and maneuverability of the entire SoS
    - requires multi-UAV coordination and cooperation

- Extending capacity and capability to deal with disruption
  - with human intervention
  - autonomously
Resilient Multi-UAV Conceptual Schema

- Environment
  - Resilient Multi-UAV SoS
    - Disruption
      - Resilience Mechanism
        - SoS Type
          - Mission Objectives
            - coordination and cooperation
              - takes into account
                - constraints
                  - SoS Type
                - drives
                  - takes into account
                    - needs to respond to
                      - impacts
                        - causes
                          - impacts
                            - satisfies by
                              - Resilient Multi-UAV SoS
                                - Employs
                                  - Resilience Mechanism
                                    - takes into account
                                      - impacts
Resilience Mechanisms (RM)

- A series of actions or steps taken to perform one or more of the following: anticipate, resist, absorb, respond to, adapt to, and recover from disruptions
- Can be an algorithm, set of rules, or heuristics to deal with known and unknown disruptions
- Resilience Mechanisms enable two key functions: observe and detect, and guide and control
  - activities such as data analytics, context management, and real-time trade-off analysis support these two primary function
Multi-UAV SoS Dealing with Disruption

Observe
- Monitoring
- Prediction
- Internal Model

Orient
- Data Analytics
- Context Management

Decide
- SoS Level
- Trade-off Analysis
- System Level

Act
- Recovery
- Adaptation
- SoS Level
- System Level

Environment
- Operate
- Impact

State Feedback
- AKB

Similar to OODA loop introduced by John Boyd

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Trade-off Analysis Framework for SoS Network

Identify SoS Requirement

Generate Option

Network/SoS Level Loop

Evaluate Option

Evaluate Option

Identify System-level requirement

Root Cause Analysis

Verifying solution against requirement

Evaluate Option

Node/System Level Loop

Generate Option

Proceed to execution
Notional Flow for employing RMs to Recover from Disruptions

(a)

Observe System Performance

Performance Out of Boundaries?

Yes

Identify Disruption type

SoS Level?

No

Employ SoS RM

Adjust Systems

SoS Performance Improved?

Yes

No

Employ System Level RM

Adjust SoS

System Performance Improved?

Yes

No

Continue Operation

Mission Objective Reached?

Yes

Stop

No

Adjust Course of Action

Continue Operation

Go to (a)

AKB

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Example Criteria for RM Comparison in Multi-UAV SoS

■ Flow Rate
  ➢ maintain accurate, timely, and consistent data flow
  ➢ maintain high situation(state) awareness

■ Response time
  ➢ remain responsive when dealing with disruption
    • round-trip time between sending a command and receiving a response (including latency)

■ Recovery time
  ➢ keep recovery time minimum
    • time between detecting a failure and restoring operation

■ Feasibility
  ➢ resources and capabilities with multi-UAV SoS
Current Implemented Model

Desired Trajectory

Waypoints

Obstacle Position (X,Y,Z)

Obstacle Detection

Position X, Y, Z (altitude)

Position

Attitude (Roll, Pitch, Yaw)

Environment (static obstacles)

Quadcopter Nonlinear Dynamics

Sensors

Autopilot

Position Controller

Attitude Controller
Multi-Quadcopters Operation: Avoiding Static Obstacles

Quadcopter color changes with altitude

Static Obstacle

Desired path

Quadcopter 1 path

Quadcopter 2 path

Quadcopter 3 path
Way Ahead

- Extend current model to include dynamic disruptions, multi-UAV coordination
- Identify combination of resilience approaches to deal with disruptions
- Simulate multiple scenarios and collect data
- Summarize findings
References


Thank You