System Re-tasking to Achieve Resilience in a System-of-Systems (SoS)

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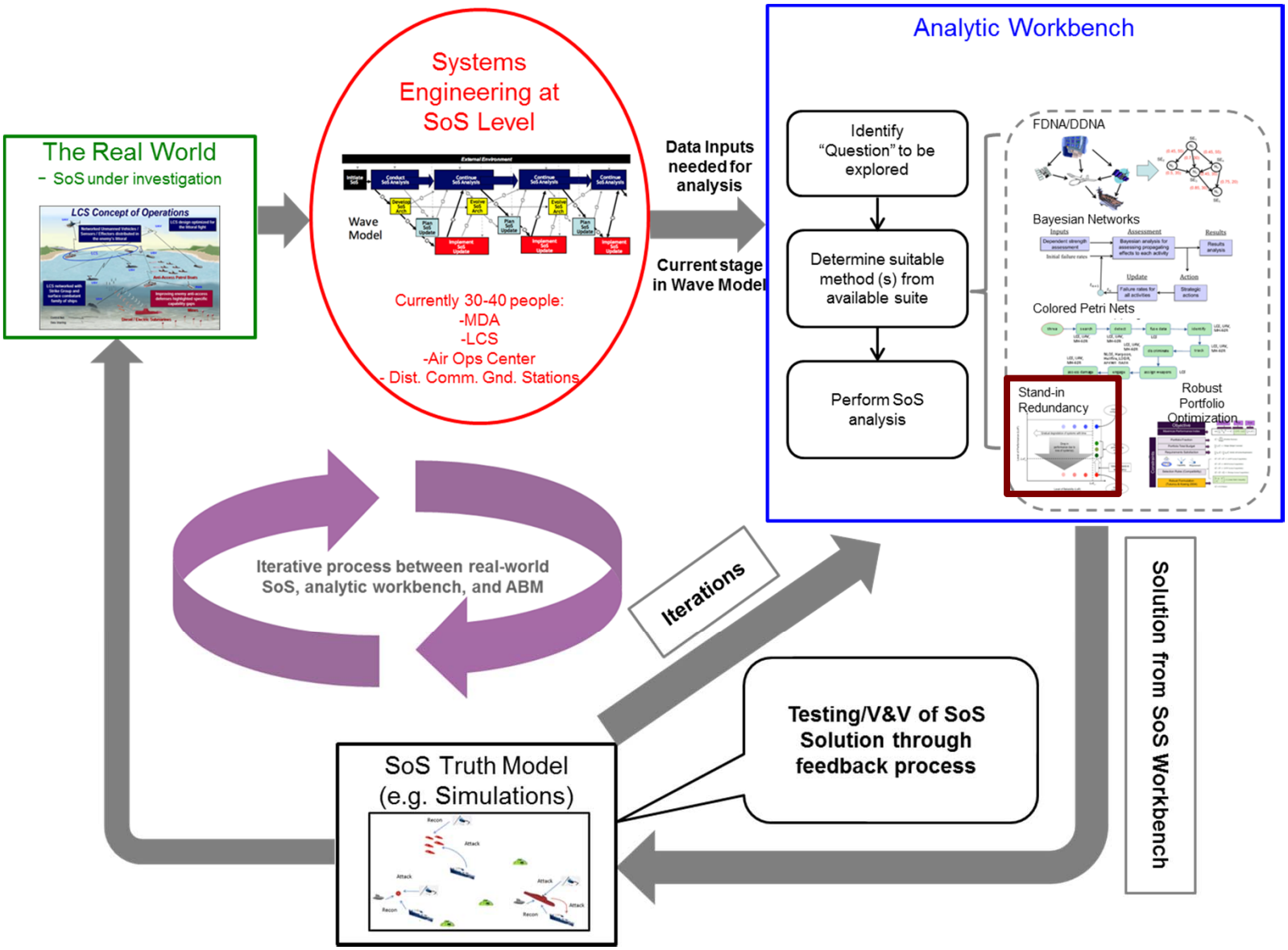
Outline

- RT – 44b : “Big Picture”
- Background: Overview of Resilience
- Representation of a SoS
- Analytic framework
- Illustrative example
  - Notional 5-node SoS
  - Results and discussion
- Current Work
- Summary and Future work

RT-44b: SoS Analytic Workbench



Background:
Introduction to Resilience

- What is resilience?
  - "Resilience is the ability of a system or organization to react to and recover from disturbances at an early stage with minimal effect on its dynamic stability"

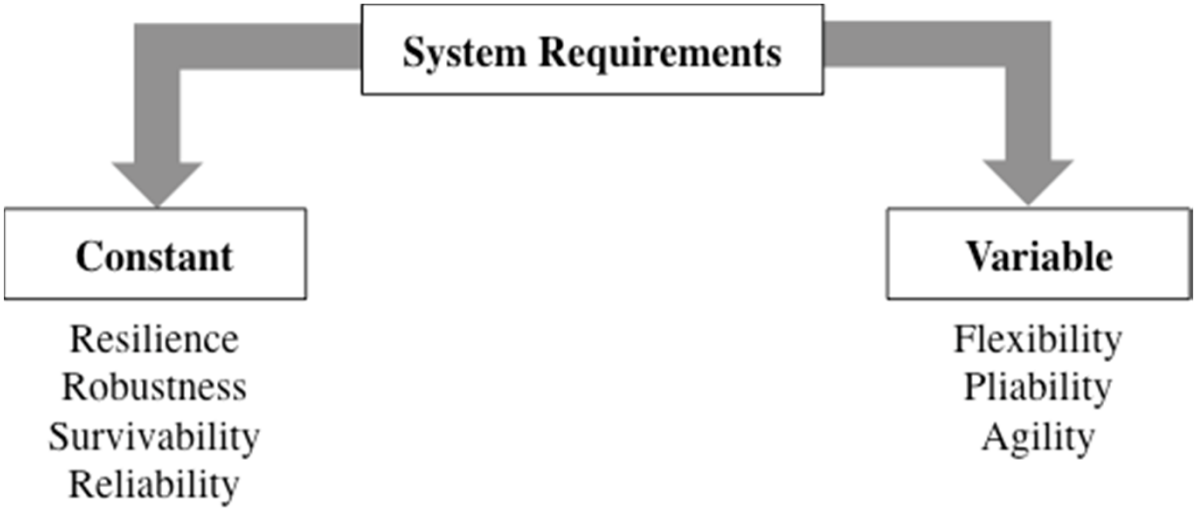
    (Resilience Engineering: Concepts and Precepts (2010))

- Distinction between reliability, robustness, and resilience:
  - A system is ***reliable*** if it is able to perform specified functions despite failures in its components, for an expected range of operating conditions.
  - A system is ***robust*** if it continues to deliver on-time performance despite less than ideal conditions
  - A system is ***resilient*** if it can continue to deliver passengers to their destination despite rare or unexpected disruptions

Background:
Resilience vs. related attributes

- Systems have to cope with changes that can be:
  - (a) ***external***, for example, disruptions due to operating environment threats, changing policies, and global economics, or
  - (b) ***internal***, for instance, component and link failures. In some cases, the differences between the definitions are explicit, while in others the differences are subtler

- Classification of attributes based on impact of change on system requirements:



Background: Multi-disciplinary review of resilience

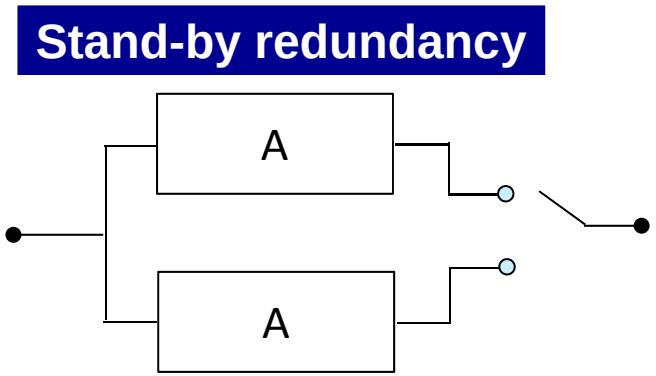
- Physics
  - Physical property of a material that characterizes its resistance to shocks
- Psychology
  - Successful adaptation despite risk and adversity, or unexpected achievement in spite of stress
- Ecology
  - Capacity to resist disruptions or to return to equilibrium after perturbations
  - Ability to move to a different equilibrium to maintain functionality in the face of a disruption
- Organizational studies
  - Ability to continue operations during and after a major mishap/continuous stresses
  - Ability to turn challenges into opportunities and thereby creating superior performance than before

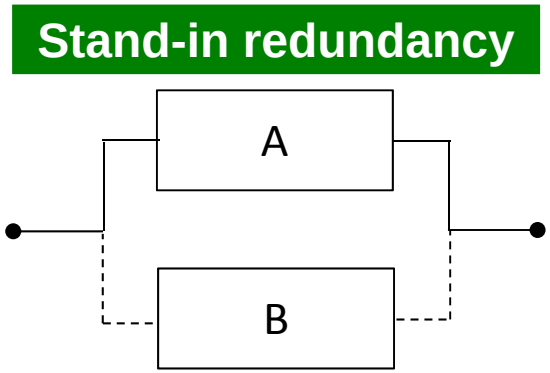
Background:
Resilience in Engineering

- Resilience in engineering stems from fundamental risk and reliability considerations
- Historical approach:
  - Improve resilience through over-design
  - Traditional systems engineering practices anticipate and resist disruptions
  - Resilience incorporated through classical reliability methods:
    - Redundancy
    - Preventive maintenance
- Not suitable for SoSs:
  - Heterogeneity, geographical distribution, interdependencies
  - Backup systems are costly and impractical

Stand-in redundancy in SoSs

- Stand-in redundancy:
  - Compensate for loss of performance in one constituent system by re-tasking remaining systems
  - As one node experiences degradation, other nodes can alter their operations to compensate for this loss

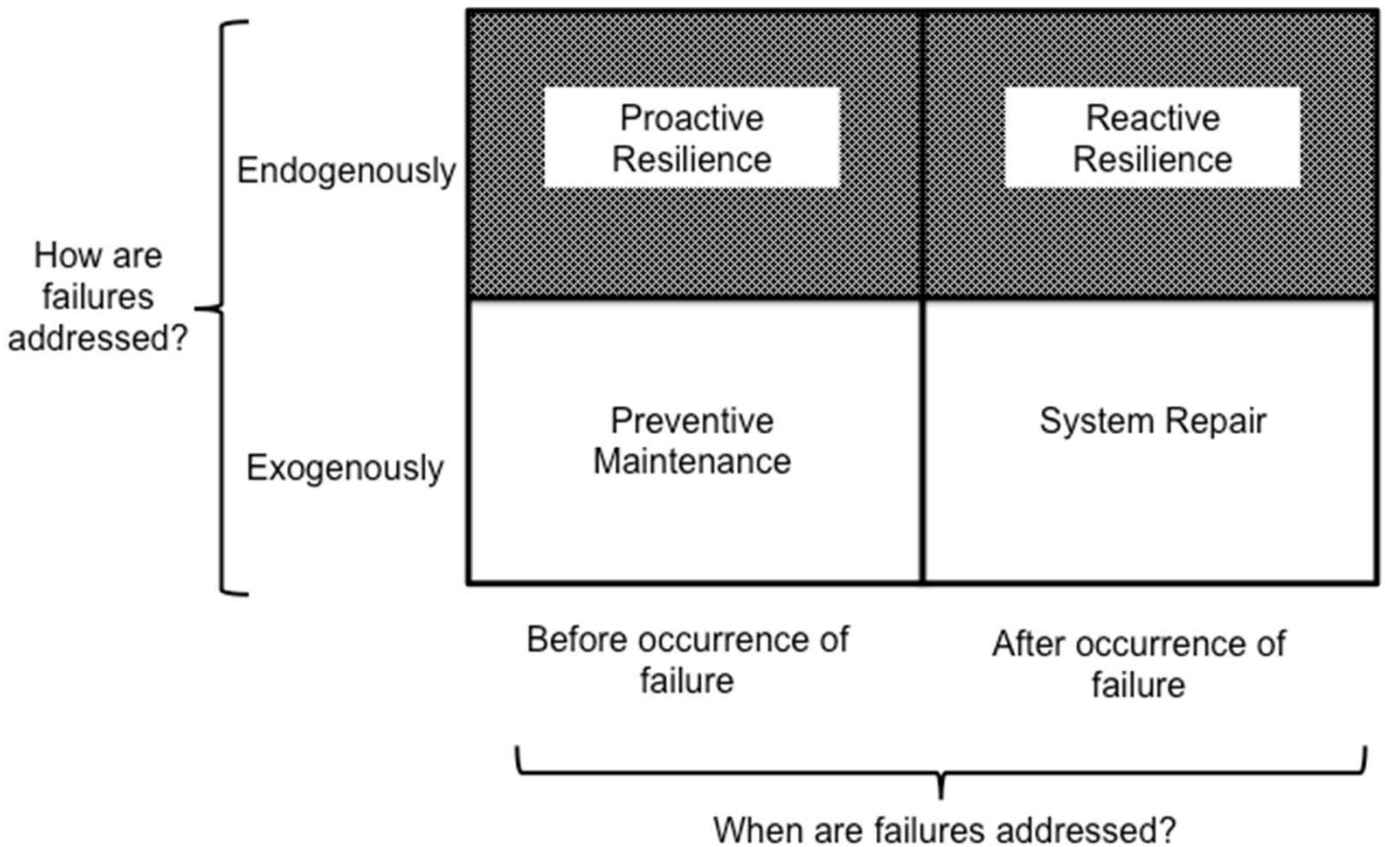




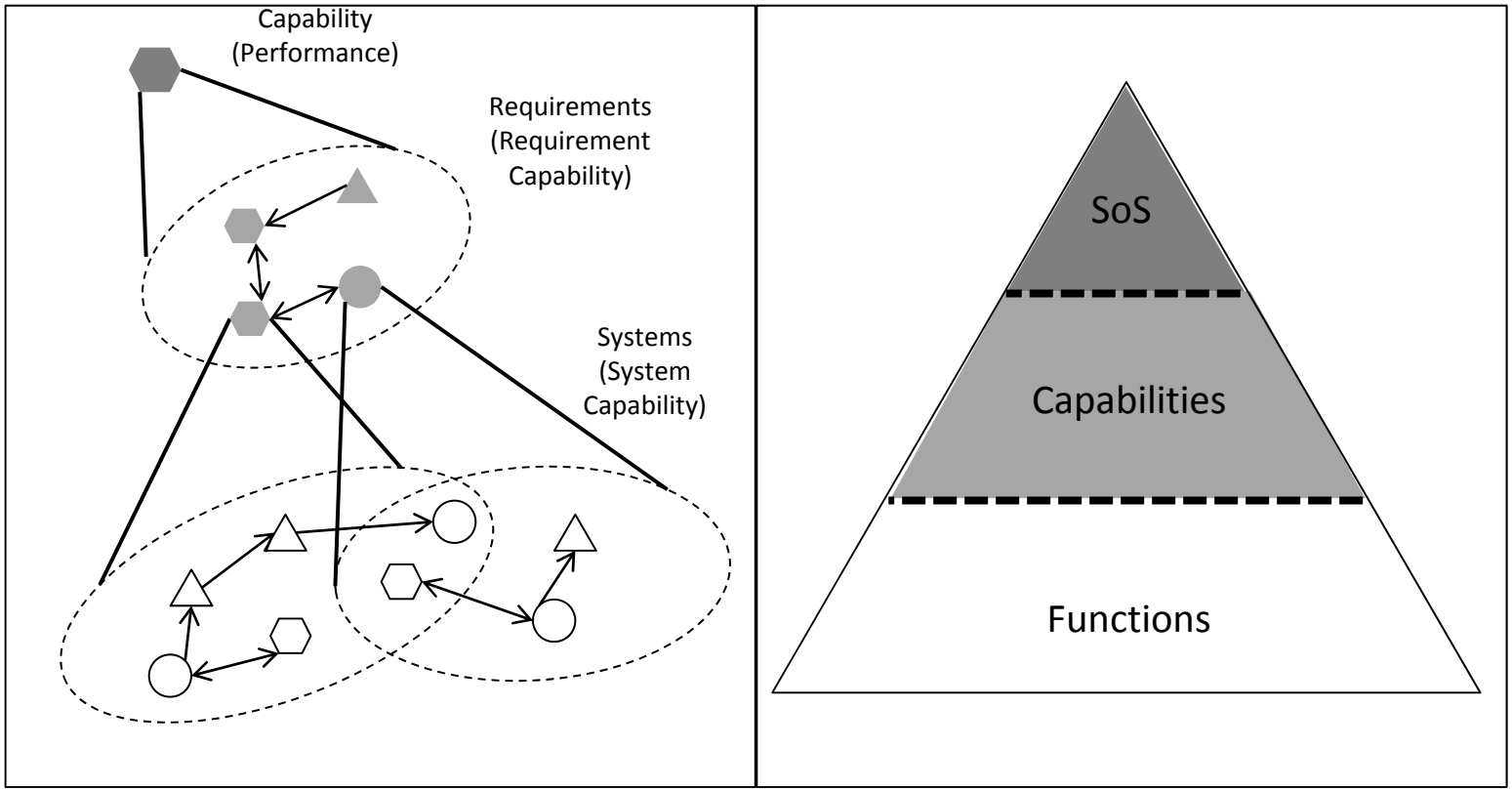
- Raises interesting questions:
  - Given a system failure, what is the best configuration to compensate for the loss?
  - What level of performance can be recovered with new configuration?
  - What is upstream effect of stand-in redundancy on development costs and risks?

Stand-in redundancy in SoSs

- Impact of stand-in redundancy on resilience of SoS:
  - Reactive Resilience
  - Proactive Resilience

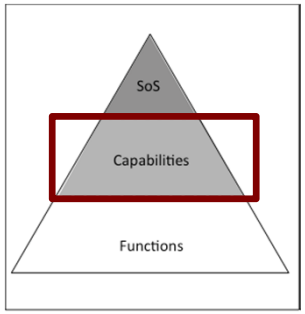


SoS Representation

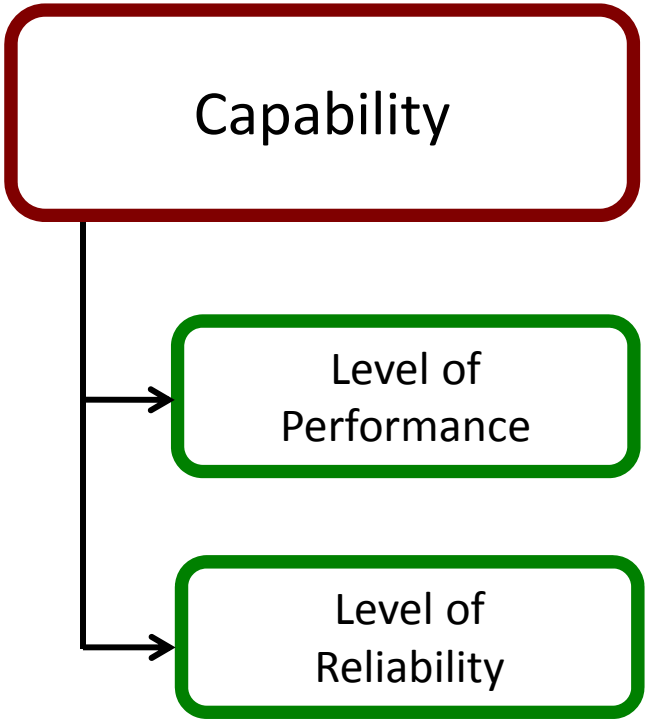


SoS Representation

- Consider metrics at capability level:
  - Level of Performance (LoP)
  - Level of Reliability (LoR)

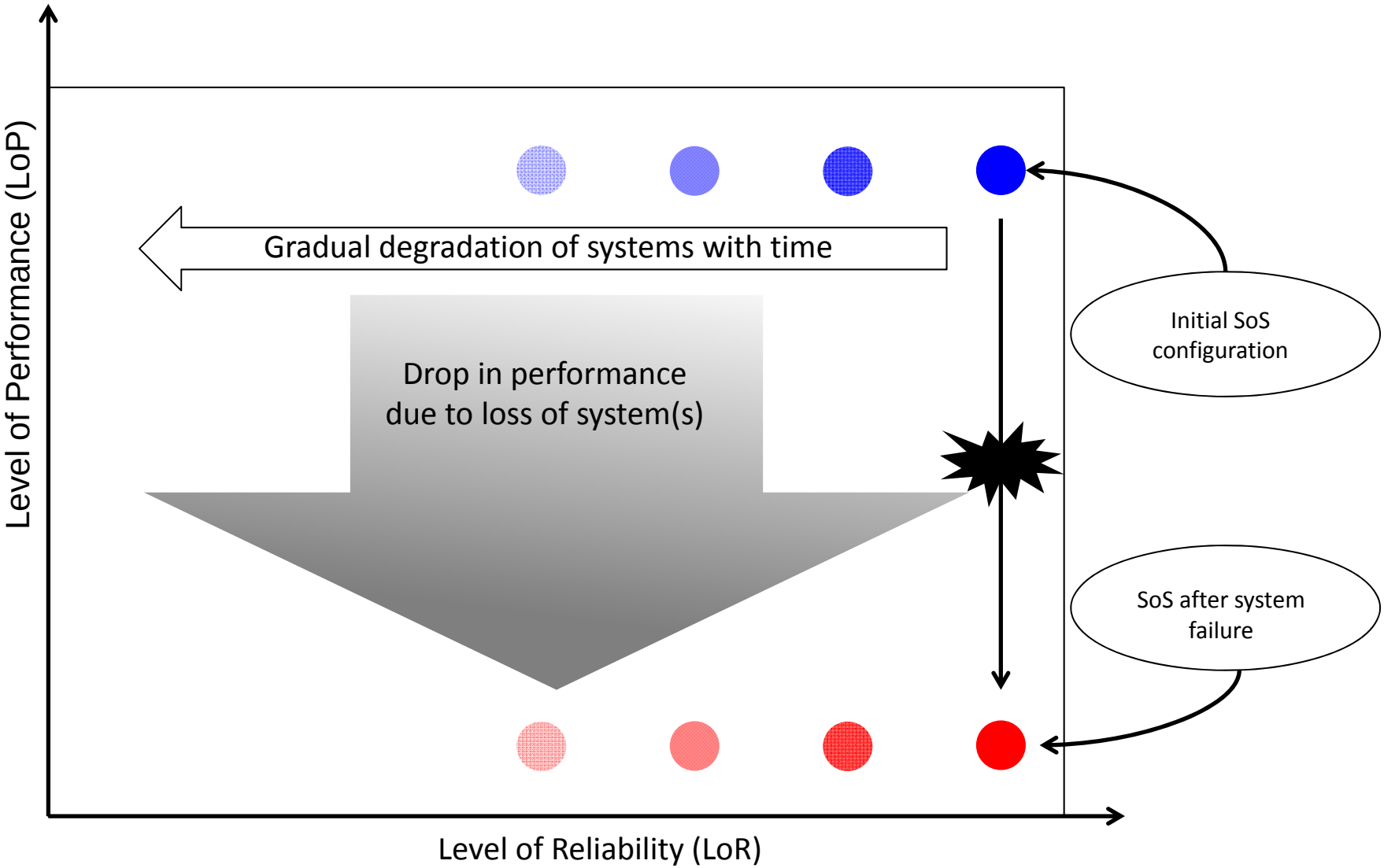


- LoP depends on systems, functions, performance metrics, interdependencies

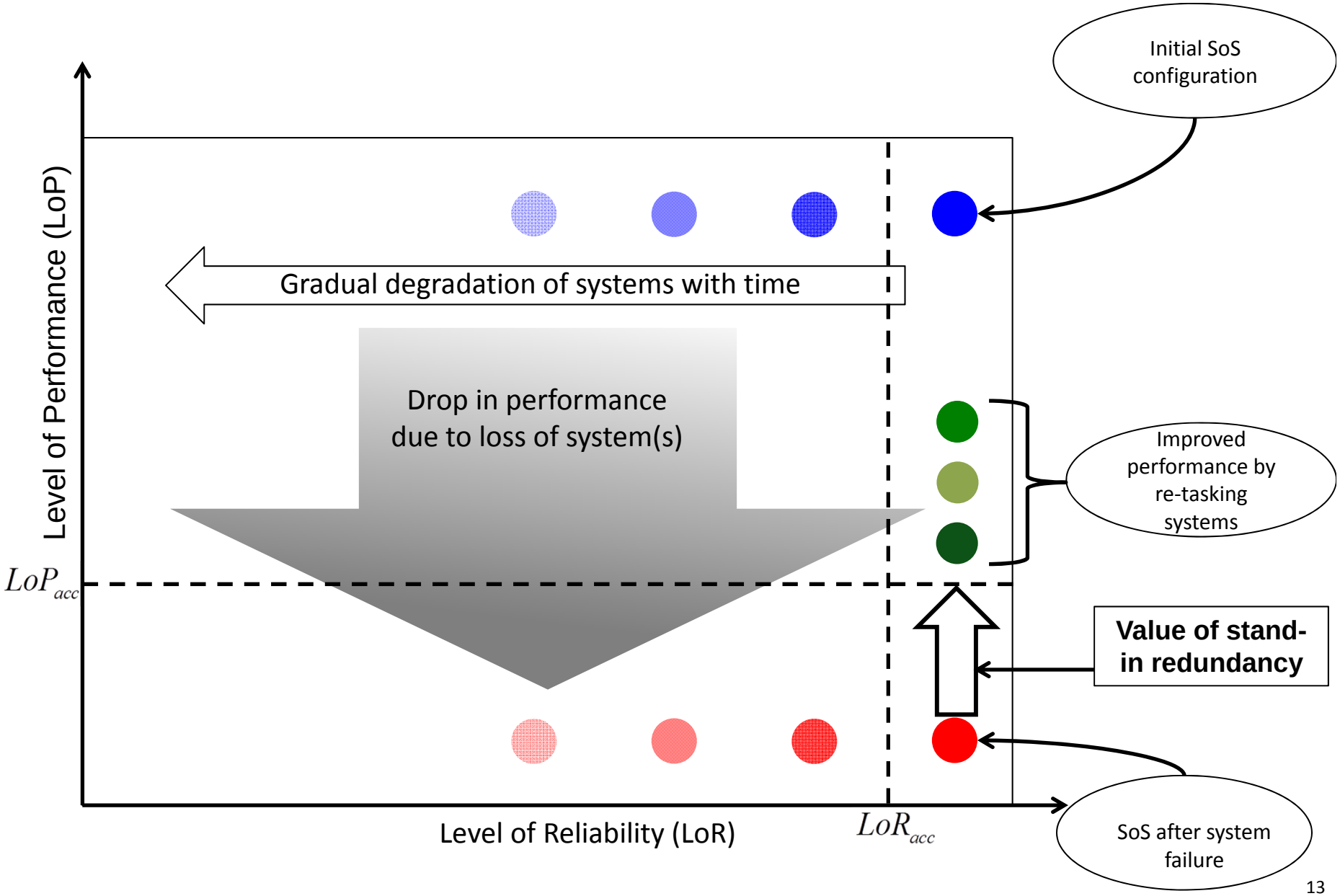


- LoR depends on reliability of individual systems

Analytic framework



Analytic framework



Analytic framework

Minimize $SoS\ operations\ cost$

Subject to : $LoP_i \geq LoP_i^T$

$LoR_i \geq LoR_i^T$

SoS Operations Cost

Fully functional state: Number of systems, operating cost of each system

Failed system state:
Operating costs of remaining systems, cost to repair/replace system, downtime costs

Re-tasked state:
Operating cost of remaining systems, acquisition costs of additional features

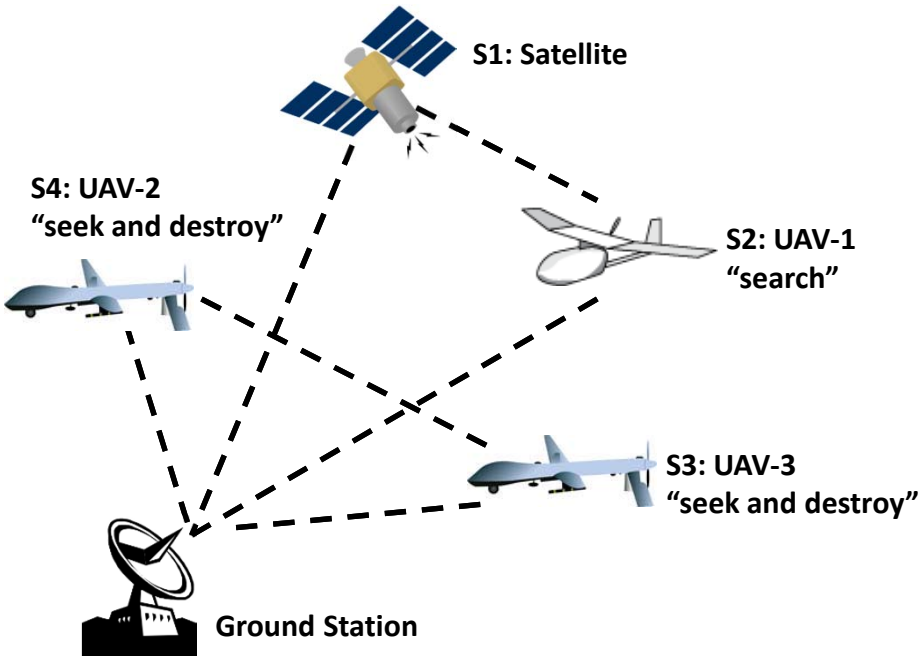
LoP:
systems, functions, performance metrics, interdependencies

LoR:
reliability of individual systems

Desired LoP, LoR:
Min. level of high performance and high reliability original SoS should satisfy

Acceptable LoP, LoR:
Min. acceptable level re-tasked systems must provide

Illustrative example



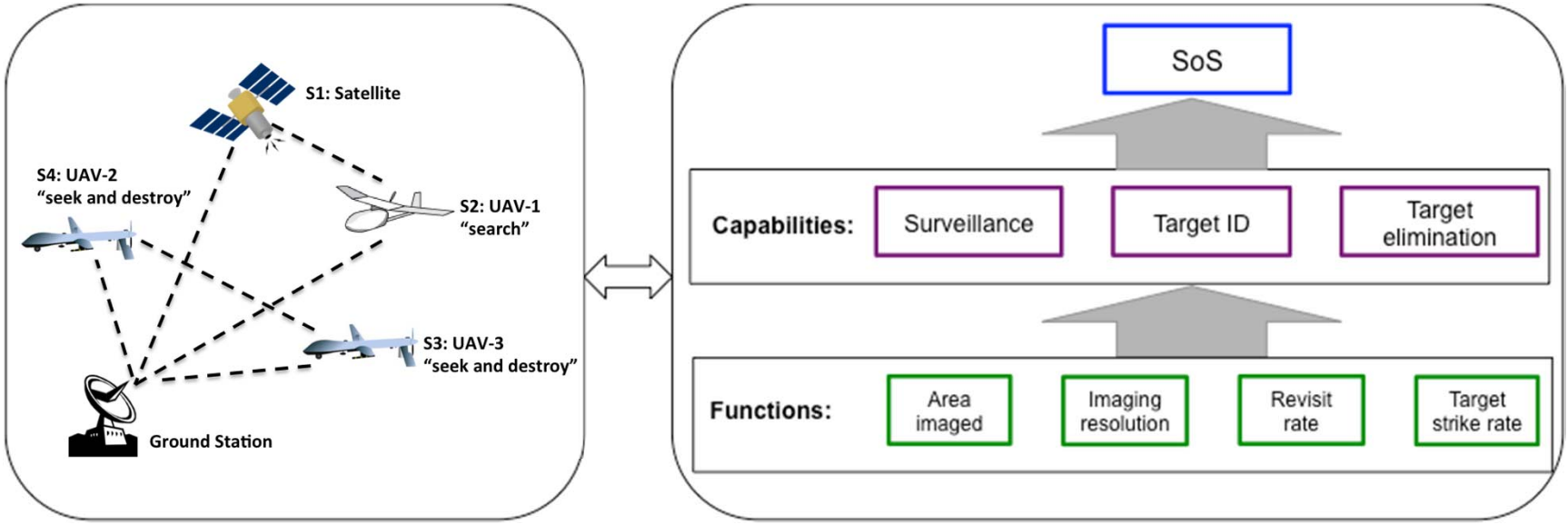
Features available on each system:

UAV1: High-definition camera
UAV2: Basic camera + weapons
UAV3: Basic camera + weapons

Capability	Description	Systems Needed
C1	Surveillance	S1
C2	Target identification	S1, S2
C3	Target elimination	S3, S4

Illustrative example

- Representation of SoS:

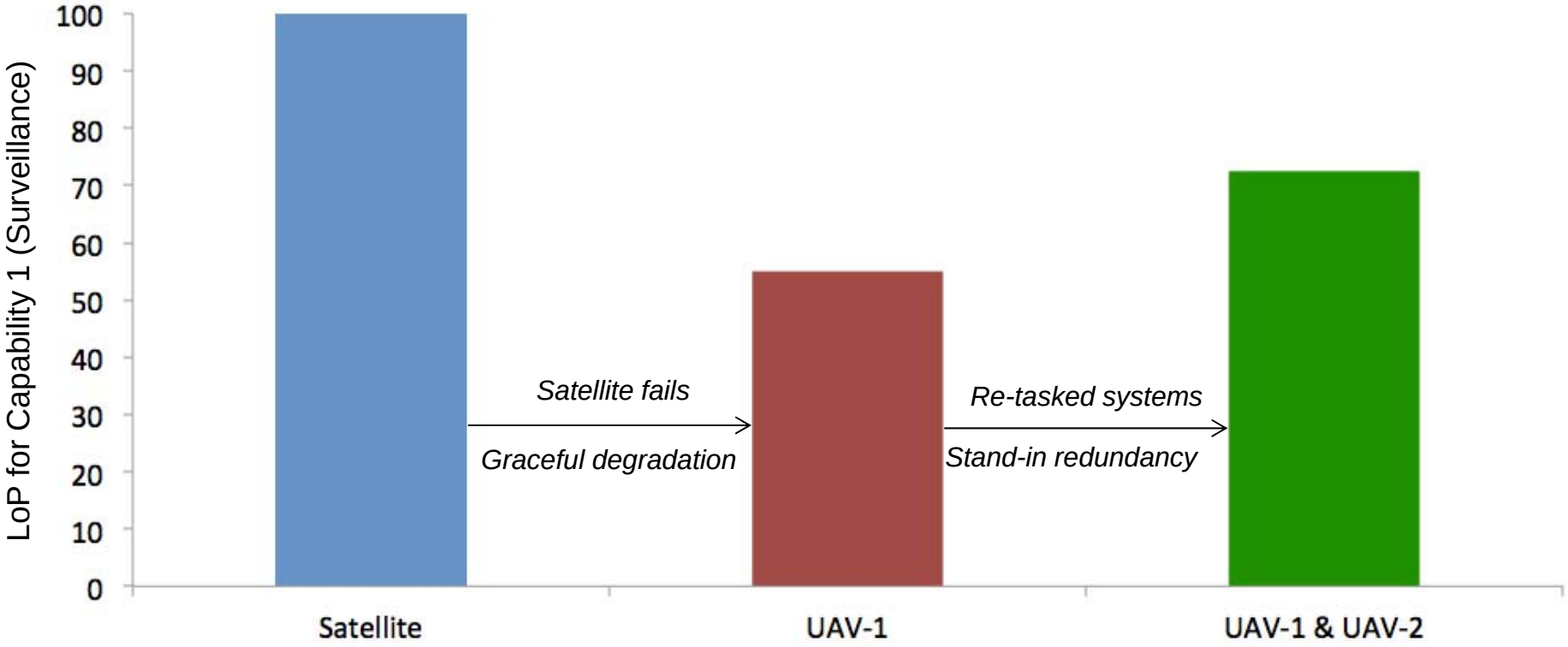


Systems and functions

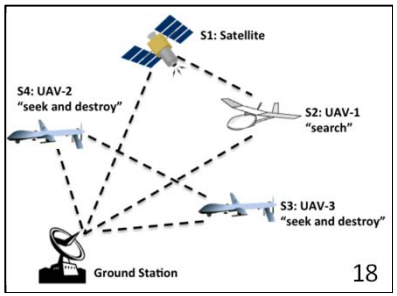
Systems ↓	← Individual system functions/features →			
	Area imaged	Imaging resolution	Revisit rate	Target strike-rate
Satellite	✓	✓	✓	-
UAV-1 "search"	✓ ↑	✓ ↑	✓	-
UAV-2 "seek and destroy"	✓ ↑	✓ ↑	✓	✓
UAV-3 "seek and destroy"	✓ ↑	✓ ↑	✓	✓

- Modifications/enhancements in SoS:
  - Features on satellite cannot be changed
  - Easier to retrofit UAVs with higher performance devices
  - (UAVs can also be reprogrammed for higher revisit rates)

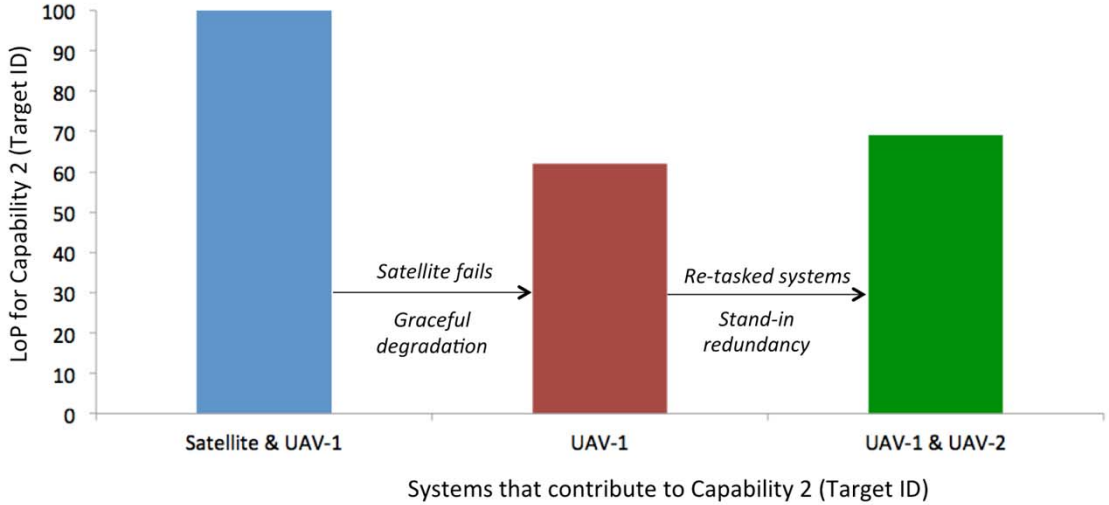
Results: Surveillance (C1)

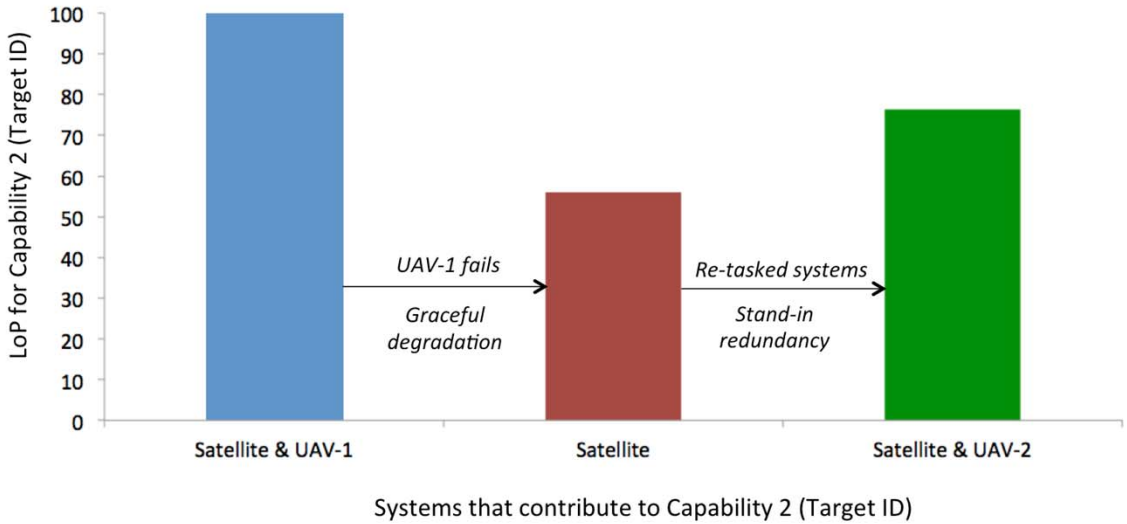


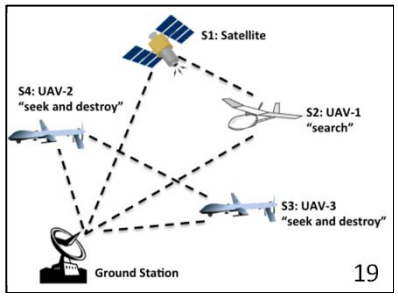
Systems that contribute to Capability 1 (Surveillance)



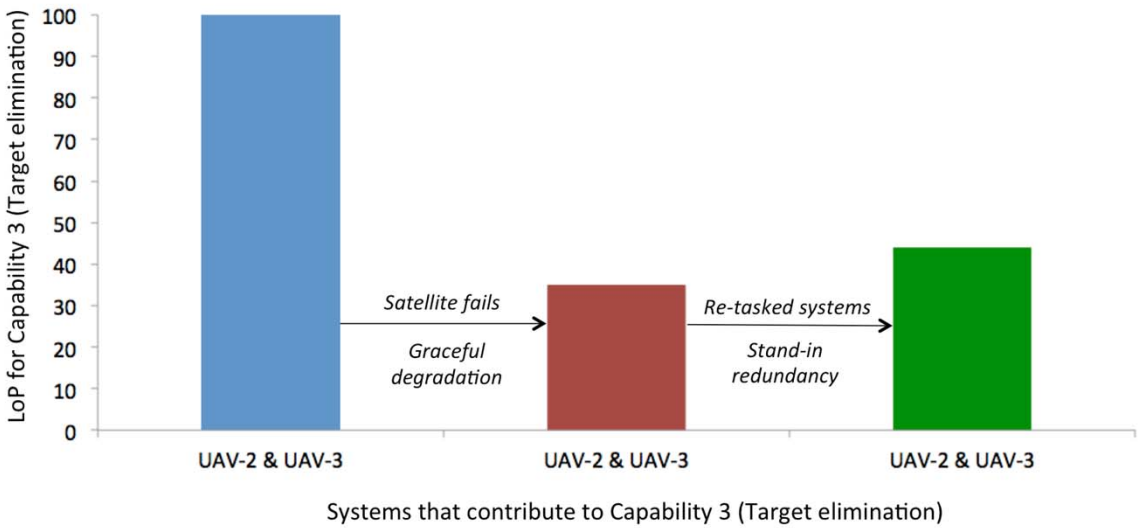
Results: Target identification (C2)



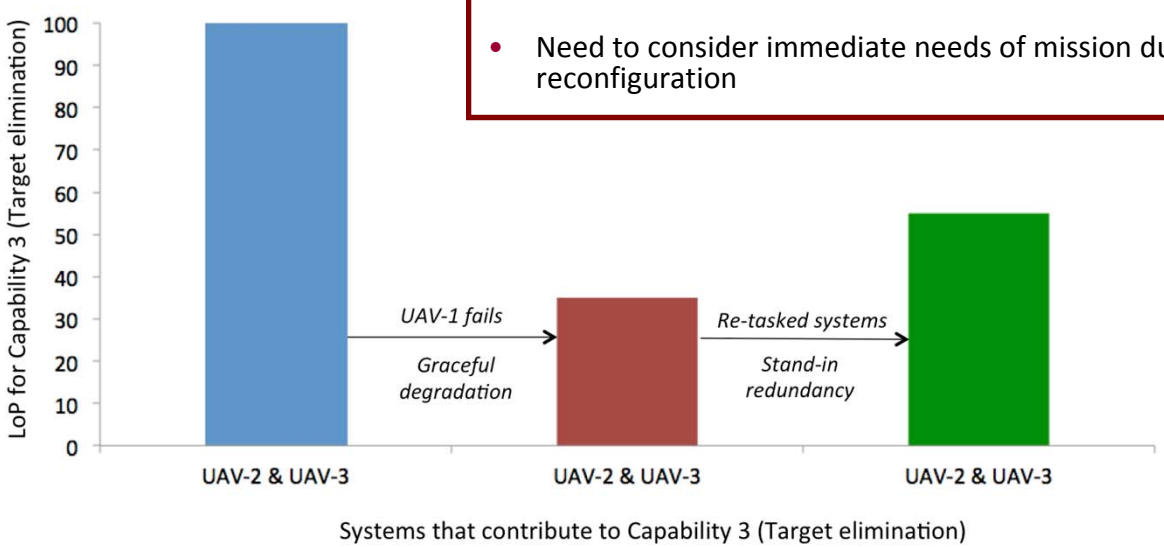


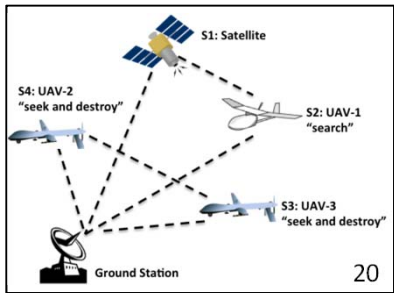


Results: Target elimination (C3)



- Indirect impact of system failure on capabilities
- Need to consider immediate needs of mission during functional reconfiguration



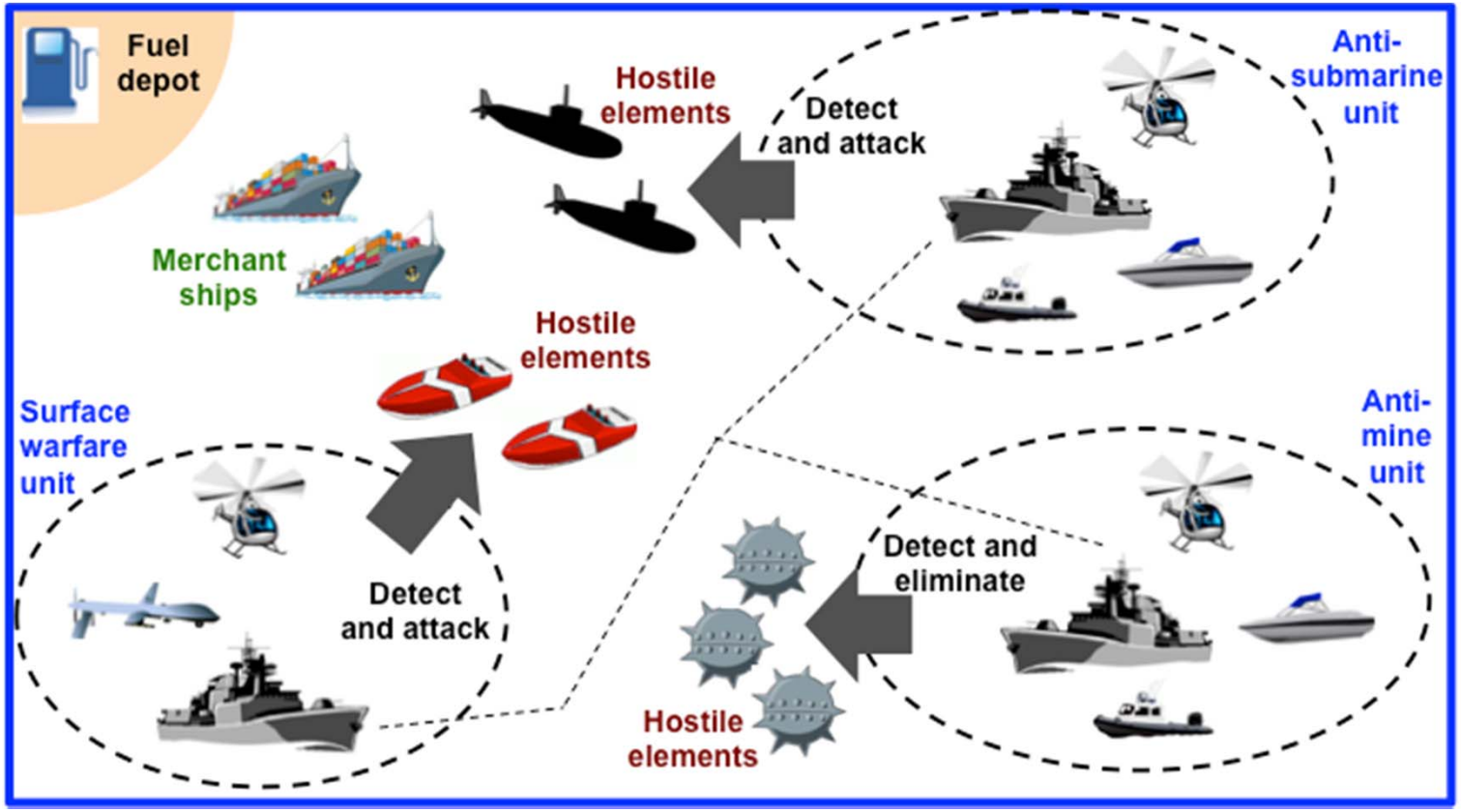


Discussion

- Using stand-in redundancy, systems can:
  - Contribute to SoS-level capabilities in ideal case, and
  - "Stand-in" for failed functions during failures
- Limit to level of stand-in redundancy that can be included
  - Appropriate resource allocation
- Next step: Incorporate cost-benefit analysis to enable decision-making
- Need to consider balance between ***resilience***, ***costs***, and ***adaptability*** of the SoS
  - For example, multi-modal transportation networks are designed for long lifetimes with gradual modifications and/or upgrades

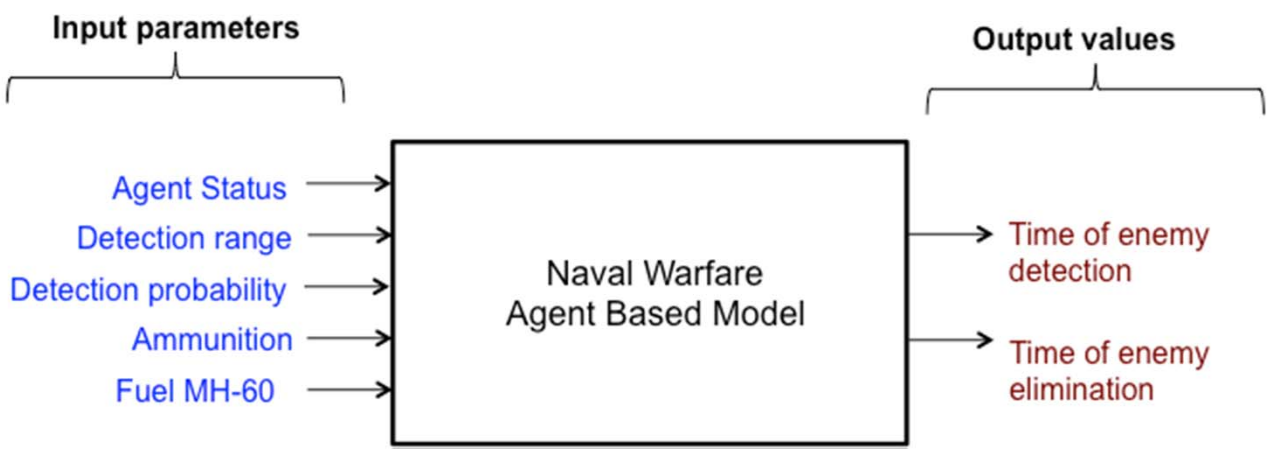
Current work: Naval Warfare ABM (1)

- Naval Warfare ABM developed at Purdue
- ABM consists of three different Littoral Combat Ship mission packages, hostile units and neutral units



Current work: Naval Warfare ABM (2)

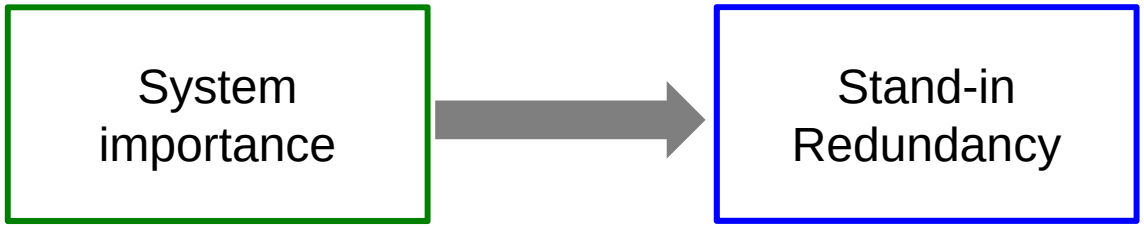
- Implement stand-in redundancy by changing:
  - Nodes
  - Links
- Scenarios under investigation:
  - Baseline: Nominal case where all systems function perfectly
  - Performance degradation: Study impact of system failures on overall capability
  - Re-tasked SoS: Impact of system re-tasking on overall capability



System Importance Measures (1)

How can we measure resilience?

How can we improve resilience?



- Motivation: **Component Importance (CI) measures** in reliability theory

CI measure	Description
Birnbaum importance	What is the reliability importance of component *i*?
Risk Achievement Worth (RAW)	What is the decrease in system reliability if component *i* fails?
Risk Reduction Worth (RRW)	What is the decrease in system reliability if component *i* is replaced by a perfect component?
Fussell-Vesely measure	What is the fractional contribution of component *i* to overall system reliability?

System Importance Measures (2)

- Assumptions behind CI measures
  - Component states are binary
  - System structure and component sets are fixed
  - Components are independent
  - No uncertainties present

- Potential benefits in SoS context
  - Determine and rank systems importance with respect to overall SoS performance
  - Identify “weak” systems to prioritize resilience improvement activities
  - Guide resource allocation decisions

Summary and future work

- Large scale SoSs evolve with time along with changing environment
- This approach indicates incremental enhancements/modifications to existing systems can provide inherent resilience
- Approach can help decision-makers quantitatively assess resilience of different SoS architectures
- Future work:
  - Expand static model to dynamic model (resilience under uncertainty)
  - Use System Importance (SI) measures to inform stand-in redundancy options
  - Consider multi-system failures

For Additional Information

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