SYSTEM OF SYSTEMS ENGINEERING COLLABORATORS INFORMATION EXCHANGE (SOSECIE)

SYNTHESIZING AND SPECIFYING ARCHITECTURES FOR SYSTEM OF SYSTEMS

28 APRIL 2015

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PURDUE ENGINEERING

INDUSTRIAL ENGINEERING

TODAY'S TALK

TWO SOURCES TO GIVE YOU THE END-TO-END STORY

Selected material from two papers

- Kenley, C. Robert, Timothy M. Dannenhoffer, Paul C. Wood, and Daniel A. DeLaurentis. 2014. Synthesizing and Specifying Architectures for System of Systems. Paper read at 24th Annual INCOSE International Symposium, 30 June–3 July 2014, at Las Vegas, US-NV.
- Mane, Muharrem, and Daniel DeLaurentis. 2012. Sensor Platform Management Strategies in a Multi-Threat Environment. Paper read at Infotech@Aerospace 2012, 19 - 21 June, at Garden Grove, US-CA.

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Synthesizing and Specifying Architectures for System of Systems

C. Robert Kenley, Timothy M. Dannenhoffer, Paul C. Wood, and Daniel A. DeLaurentis

Purdue University

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A common question about SoS

- What is it that I should be doing for systems of systems that is different from what I always have done when engineering a system?

Our answer comes in two parts

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- Part 1
  - Experience-based practices for generating and evaluating C2BMC architectures
- Part 2
  - Review of applicable model-based systems engineering methods
  - Showing how model-based methods apply to our C2BMC example

Experience-based practices for generating and evaluating C2BMC architectures

PART 1

A Missile Defense System of Systems

- US Ballistic Missile Defense System (BMDS)
  - Land-, sea-, air-, and space-based assets
  - "Acknowledged" system of systems (Dahmann and Baldwin 2008)
    - Objectives, management, funding, and authority are established for the system of systems
    - The participating systems retain their own management, funding, and authority in parallel

Reference Process for Synthesizing Architectures

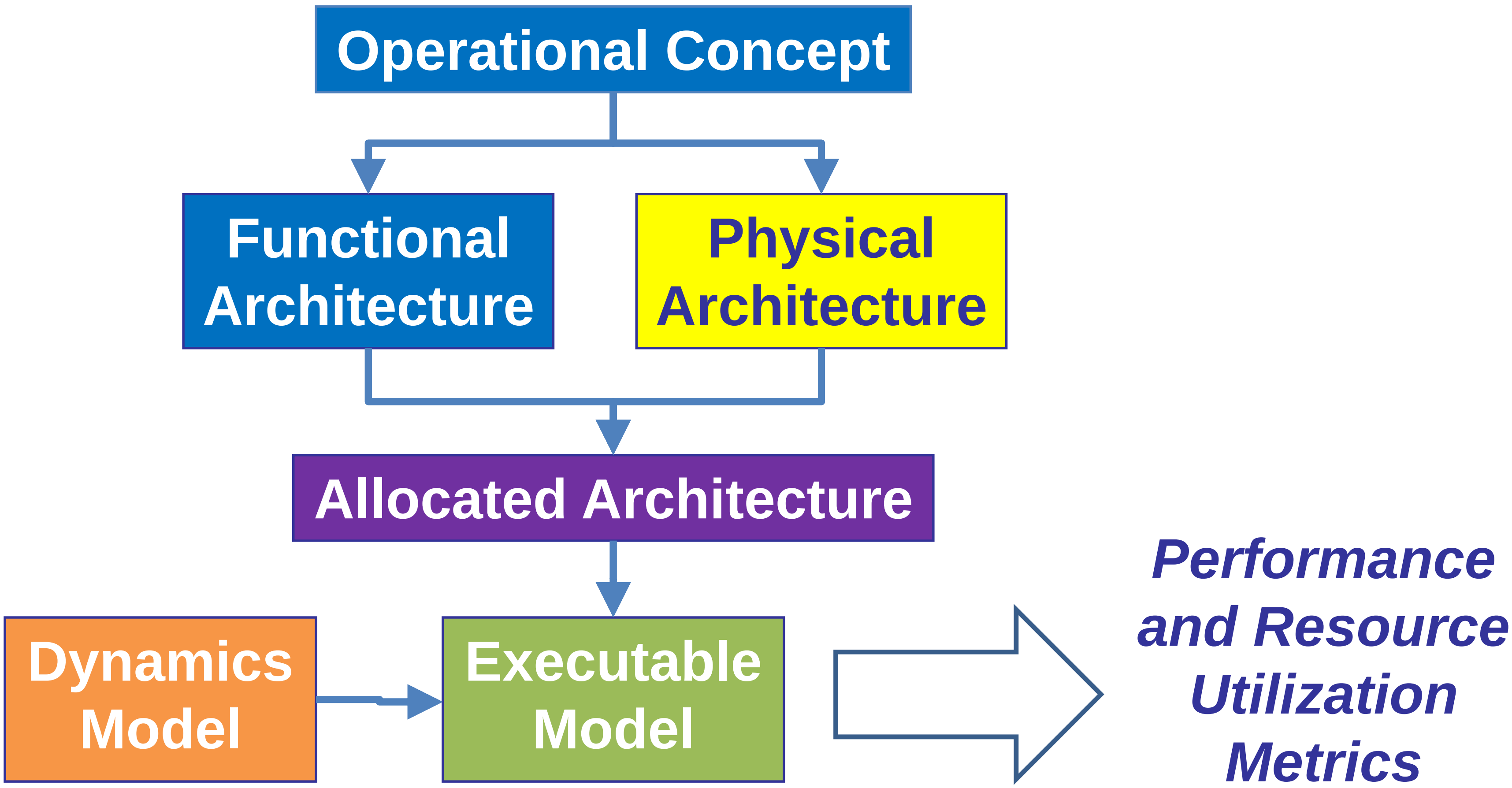

Figure adapted from Levis, Alexander H., and Lee W. Wagenhals. 2000. "C4ISR architectures: I. Developing a process for C4ISR architecture design." *Systems Engineering* no. 3 (4):225-247.

BMDS Operational Concept

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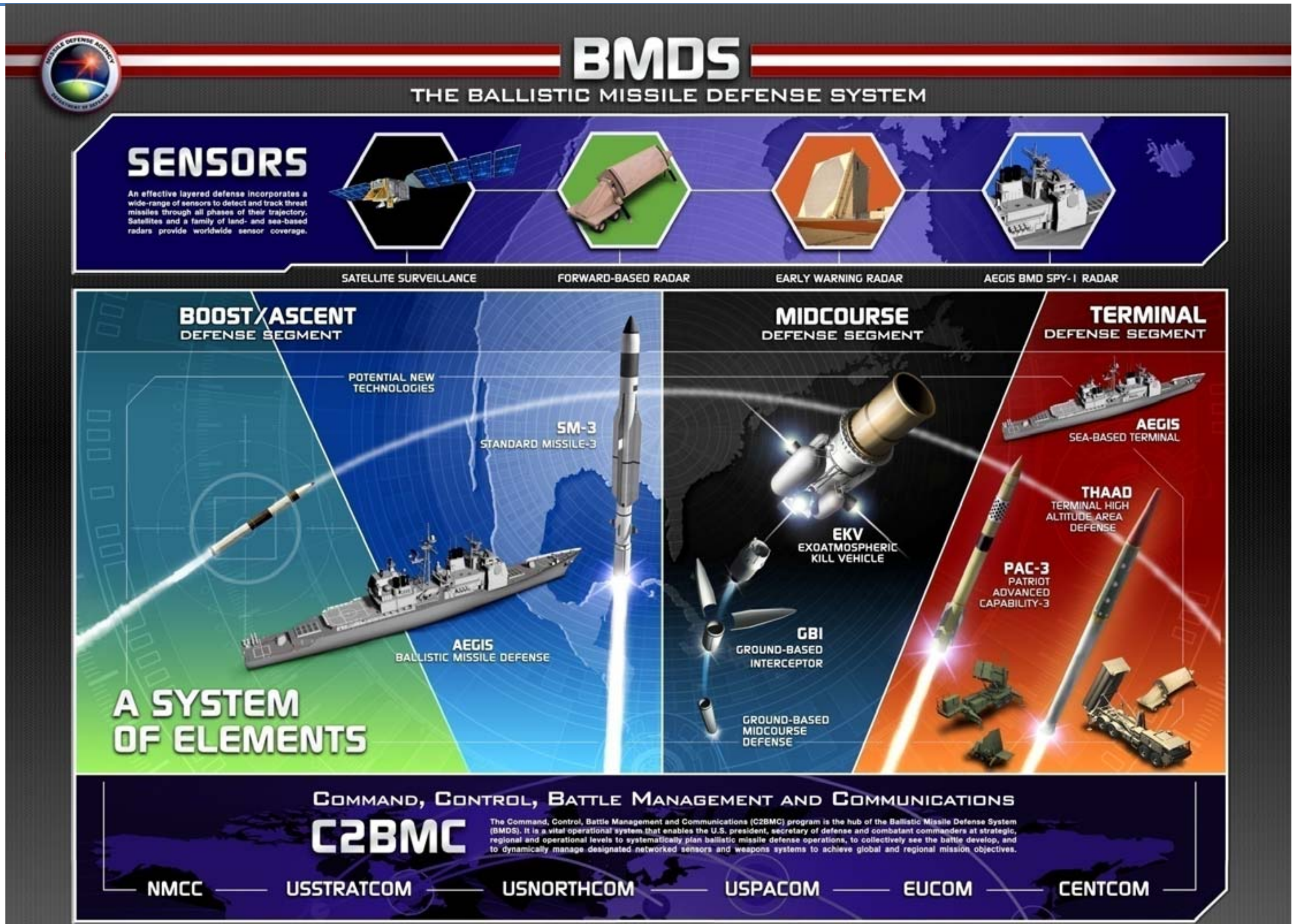

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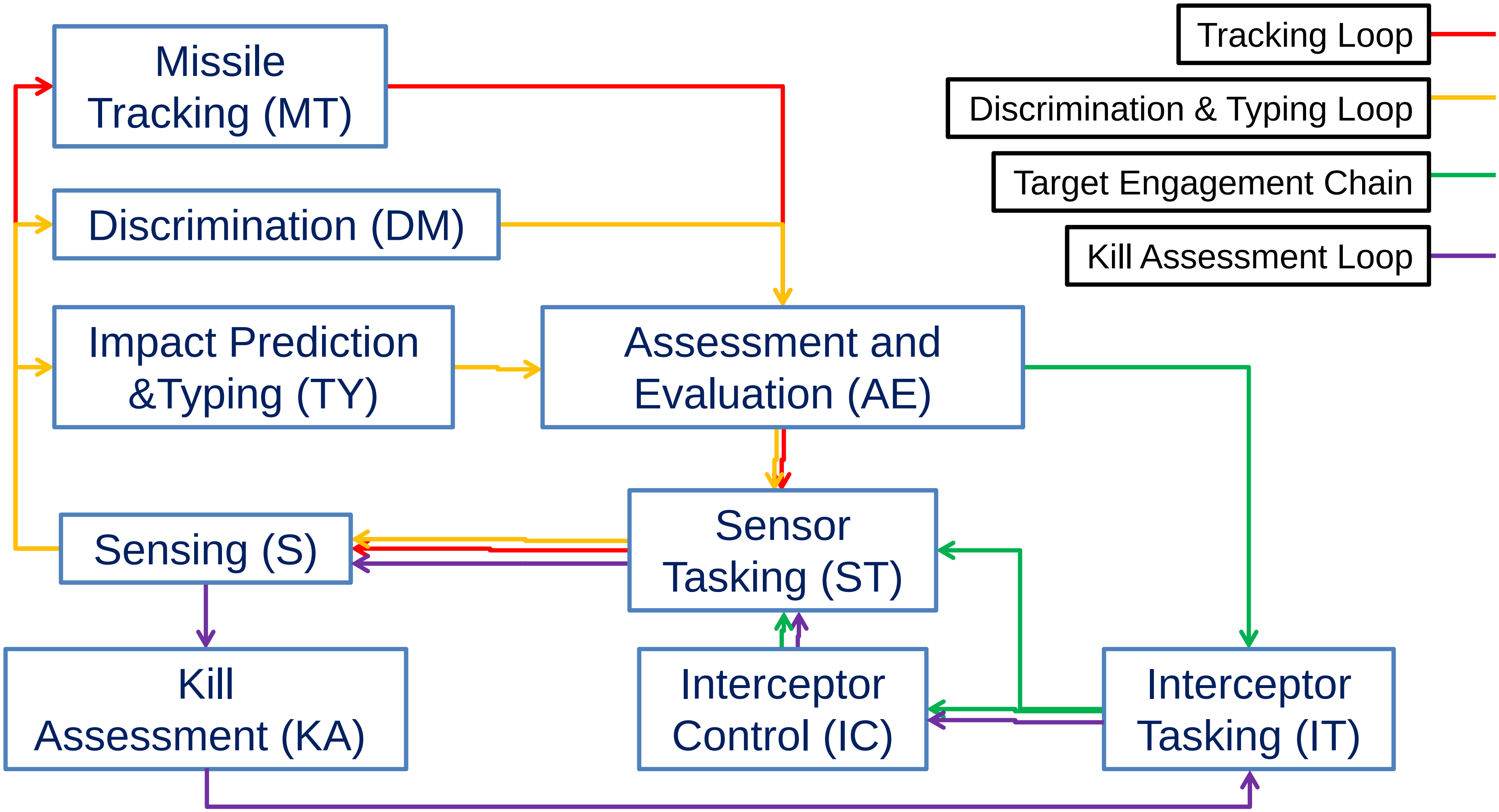
Functional Architecture: Control and Information Flow



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Physical Architecture: Platforms and Communications Links

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Class	Physical Entity	Relevant Attributes
Platform	• Aircraft • Satellite • Ground Station • C2 Node • Interceptor	• Location and Trajectory • Processing Resources • Interfaces to Communications Links
Communications Link	• Satellite • Wireless • Fiber	• Communication Protocols and Capacities

When is the SoS distinction manifest in the process?

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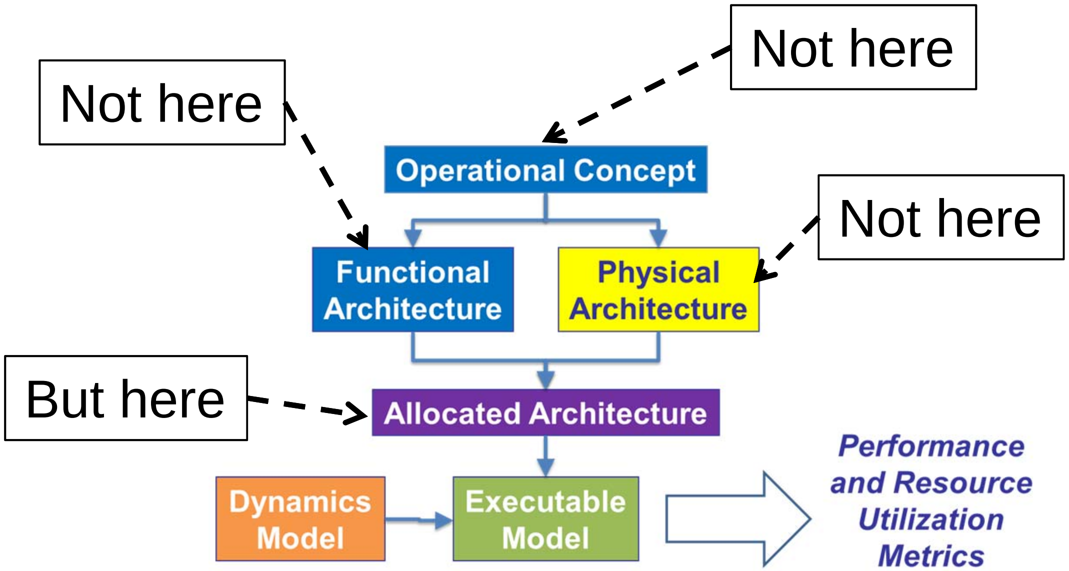
- It is in defining the allocated architecture that the distinguishing trait of operational independence is exhibited.



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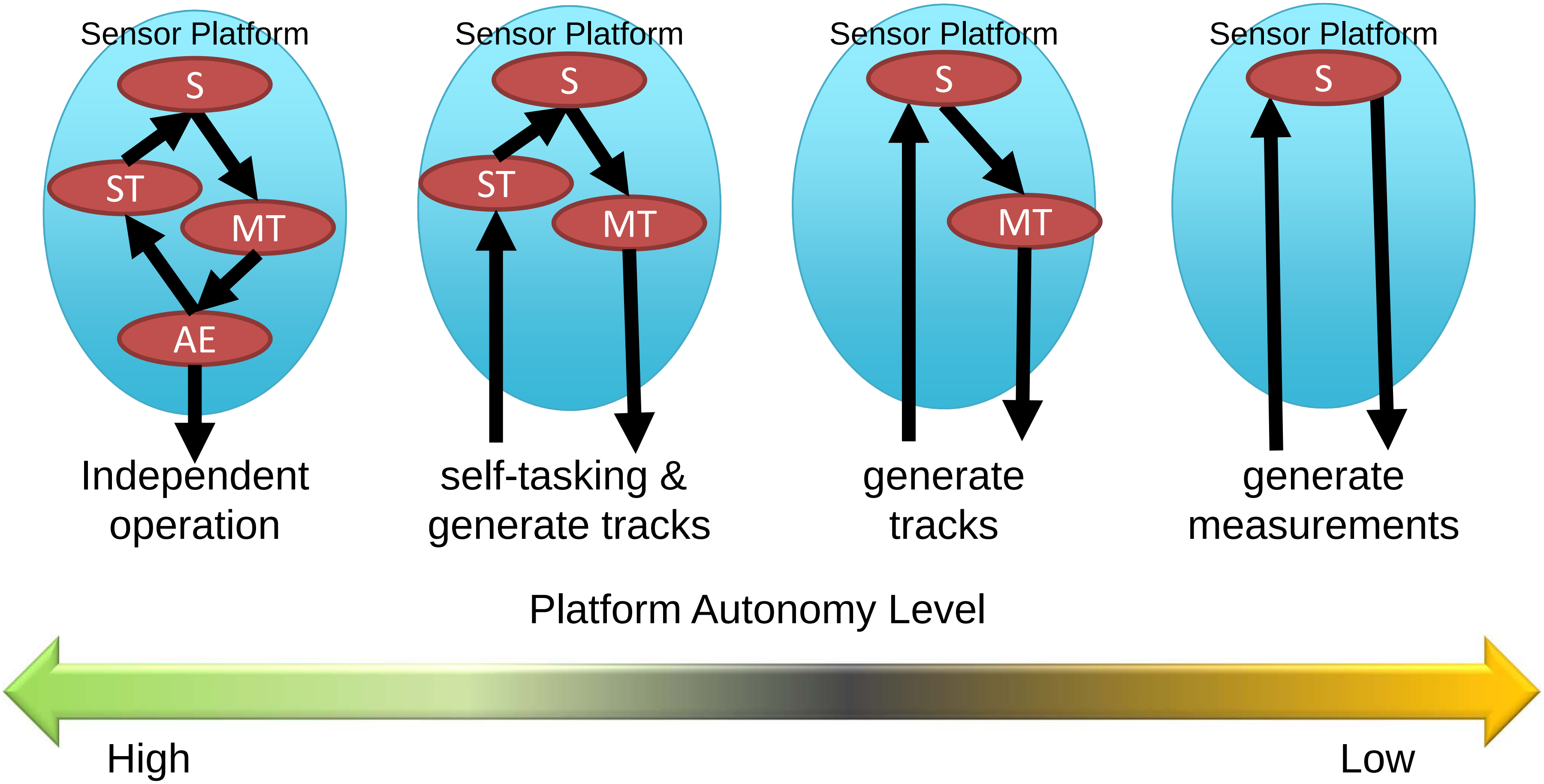
Allocated Architecture:
Options for Allocating Functions to a Sensor Platform



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Allocated Architecture: Example of Centralized vs. Decentralized Tracking

		Location of Functionality According to Architecture Centralization			
		Centralized	Centralized Tracking and Prioritization	Centralized Tracking	Decentralized
Functions	Missile Tracking (MT)	C2	C2	C2	Sensors
	Assessment and Evaluation (AE)	C2	C2	Sensors	Sensors
	Sensor Tasking (ST)	C2	Sensors	Sensors	Sensors
	Sensing (S)	Sensors	Sensors	Sensors	Sensors

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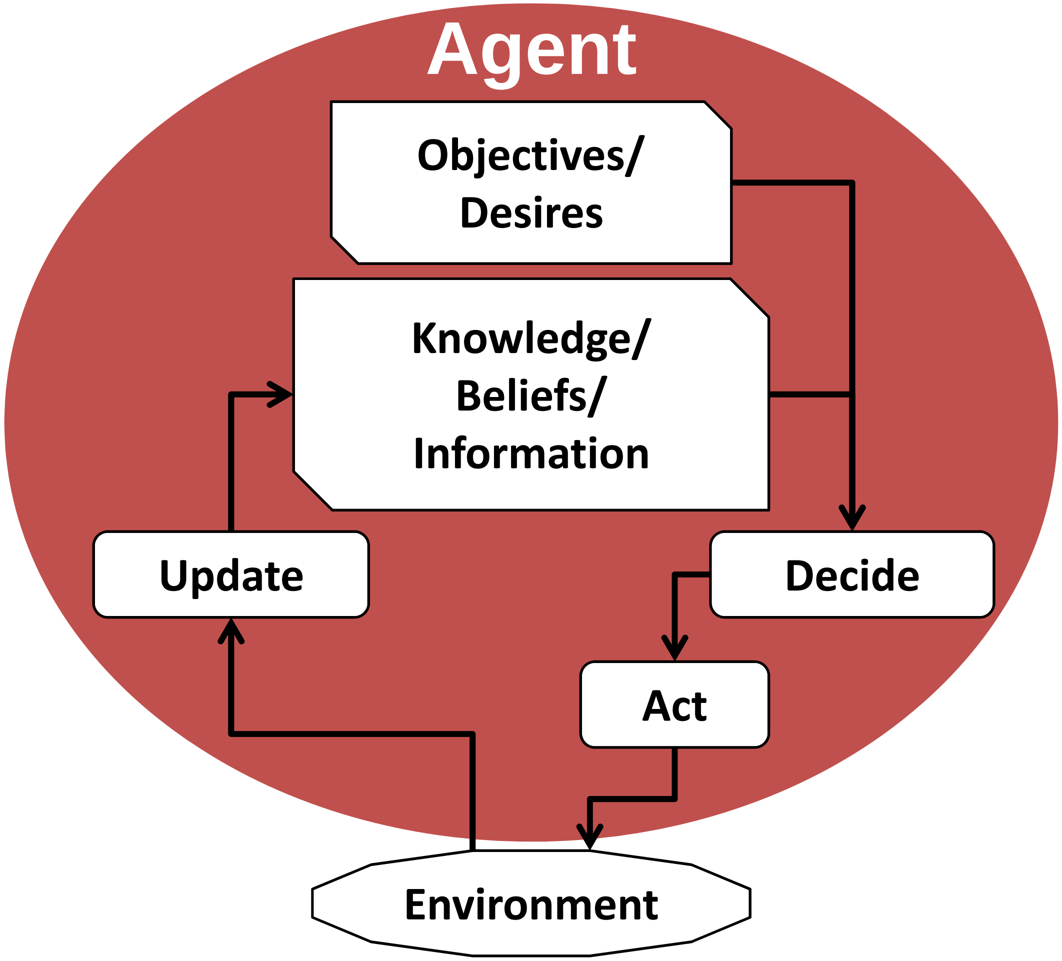
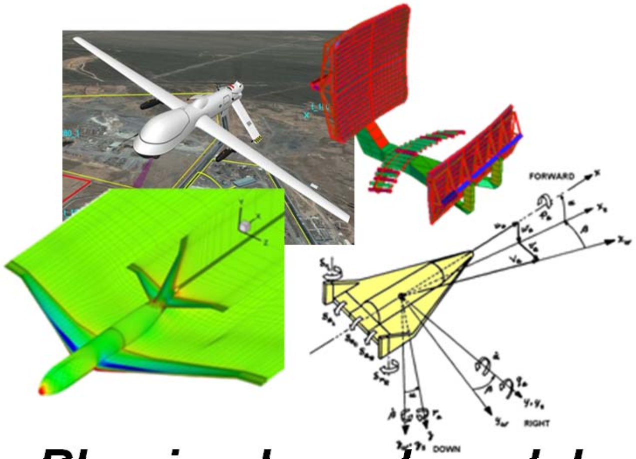
Agent-Based Dynamics Model

- Modeling functions as agents captures operational independence



Executable Model: Discrete Agent Framework (DAF)



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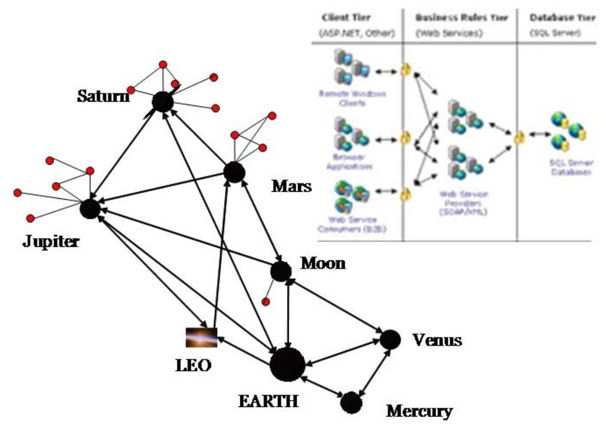

= **DAF**

Physics-based models ***Architecture-based models***

- Individual system behavior
  - Physics-based and heuristic-based behavior models
- Architecture of systems or systems-of-systems
  - Modes and types of interactions across multiple system types (e.g. human, technological, etc.)
  - Interdependencies between systems (e.g., exchange of info, data, energy, etc.)
- *New knowledge via design of agents, their capabilities, and interaction rules*

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Generating Communications Architectures

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- Architecture for a system of systems is defined by interfaces [Maier (1998)]
- For C2BMC
  - Interfaces = Communications Network
  - Logical agent-to-agent connections prescribed by functional architecture
- SoS architect allocates agents to platforms to create architectures
- Physical network connections (communications architectures) must be defined for all logical connections

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What Our Model Builder Does

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- Architect specifies which agents are to be logically connected, ignoring complexities of physical network paths
- Architect specifies constraints and assumptions for physical network (e.g., each ground station is connected to only a single type of sensor)
- Model builder automatically creates physical communication paths between agents based on a shortest path algorithm
  - Distance can be defined in several ways (number of links, or total time to transmit, which favors fiber connections over lower speed links)
- Benefits
  - Reduces bookkeeping burden and errors
  - Increases productivity and coverage (large number of architectures can be created for evaluation)

- Review of applicable model-based systems engineering methods
- How the methods apply to our C2BMC example

PART 2

Desiderata for Specifying SoS Using MBSE

- MBSE methods that specify SoS dynamics models and executable models must support
  - Agent-based modeling of actions
  - Interactions of actors who perform concurrent, asynchronous activities

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Using UML for Agent-Based Modeling [Park, Kim, and Lee (2000)]

Intra-agent Models

Model	Approach
Goal	Object model of a goal hierarchy
Belief	Object model of beliefs and external message protocols
Plan	Update beliefs; and determine actions to take and messages to send
Capability	Logic for actions to be taken by the agent

Inter-agent Models

Model	Approach
Agent Mobile	Define how an agent coordinates its actions to perform a task with other agents (assumes a coordinator agent)
Agent Communication	Define how messages are exchanged between agents including sequence diagram of agent actions and messages

- Based on UML 1.1: does not assume complete autonomy among the agents nor does it assume concurrency

Mapping Dynamics Models to Executable Petri Net Models

- Petri nets
  - Executable models for simulating interactions of concurrent, asynchronous activities
- Pre-UML 2.0 Examples
  - Mapping a business-process workflow model of the dynamics of a biological system to a Petri net [Peleg, Yeh, and Altman (2002)]
  - Converting a UML 1.3 specification for the dynamics of a C4ISR system to a colored Petri net [Wagenhals, Haider, and Levis (2003)]

UML 2.0 to the Rescue

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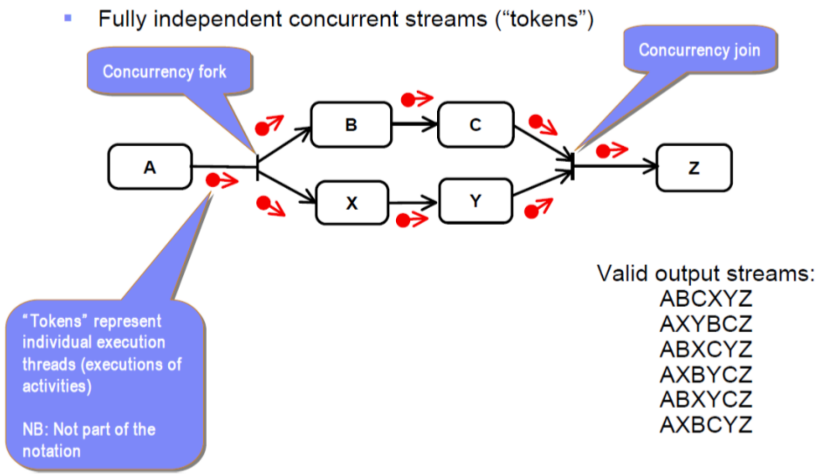
Figure from Quatrani's 2005 "Introduction to UML 2.0"



Claims in the UML 2.0 spec

- "Petri-like semantics instead of state machines" to allow for concurrency that includes tokens [OMG, OMG Unified Modeling Language: Superstructure (final adopted spec, version 2.0, 2003-08-02), Technical report, Object Management Group (2003)]

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UML 2.0 and Petri Nets

- Mapping UML 2.0 activity diagrams to
  - Colored Petri nets [Störrle (2005)]
  - Fundamental Modeling Concepts version of Petri net diagram [Staines (2008)]
- Proposal to extend UML [Sinclair (2009)]
  - Add explicit UML constructs for hierarchical and timed colored Petri nets
  - Purpose is to enable modeling and simulation of system of systems

UML Activity Diagram for Completely Centralized Tracking Architecture

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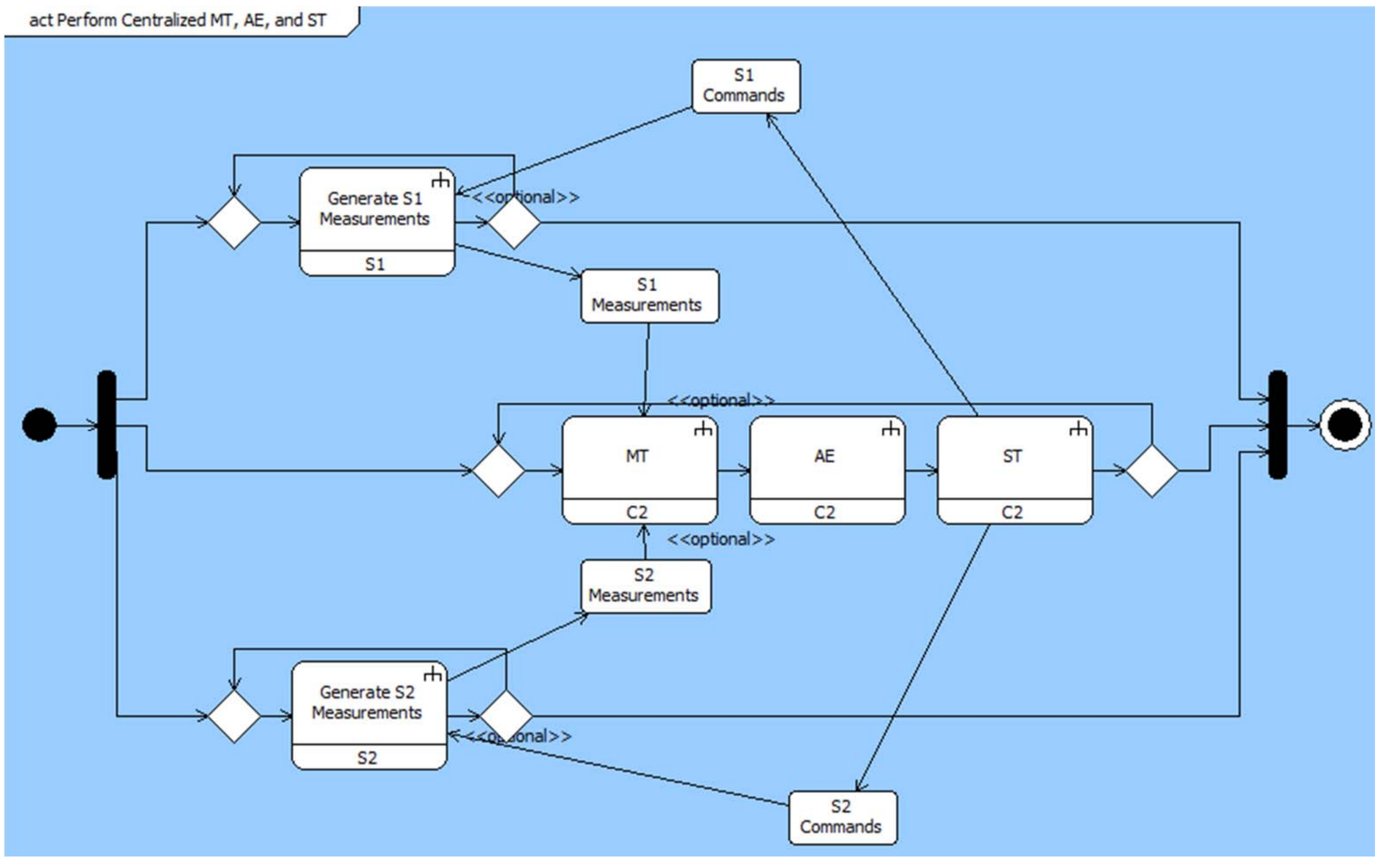

S1= Sensor 1, S2 = Sensor 2, MT = Missile Tracking, AE = Assessment and Evaluation, ST = Sensor Tasking, C2 = Command and Control

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UML Activity Diagram for Generic Agent

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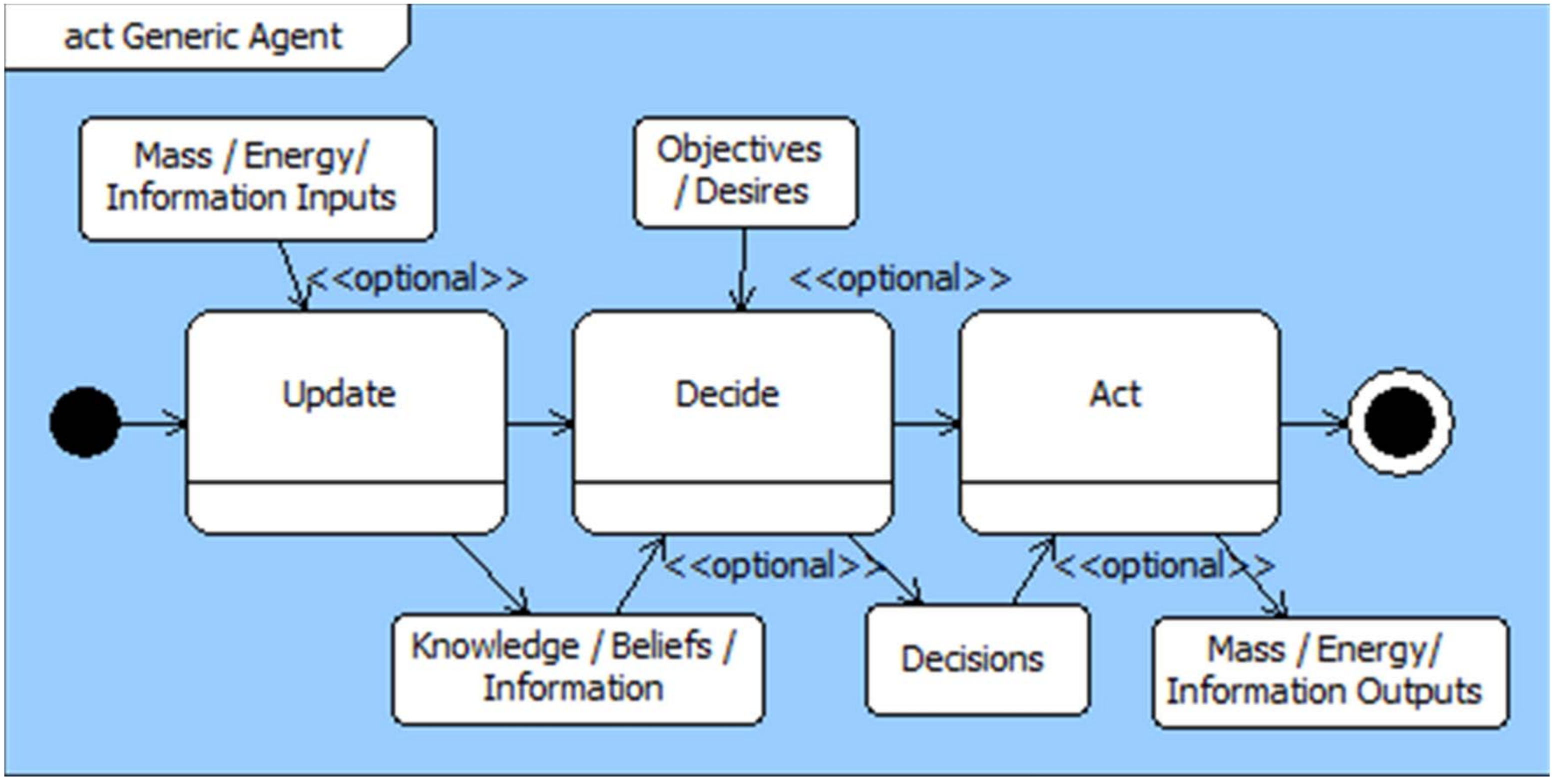

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UML Activity Diagram for Missile Tracking Agent

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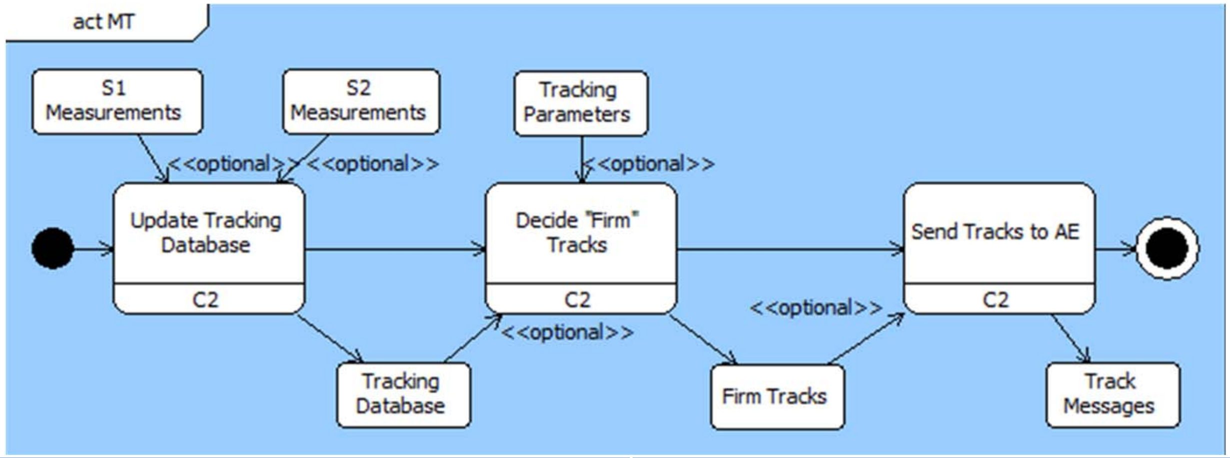

Generic Agent Item	Missile Tracking Agent Item
Mass / Energy / Information Inputs	S1 and S2 Measurements
Update	Update Tracking Database
Knowledge / Beliefs / Information	Tracking Database
Objectives / Desires	Tracking Parameters
Decide	Decide “Firm” Tracks
Decisions	Firm Tracks
Act	Send Tracks to AE
Mass / Energy / Information Outputs	Track Messages

UML Activity Diagram for Centralized MT with Distributed AE and ST

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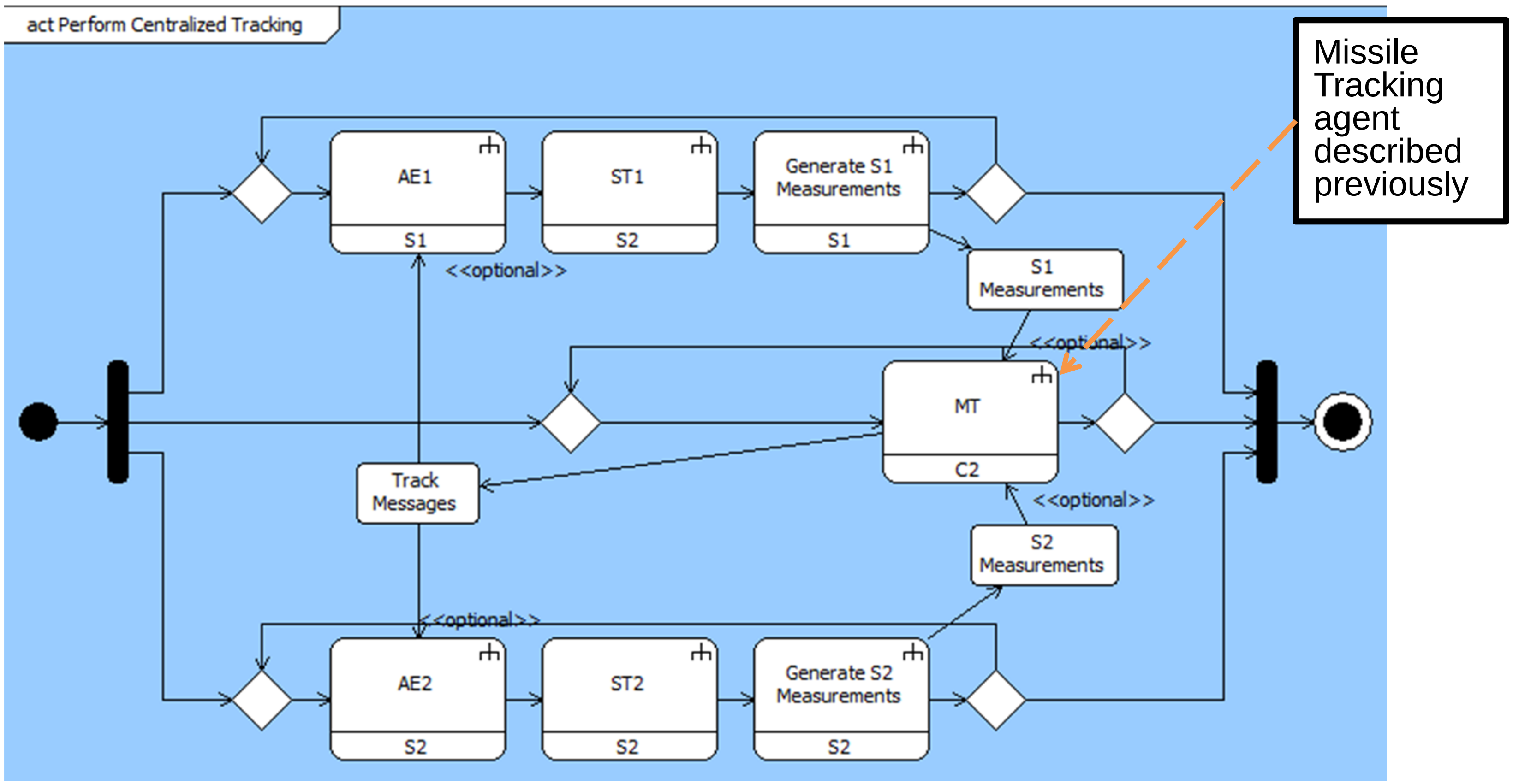

Sn= Sensor *n*, MT = Missile Tracking, AEn = Assessment and Evaluation *n*, STn = Sensor Tasking *n*, C2 = Command and Control

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What We Have Done

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- Applied "traditional" systems architecting process to SoS
- Discovered that the dynamic modeling of a SoS is key step in applying the process
  - Used agent-based modeling to capture emergent behavior that derives from complex interactions of systems of systems.
- Developed methods to ease burden of manually synthesizing network architectures
- Developed a "pattern" for agent-based models using UML activity diagrams to specify the independently operating constituent systems within SoS

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What Next?

- Investigate the details of going from UML activity diagrams to executable models
  - Agent-based modeling tools such as Purdue's Discrete Agent Framework
    - Maheshwari, Apoorv, C. Robert Kenley, and Daniel A. DeLaurentis. 2015. Creating Executable Agent-Based Models Using SysML. Paper to be read at 25th Annual INCOSE International Symposium, 13–16 July 2015, at Bellevue, US-WA.
  - Petri-net modeling tools
- Look at usefulness of other UML constructs
  - Executable models based on state machine diagrams

Sensor Platform Management Strategies in a Multi-Threat Environment

Muharrem Mane

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Approved for Public Release 12- MDA-6880 (6 June 12)

Infotech@Aerospace 2012

Reference Process for Synthesizing Architectures

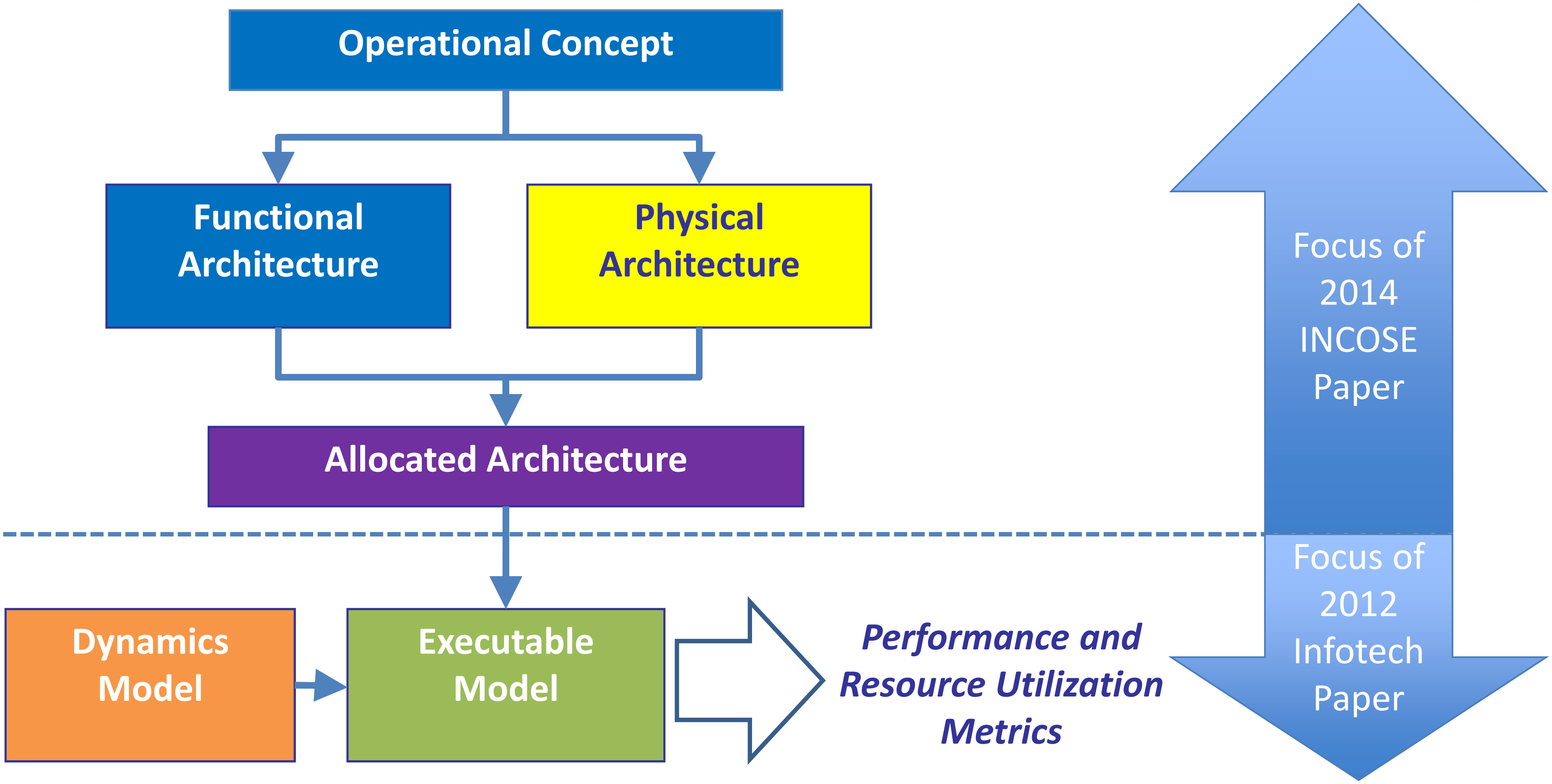
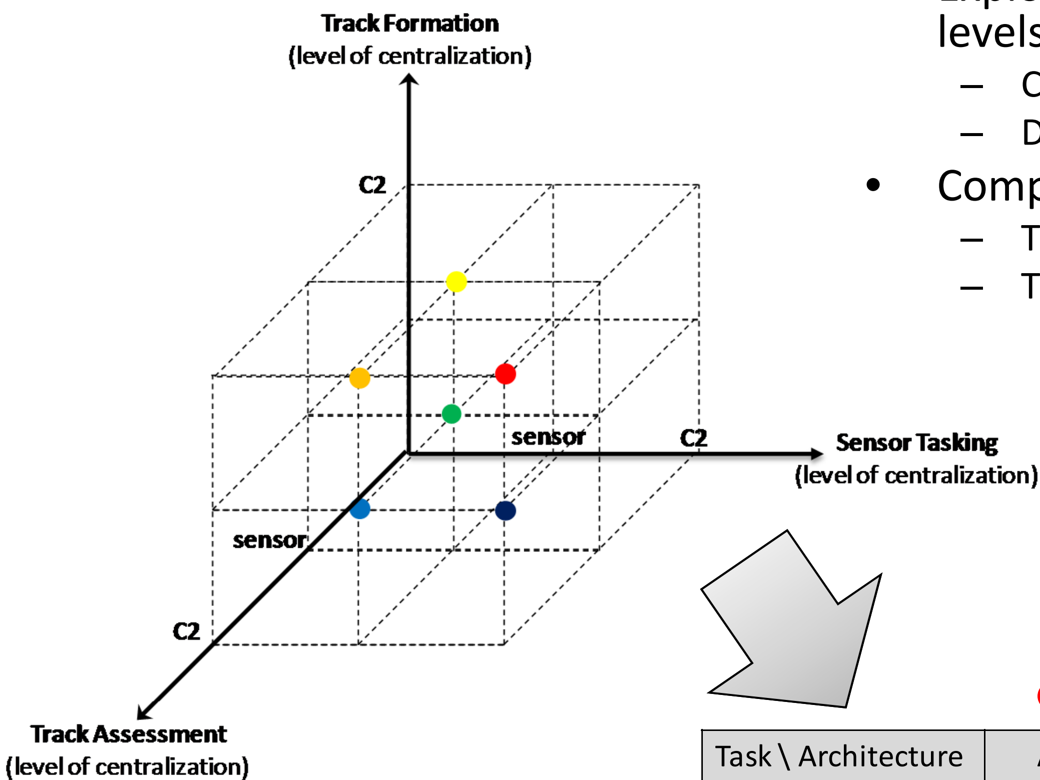


Figure adapted from Levis, Alexander H., and Lee W. Wagenhals. 2000. "C4ISR architectures: I. Developing a process for C4ISR architecture design." *Systems Engineering* no. 3 (4):225-247.

Example Analysis

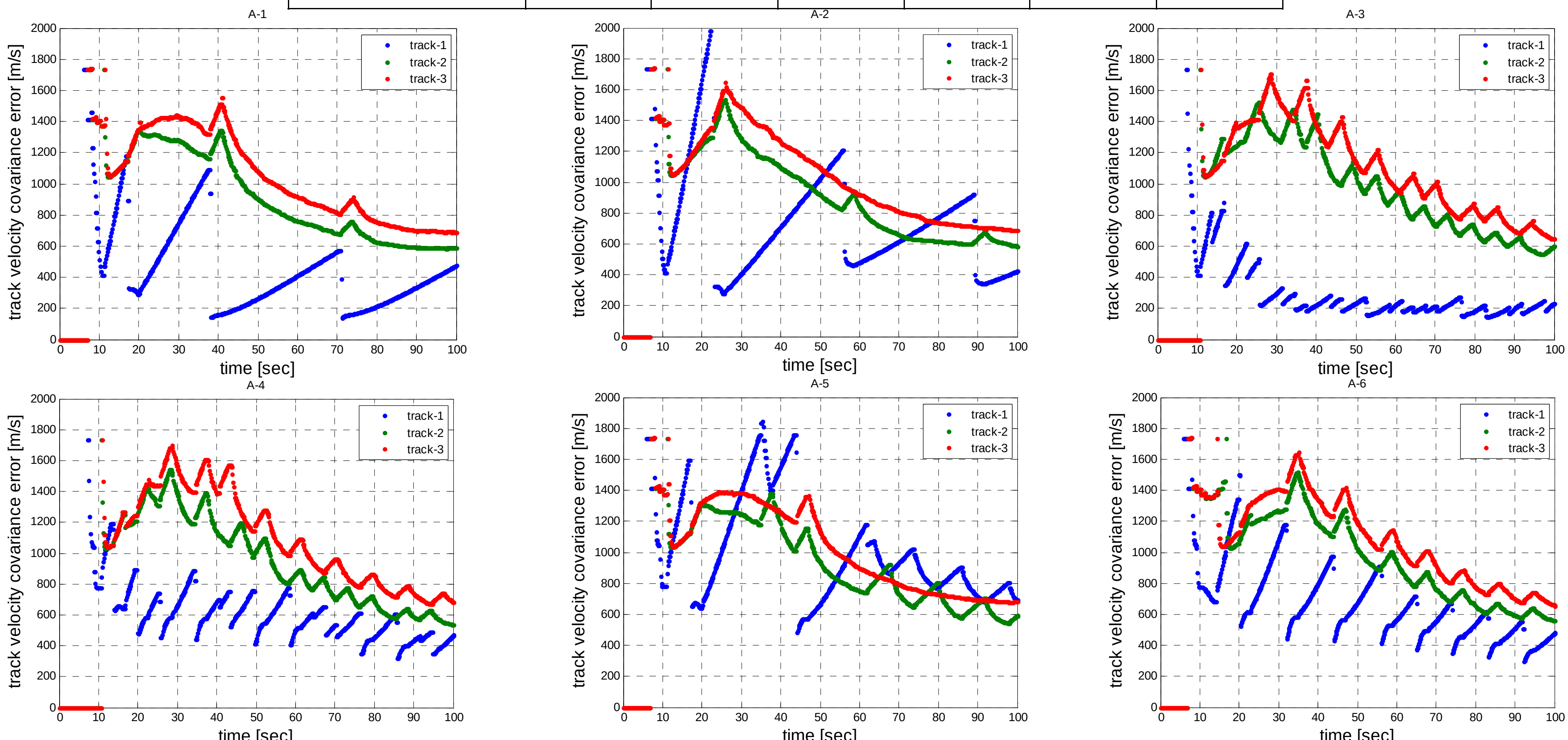


- Explore architecture dimensions with two levels of centralization
  - Centralized: at C2 (command and control) node
  - Decentralized: at sensor
- Compare performance
  - Track quality
  - Track accuracy

Task \ Architecture	A-1	A-2	A-3	A-4	A-5	A-6
Track Formation	C2	C2	C2	Sensor	Sensor	Sensor
Track Assessment	C2	C2	Sensor	Sensor	C2	C2
Sensor Tasking	C2	Sensor	Sensor	Sensor	Sensor	C2

Results

Task \ Architecture	A-1	A-2	A-3	A-4	A-5	A-6
Track Formation	C2	C2	C2	Sensor	Sensor	Sensor
Track Assessment	C2	C2	Sensor	Sensor	C2	C2
Sensor Tasking	C2	Sensor	Sensor	Sensor	Sensor	C2



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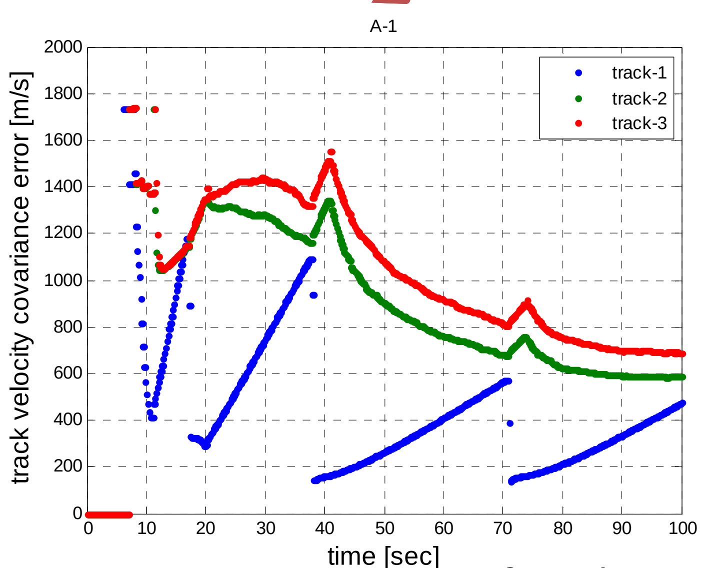
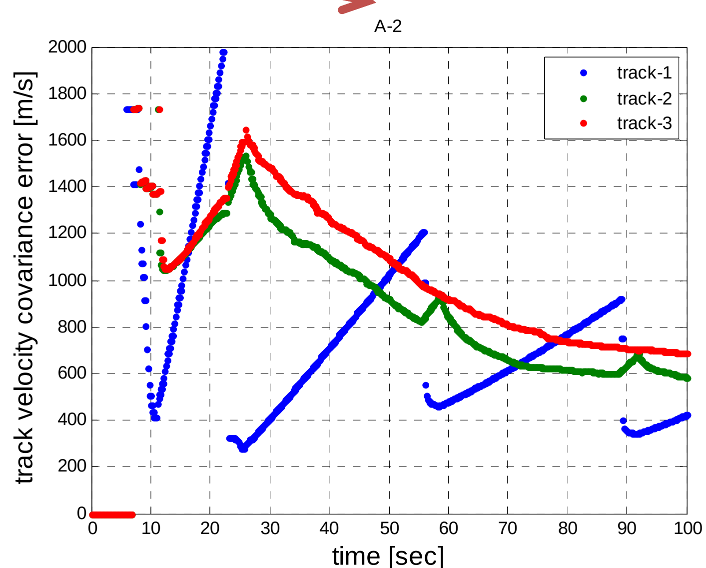
Impact of Sensor Tasking

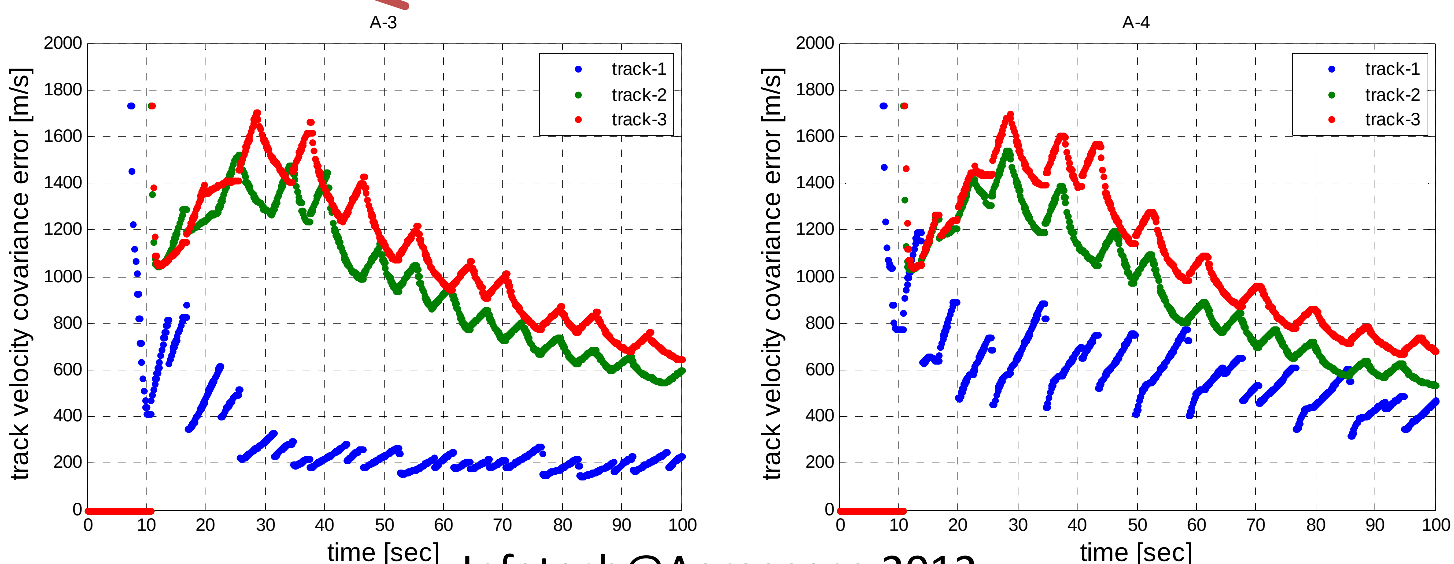
Task \ Architecture	A-1	A-2	A-3	A-4	A-5	A-6
Track Formation	C2	C2	C2	Sensor	Sensor	Sensor
Track Assessment	C2	C2	Sensor	Sensor	C2	C2
Sensor Tasking	C2	Sensor	Sensor	Sensor	Sensor	C2





Impact of Track Formation

Task \ Architecture	A-1	A-2	A-3	A-4	A-5	A-6
Track Formation	C2	C2	C2	Sensor	Sensor	Sensor
Track Assessment	C2	C2	Sensor	Sensor	C2	C2
Sensor Tasking	C2	Sensor	Sensor	Sensor	Sensor	C2



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Summary

- Missile tracking architecture centralization taxonomy
  - Guides exploration of architecture design space
- Modeling and simulation framework
  - Behavioral-model-based simulation framework
  - Enable performance comparison of architecture concepts
  - Capture interaction between functions (and systems)
- Sample scenario observations
  - Centralization of sensor tasking can coordinate and effectively use sensor resources to have impact on track quality
  - Centralization of track formation larger impact on track quality

WHAT DID WE PRESENT TODAY?

- Showed applicability of “traditional” systems architecting process to SoS
- Reviewed experience-based practices for generating and evaluating C2BMC architectures
- Described one method to ease burden of manually synthesizing network architectures
- Reviewed applicable model-based systems engineering methods for specifying SoS architectures
- Showed how model-based methods apply to our C2BMC example
- Described a “pattern” for agent-based models to specify independently operating constituent systems within SoS
- Showed how agent-based modeling captured emergent behavior for our C2BMC example
- Provided you background for our 2015 INCOSE paper to be presented on 16 July

THANK YOU

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