



Uncovering Architectural Challenges in a System of Systems



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Michael Gagliardi has more than 25 years of experience in real-time, mission-critical software architecture and engineering activities on a variety of Department of Defense (DoD) systems. His current work involves the development of architecture evaluation methods for system-of-systems architectures and system architectures.



Problem

Integration and operational problems arise due to inconsistencies, ambiguities, and omissions in addressing quality attributes between system and software architectures.

This is further exacerbated in an System of systems (SoS).

Example quality attributes: predictability in performance, security, availability/reliability, usability, testability, safety, interoperability, maintainability, force modularity, spectrum management.

Functionality and capability are critically important, but the architecture must be driven by the quality attributes. Specifying and addressing quality attributes early and evaluating the architecture to identify risks is key to success.



The Need for Augmented End-to-End Mission Threads in DoD SoS Architecture Definition

DoDAF provides a good set of architectural views for an SoS architecture. However, it inadequately addresses cross-cutting quality attribute considerations.

System use cases focus on a functional slice of the system.

More than DoDAF and system use cases are needed to ensure that the SoS architecture satisfies its cross-cutting quality attribute needs.

SoS end-to-end mission threads augmented with quality attribute considerations are needed to help define the SoS Architecture and then later evaluate the SoS architecture and constituent system/software architectures.



Definitions (DoD Context)

Vignette: A description of the geography, own force structure and mission, strategies and tactics, the enemy forces and their attack strategies and tactics, including timing. There may be associated Measures of Performance (MOP) and Measures of Effectiveness (MOE). A vignette provides context for one or more *mission threads*.

Mission Thread: A sequence of end-to-end activities and events beginning with an opportunity to detect a threat or element that ought to be attacked and ending with a commander's assessment of damage after an attack. C4ISR for Future Naval Strike (Operational)

Sustainment: A sequence of activities and events which focus on installation, deployment, logistics and maintenance.

Development: A sequence of activities and events that focus on re-using or re-engineering legacy systems and new adding capabilities

Acquisition: A sequence of activities and events that focus on the acquisition of elements of an SoS, and the associated contracts and governance



Vignettes Are the Starting Point

– Example Wording

Two ships (Alpha and Beta) are assigned to integrated air and missile defense (IAMD) to protect a fleet containing two high-value assets (HVA). A surveillance aircraft SA and 4 UAVs are assigned to the fleet and controlled by the ships. Two UAVs flying as a constellation can provide fire-control quality tracks directly to the two ships. A three-pronged attack on the fleet occurs:

- 20 land-based ballistic missiles from the east
- 5 minutes later from 5 aircraft-launched missiles from the south
- 3 minutes later from 7 submarine-launched missiles from the west.

The fleet is protected with no battle damage.



Mission Threads Flow from Vignettes – Example (Non-Augmented)

1. 20 land-based missiles launched - X minute window
2. Satellite detects missiles - cues CMDR
3. CMDR executes re-planning – reassigns Alpha and Beta
4. Satellite sends track/target data - before they cross horizon
5. Ships' radars are focused on horizon crossing points

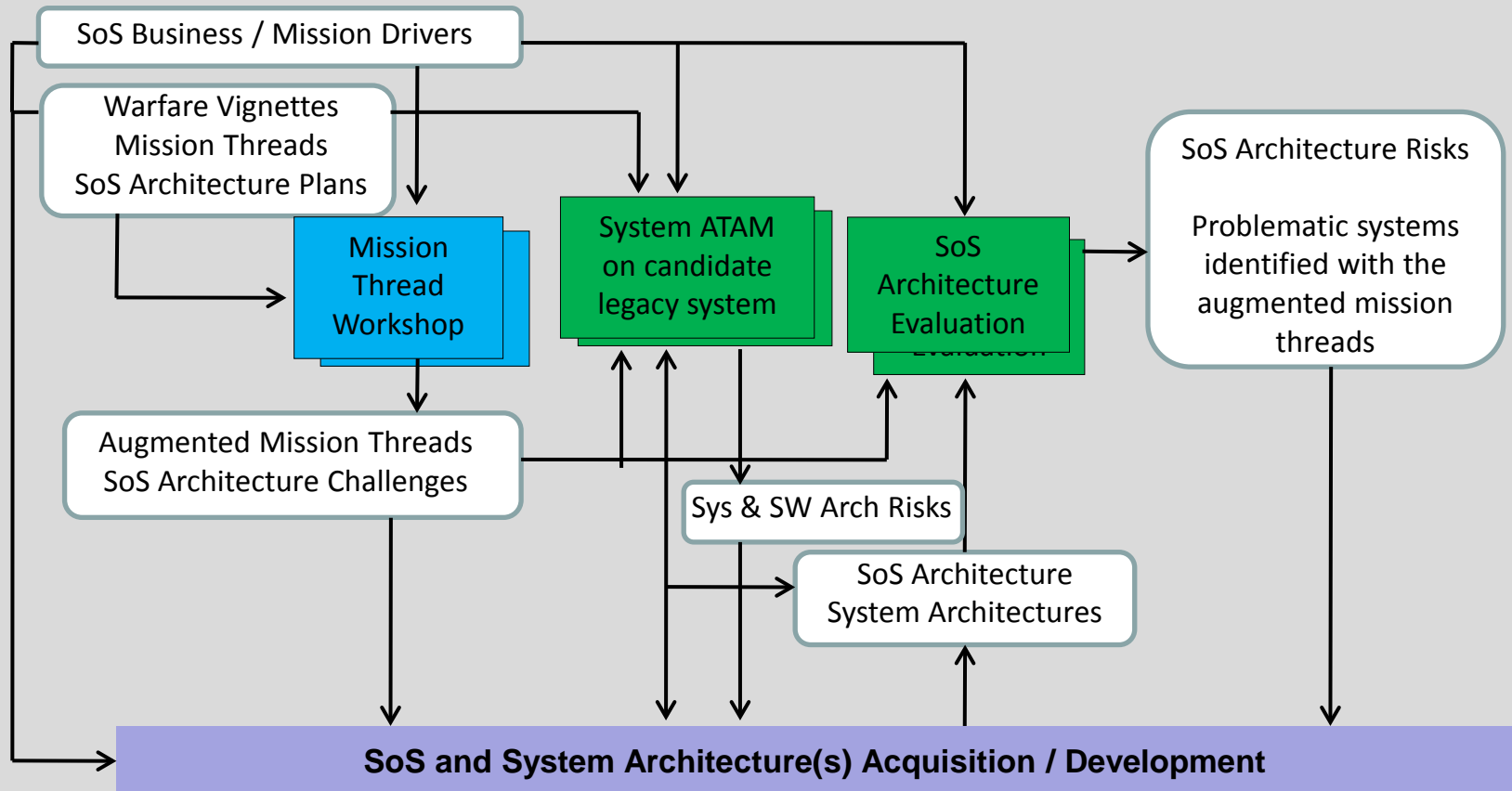
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- N Engagement cycle is started on each ship
- N+1 Aircraft are detected heading for fleet
- N+2 SA detects missile launches – tells CMDR
- N+3 CMDR does re-planning - UAVs are re-directed
- N+4 FCQ tracks are developed from UAV inputs



SoS Architecture Quality Attribute Specification and Evaluation Approach

- Early elicitation of quality attribute considerations
- Early candidate legacy system architecture evaluation
- Early identification and mitigation of architectural risks



Mission Thread Workshop - Goal

To augment a set of end-to-end System of Systems (SoS) mission threads with quality attribute and engineering considerations with the stakeholders.

To capture at each step of the mission thread AND each SoS quality attribute

- the engineering considerations from diverse stakeholders
- the quality attribute concerns associated with the mission thread
- the applicable use cases for the different nodes and/or systems

To develop technical challenges associated with the threads, and to aggregate the challenges over a number of MTWs

Outputs will inform and drive SoS Architecture Decisions.



Augmentation Process – Per Mission Thread

Two Passes over the Mission Thread:

1) For each event in the mission thread:

- Elicit quality attribute considerations. Capturing any engineering issues, assumptions, challenges, additional use cases and mission threads (with QA context etc.)
- Capture any capability and/or mission issues that arise.

2) For each Quality Attribute - elicit any over-arching quality attribute considerations

- Capturing any over-arching assumptions, engineering issues, challenges, additional use case and mission threads (with QA context), etc.
- Capture any capability and/or mission issues that arise.

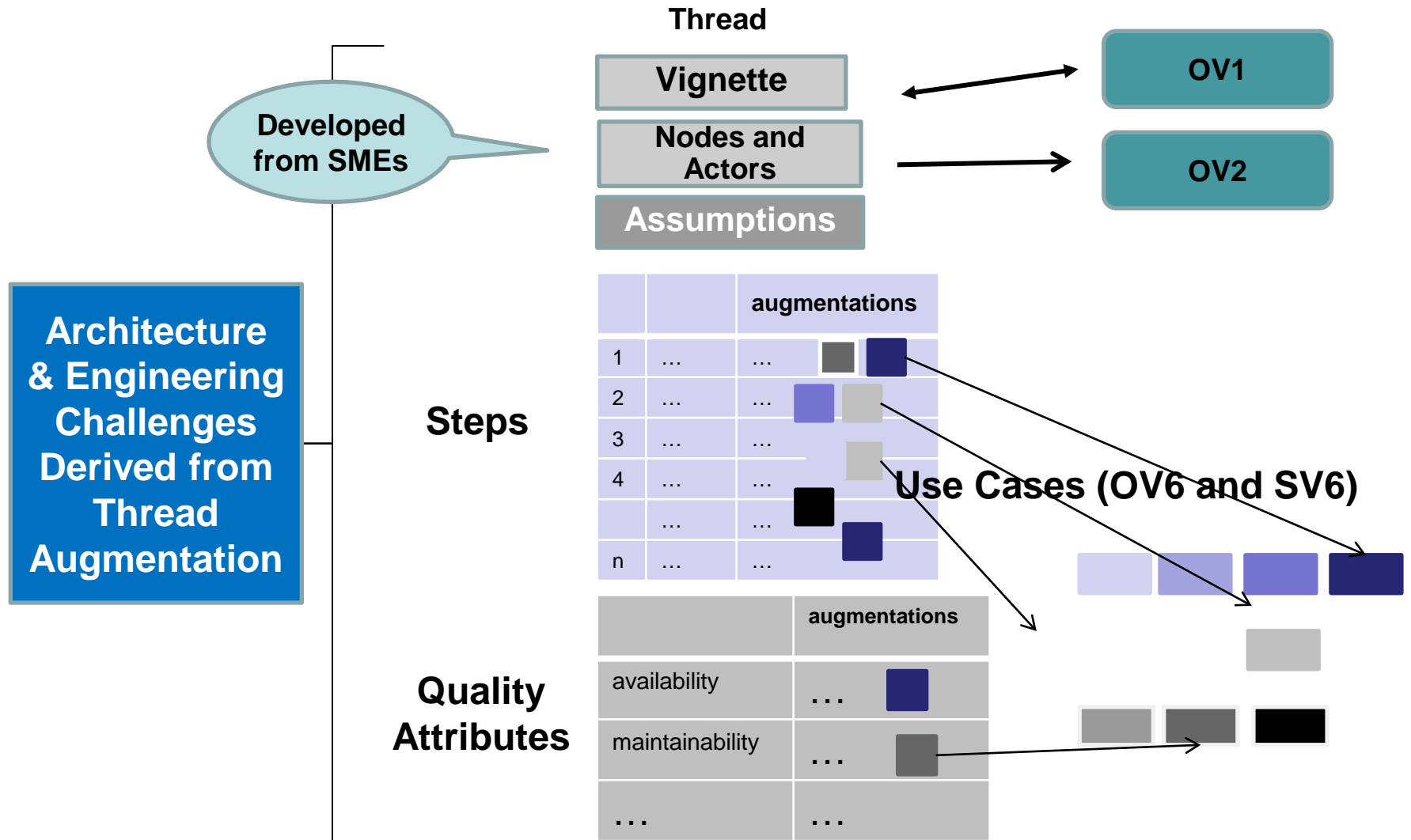
Capture any MT extensions for later augmentation

Capture Parking Lot issues – for organization, programmatic, non-technical issues that arise (will not be further pursued in the MTW).

Stakeholder Inputs are Key.



Mission Thread (augmented via the Mission Thread Workshop)



Nodes, Actors and Assumptions Augmentation

Name	Protect Fleet Assets against Cruise Missile Attacks
Vignette (Summary Description)	<p>Two ships (Alpha and Beta) are assigned to air defense (AD) to protect a fleet containing two high-value assets (HVA). A surveillance aircraft (SA) and four UAVs (two pairs) are assigned to the fleet and controlled by the ships (Alpha and Beta). A pair of UAVs flying as a constellation can provide fire-control quality (FCQ) tracks directly to the two ships. A two-pronged attack on the fleet occurs:</p> <ul style="list-style-type: none"> • five aircraft-launched missiles from the Southeast • three minutes later seven submarine-launched missiles from the Southwest. <p>The fleet is protected with no battle damage.</p>
Nodes Actors	<ul style="list-style-type: none"> • two ships (Alpha and Beta) • four UAVs • two HVAs • one SA • five enemy aircraft and their missiles • seven enemy submarines and their missiles
Assumptions	<ul style="list-style-type: none"> • Enemy aircraft are flying along a route normally used for training, and suddenly change direction and head for the fleet. They are being tracked. • The submarines are undetectable until they fire their missiles. <ul style="list-style-type: none"> • <i>No sonabouys are deployed, but they could be in a new vignette.</i> • The vignette is not concerned with counter-attacking the enemy aircraft or submarines. • It is not a wartime situation; ships are at battle condition 3. • Sea state is 3. • Ships' readiness condition is YOKE. • Alpha controls two UAVs and Beta two other UAVs. <ul style="list-style-type: none"> • <i>Each ship has two organic UAVs.</i> • During normal operations the UAVs have separate non-overlapping areas of regard (AORs). • The SA has an area of regard that will detect both the launched missiles. • The Air Defense Commander (ADC) is on-board Alpha. • <i>Alpha ship's Helo is in the air.</i> • <i>Both ships are aware that a potentially hostile country has some fighter aircraft conducting training missions nearby.</i>



Step by Step Augmentation

Mission Steps	Description	Engineering Considerations, Issues, Challenges
1	Alpha develops the air defense plan (ADP) and rules of engagement (ROE) and sends them to Beta. The plan assigns to Alpha the area of regard (AOR) to the west, and Beta the AOR to the east. Alpha configures surveillance and weapons systems to support eastern engagements.	<ol style="list-style-type: none"> 1. <i>How much is pre-defined and how much is done manually?</i> 2. <i>ROE dictates a "shoot-look-shoot" defense.</i> 3. <i>How is this communicated to Beta? Using the fleets NRTC: near real-time communications</i>
2	The SA aircraft detects that the five enemy aircraft have changed towards the fleet at low altitude.	<ol style="list-style-type: none"> 1. <i>The enemy aircraft are within the area of regard (AOR) of the SA sensors. The SA has been tracking these aircraft and sending tracks to Alpha and Beta.</i> 2. <i>Need a "fleet" SA use case</i>
3	SA informs both Alpha and Beta of the change.	<ol style="list-style-type: none"> 1. <i>Within X seconds of detecting the change</i> 2. <i>Using the Global Information Grid (GIG). Is the GIG usable for tactical near real-time data? Probably not!</i> 3. <i>Need a use case on assigning the UAVs to track the aircraft at this point</i>
4	Alpha (and Beta) go to General Quarters	<ol style="list-style-type: none"> 1. <i>ADC informs the captain who orders general quarters</i> 2. <i>Using Internal Communications</i>
5	SA detects that missiles have separated from the enemy aircraft and informs Alpha and Beta.	<i>Within X seconds</i>
6	Alpha assigns its two UAVs to track the missiles.	<ol style="list-style-type: none"> 1. <i>The legacy Defensive Engagement System (DES) cannot use external tracks to form a FCQ track.</i> 2. <i>Within X seconds</i> 3. <i>Does the ADC have to do this manually?</i> 4. <i>Would they start tracking automatically if the missiles were within their AOR?</i> 5. <i>Would they have been tracking the aircraft?</i>
7	The two Alpha controlled UAVs send FCQ tracks for the five missiles to both Alpha and Beta.	<ol style="list-style-type: none"> 1. <i>The two UAVs can re-direct their payload to do this within YY seconds. (use case)</i> 2. <i>It takes XX seconds for the FCQ tracks to stabilize.</i> 3. <i>What is the comms between UAVs and Ships for maneuver and payload con-</i>



Over-Arching Quality Attribute Augmentation

Name of QA (filled in during Preparation phase)	Considerations (This column will be filled in during the Augmentation Phase)
Performance (P)	<ol style="list-style-type: none"> 1. <i>The airspace de-confliction latency is heavily dependent on the number of aircraft within the strike paths.</i> 2. <i>The timeline function from missile detection at specific distance from target until point of impact, including detection by both UAVs, engagement assignments, missile launching sequence, and fly out times has not been analyzed in detail!</i>
Availability/ Reliability (AV)	<ol style="list-style-type: none"> 1. <i>What if both UAVs cannot maneuver to their respective AORs in time?</i> <ol style="list-style-type: none"> a. <i>They will probably have to wait until they are within the ship's radar to fire.</i> b. <i>Is this a manual decision? (tradeoff with automation)</i> 2. <i>What if the ship/missile communications fails?</i> <ol style="list-style-type: none"> a. <i>It will probably have to fire another intercept missile!</i> b. <i>Can the other ship try to control the missile?</i> 3. <i>What if Alpha/Beta Comms fails?</i> <ol style="list-style-type: none"> a. <i>Revert to a pre-defined separate engagement.</i> 4. <i>What if Beta does not acknowledge engagement assignments? Revert to what was defined in ROE or assume that it will follow received orders or take some other option?</i> <ol style="list-style-type: none"> a. <i>A degraded Mode Use Case needs to be developed.</i> 5. <i>Degraded modes of operation have not been detailed yet.</i> 6. <i>Loss of comms. to SA.</i> <ol style="list-style-type: none"> a. <i>After initial detection and UAV coverage, it does not matter.</i> b. <i>Before initial detection, the UAVs will provide some coverage, but will probably have some unmonitored areas.</i> c. <i>What happens when missile goes beyond line-of-sight radar coverage?</i> 7. <i>What if one of the UAVs is deemed non-functional during operations?</i>
Accuracy (Ac)	<ol style="list-style-type: none"> 1. <i>If the tracks are relayed (see Interoperability item 2) what if they are not sufficiently accurate? Will they be?</i> 2. <i>Given multiple relay hops, how will accuracy be impacted? (Performance / accuracy tradeoff implications). How can shared resources be managed to bound latencies in this environment?</i>
Interoperability (In)	<ol style="list-style-type: none"> 1. <i>Can a UAV that is assigned and controlled by one ship be re-assigned and controlled by another ship dynamically? (Degraded mode future support?)</i> 2. <i>Can FCQ information be transferred in real time from Alpha to Beta in order to target one of the missiles?</i>



Example Rolled-Up SoS Challenges

- A. Resource Management
- B. Mission Planning
- C. Readiness/Situational Awareness
- D. External Interfaces
- E. Acquisition
- F. Super Thread
- G. Additional Analysis



A: Resource Management

There is currently no strategy for total ship resource management. It needs to support all the categories mentioned below across ship segments and missions, as well as ship shared resources.

Categories:*

- Reactive
- Time Critical Planning
- Mission/Voyage Planning
- Degraded Operation
- Manning
- Power Systems
- Radar Resources
- Signatures

Recommendations:

1. Review the survivability use cases for new RM capabilities
2. Hold Architectural Challenge Workshop



B: Mission Planning

Mission* planning occurs both daily and over an extended time period (days to weeks). In some cases, there are stove-piped tools (these must be integrated) and in others, no automation. Planning involves:

- Planning authority and accessing data from external source via EXCOMMs
- Collaborative distributed decision making involving
 - Expeditionary Strike Group, Navy Task Group, Carrier Task Force, off-board warfare commanders
 - Embarked staff/flags for planning/decision
 - External agencies (foreign, US), Ships (white, naval); aircraft (organic, joint)

Recommendation:

1. Work with SEMs to establish and prioritize a set of multi-mission planning MTWs.
2. Conduct Mission Planning Workshop with a focus on workflow automation, distributed collaboration and decision making.

* And voyage planning



Mission Thread Workshops - Numbers to Date

Client	Description	MTWs	Vignettes	Mission Threads	Stakeholders
A	IRAD New platform/capability	1	1	2	8
B	New Naval Ship	13	17	37	>200
C	Battle Command	6	3	4	>100
D	Maritime Detection	2	4	4	30
E	NSF	1	3	3	15
F	Air Force Program	1	1	1	10
G	Other Govt Agency	1	4	4	12



Lessons Learned

Preparation Activities

SoS Quality Attributes

Stakeholders

SoS Architecture Development Process

SoS Capabilities and Engineering Considerations

SoS Challenges



Preparation Activities - 1

Development of Mission Threads

Naval Ship had MTWs for each mission area (MA) and inherent capability (IC)

- NOT software related; looking for stakeholder impacts and assumptions that tie the areas together
- Focused on activities and relationships to other assets external to the ship (OV1 is critical)
- Initial leads had trouble building vignettes/threads/QA
 - Needed some coaching and oversight
 - Found good vignette fodder in AoA and DRM documents
- Leads for later workshops attended earlier workshops and developed VERY good vignettes/threads/QA
 - Reviews produced minor changes



Preparation Activities - 2

Architecture Development Strategy (ADS) and Architecture Development Plan (ADP) need to be developed incorporating the architecture-centric approach and identifying how the different products and methods are integrated to develop the architecture.

A MTW piloting effort should be performed following the guidance of the ADP and developed architectural process to provide an example for the program with supporting artifacts using operational, developmental, and sustainment-type threads.

A set of architectural quality attributes for the SoS should be defined and vetted with the stakeholders.

Training needs to be provided at the program and individual team level.



SoS Quality Attributes

Quality Attributes of interest depend on vignette/thread type

- Operational: performance, availability, security, interoperability
- Developmental: legacy reuse, extensibility, openness, integrability
- Sustainment: maintainability, training, deployability, upgradeability

New consideration examples

- Survivability: Machinery MT on how to contain compartmental flooding in a critical compartment resulted in discussion on using new pump technologies to avoid flooding.
- Availability: Machinery MT on failure of a generator has a massive impact on all ship operations and mission
- Availability: Degraded operation on a failure needs to be defined across echelons, and mitigation alternatives defined
- Reduced Manning/Automation



SoS Stakeholders

Evaluation team and customer lead for MTW must get vignette/mission thread/QA/stakeholders ready for the meeting.

Diverse operational experiences eliminate stovepipe mentality

- Discussions on operational misunderstandings, confusions, and gaps were captured

Holding 9 MTWs in 6 weeks with a core team attendance at all provided consistency

Do not mix operational and developmental threads

- They require different stakeholders

Strong third party facilitation allowed operational principles to discuss rather than defend



SoS Architecture Development Process - 1

Each MTW prepared a good OV1 diagram to support the vignette. It was found that a single NR KPP OV1 would not provide the context needed for all teams.

Diagrams developed in PowerPoint or Visio were more than sufficient to support MTW effort, but use of a modeling tool (i.e., System Architect) is probably needed to support development of artifacts in later architectural processes.

The MTs developed were the basis for building OV 2,3,5 and SV1, 2 DoDAF diagrams, but additional guidance was needed in architecting process to provide a clear transition.

Stakeholders were uncomfortable developing vignettes/mission threads without a CDD-like requirements document.



SoS Architecture Development Process - 2

Development of a Mission Thread Description Document (MTDD) is a good way to capture architecture decisions. The MTDD contains the artifacts developed to support the MTWs, outputs of the MTWs (capability gaps, quality attribute augmented mission threads and architectural challenges) and ties to high level use cases.

SoS Architectural Guidelines are needed to provide consistent guidance through the architecting process.



SoS Capabilities and Engineering

High percentage of the data captured was about engineering considerations and gaps

Use cases were identified (and built at later date)

Legacy System Impacts

- One SoS assumed that the legacy systems (sensor, weapon, electrical, mechanical, etc.) would be re-used.
- Another SoS assumed legacy system re-engineering
- Another applied it to extended operational need



SoS Challenges

Each MTW resulted in individual challenges (5-7) for the operation were created by facilitation team and recommended mitigations suggested

- Vetted by the principles
- Led to engineering studies

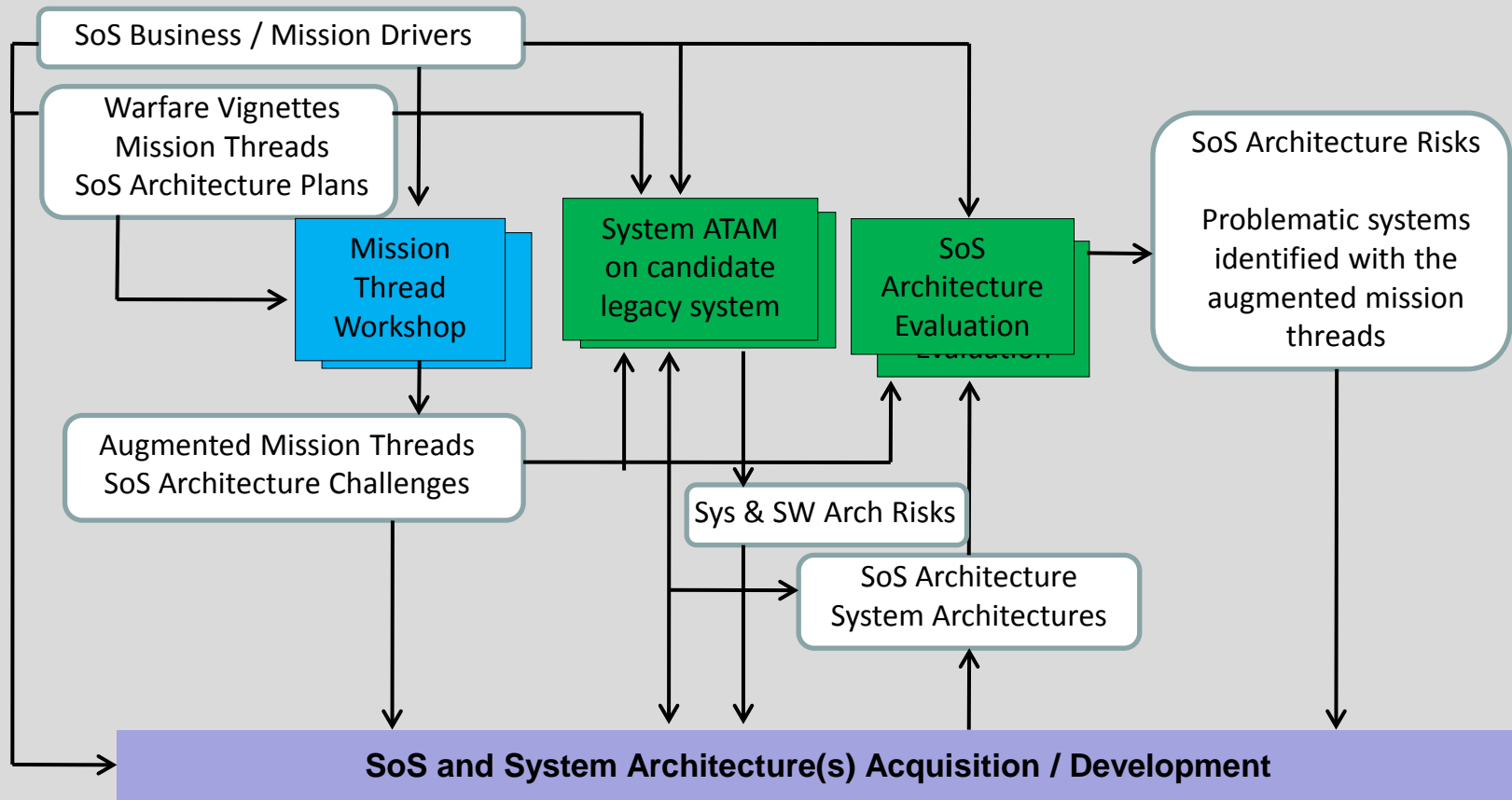
Where multiple MTWs were held, a set of aggregated challenges were built and mitigations suggested

- Response to a large scale failure, multi-mission planning, global situational awareness, reduced manning, reduced SMEs
- Automated field configuration, training
- Need to allocate additional time in schedule to gain consensus on aggregate challenges



SoS Architecture Quality Attribute Specification and Evaluation Approach

- Early elicitation of quality attribute considerations
- Early candidate legacy system architecture evaluation
- Early identification and mitigation of architectural risks



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Q&A

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