Naval Integrated Fire Control - Counter Air

Capability-based System of Systems Engineering

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1.0 Introduction

"Understanding the environment in which a system or System of Systems (SoS) will be developed is central to understanding how best to apply systems engineering (SE) principles within that environment"[1]. Since 1996, the Naval Integrated Fire Control-Counter Air (NIFC-CA) project has been striving to develop a SoS capability to defeat overland cruise missile and Over-the-Horizon (OTH) air warfare threats. Lacking the luxury of a "directed" SoS SE organization with component systems subordinated to the overarching SoS, the NIFC-CA project has utilized the "acknowledged" SoS SE methodology. This approach empowers a SoS SE team to work collaboratively with independent component system SE teams to achieve SoS capabilities and objectives. The NIFC-CA SoS SE approach has been very challenging but also rewarding and is viewed by the Deputy Under Secretary of Defense for Acquisition and Technology (DUSD(A&T)) as a pilot model for future SoS acquisition programs. With the successful completion of all critical design review (CDR) milestones in 2009 a review of the NIFC-CA SE environment, approach and accomplishments is timely and instructive for similar developmental programs.

2.0 NIFC-CA Background

In a letter dated January 11, 1996, Mr. Paul Kaminski, then Under Secretary Defense for Acquisition and Technology (USD(A&T)), and the Vice Chairman, Joint Chiefs of Staff (VCJCS), Admiral W. A. Owens, initiated action to address the emergence of the overland cruise missile threat[2]. Very challenging situations are presented by this threat when the detection and illumination of cruise missiles, that can also change course and speed, become blocked by the Earth's curvature, coastal hills, mountains and varying types of terrain.

Beginning with the 1996 letter, technologies and acquisition programs were given direction or guidance to ensure emerging developmental systems would include capabilities supporting the resultant Overland Cruise Missile Defense (OCMD) SoS. Specifically, OCMD was to be supported by the development of the Army aerostat[3] program, improvements to the Navy E-2C and Air Force E-3 early warning aircraft and advanced interceptor seeker development.

In 2002, the OCMD program was officially recast as the NIFC-CA project in a joint ASN(RDA) and VCNO letter[4]. This recasting documented the growth of project scope to defeat the OTH manned fighter and OTH anti-ship cruise missile (ASCM) threat in addition to the original OCMD mission. The letter also directed Program Executive Officer - Integrated Warfare Systems (PEO IWS) to establish a NIFC-CA Systems Engineering and Integration Project Office to "integrate across the elemental programs in support of the development and acquisition of a

[1] Deputy Under Secretary of Defense for Acquisition and Technology (DUSD(A&T)), Systems Engineering Guide for Systems of Systems (U), Version 1.0, August 2008 (www.acq.osd.mil/**se**/docs/**SE**-**Guide**-for-**SoS**.pdf)
[2] USD(A&T) memo of 11 Jan 96; Subj: Land Attack Cruise Missile Defense (CMD)
[3] Today known as the Army **J**oint **L**and Attack Cruise Missile Defense **E**levated **N**etted **S**ensor (JLENS)
[4] ASN(RDA)/VCNO Memo of 11 Oct 2002; Subj: Updated Responsibilities for Management of Naval Integrated Fire Control – Counter Air (NIFC-CA)

NIFC-CA Capability". NIFC-CA was to execute as a capabilities-based acquisition project, levying minimal requirements onto the component systems while deriving SoS capability from the union of these independent systems.

In 2010, NIFC-CA has resolved into an advanced Family of SoS (FoS) engineering project that is working to combine multiple sensors through IFC-compliant combat systems to support extended range active missiles. The NIFC-CA FoS officially includes three complete SoS known as "killchains" as illustrated in Table 1. Each SoS killchain consists of elevated and surface sensor(s), a sensor network, a weapon control system and an active missile. The balance of this paper will concentrate on the FTS killchain.

Table 1 - The NIFC-CA Family of System of Systems

SoS (Killchain)	Remote Sensors	Sensor Network	Weapon Control System	Active Missile
From-the-Air (FTA)	E-2D F-18 E/F	LINK-16	F-18 E/F	AMRAAM
From-the-Sea (FTS)	E-2D JLENS	CEC	Aegis ACB12	SM-6
From-the-Land (FTL)	E-2D JLENS TPS-59 G/ATOR	CTN	CAC2S	None – Currently TBD

AMRAAM – Advanced Medium Range Air-to-Air Missile (AIM-120D)
CEC – Cooperative Engagement Capability
CTN – Composite Tracking Network (CEC network hosted on USMC land-mobile vehicles)
CAC2S – Common Aviation Command and Control System
G/ATOR – Ground / Air Task Oriented Radar

3.0 The NIFC-CA SoS SE Environment

"Control your own destiny or someone else will."
– Jack Welch – former CEO of General Electric

An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities.[5]

The ability to control the outcome of any SoS development is a function of the authority available to the SoS manager or SoS integrator. In all SoS acquisition programs the developmental environment is a key driver of what can be accomplished, how the systems

[5] Department of Defense (DoD), Defense Acquisition Guidebook Ch. 4 "System of Systems Engineering," Washington, DC: Pentagon, October 14, 2004.

acquisition and systems engineering will be performed and whether the ultimate outcome is successful or not.

The SoS "type", as described below, dictates how much authority and control is available to the SoS manager and system engineering team to achieve SoS objectives. The type further addresses SoS component system independence and the manner in which the component systems are aligned, either by direction or cooperation to achieve SoS capabilities.

3.1 SoS Type

The DUSD/A&T Systems Engineering Guide for SoS describes the four types of SoS typically seen across DoD and industry. Table 2 lists all four types with a short description of each to help delineate and define the "acknowledged" SoS approach utilized by NIFC-CA.

Table 2 – SoS Types
Virtual. Virtual SoS lack a central management authority and a centrally agreed upon purpose for the system-of-systems. Large-scale behavior emerges—and may be desirable—but this type of SoS must rely upon relatively invisible mechanisms to maintain it. The DoD net-centric policies and strategies that connect all DoD systems to virtual networks for information sharing are creating a virtual SoS.
Collaborative. In collaborative SoS the component systems interact more or less voluntarily to fulfill agreed upon central purposes. The Internet is a collaborative system. The Internet Engineering Task Force works out standards but has no power to enforce them.
Acknowledged. Acknowledged SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the component systems are based on collaboration between the SoS and the component system.
Directed. Directed SoS are those in which the integrated SoS is built and managed to fulfill specific purposes. It is centrally managed during long-term operation to continue to fulfill those purposes as well as any new ones the system owners might wish to address. The component systems maintain an ability to operate independently, but their normal operational mode is subordinated to the central managed purpose.

The virtual and collaborative types are not utilized for the development of SoS that have the intended purpose of delivering lethal force. The more intentional systems engineering processes inherent in the acknowledged and directed types of SoS is essential for lethal systems development.

The Missile Defense Agency (MDA) is a contemporary example of a directed SoS type. On January 2, 2002 the Secretary of Defense refocused and reorganized the existing Ballistic Missile Defense (BMD) program into the newly formed MDA with the mandate and authority to manage all aspects of the component systems as a synergistic whole. This SoS type is very attractive but a rarity, typically mandated at the secretariat level for national priority programs such as the Strategic Systems Program, the National Reconnaissance Office and the MDA.

NIFC-CA is an example of and a USD pilot project for the "acknowledged" type of SoS. NIFC-CA is charged with bringing together independent major defense acquisition programs (MDAP) as component systems of the NIFC-CA SoS. These programs have their own operational requirements, specific funding lines, independent developmental timelines and staggered deployment schedules. The mandate to collaborate with and support the NIFC-CA project management and system engineering team has been communicated from senior USD, ASN and Navy leadership but still presents a tough balancing act for all program managers involved.

3.2 NIFC-CA Acquisition Leadership and Management

Successful management of acknowledged SoS SE projects requires reaching across organizational boundaries to establish an end-in-mind set of objectives and the resourced plan for achieving those objectives. The acknowledged SoS type increases the complexity, scope, and cost of both the planning process and systems engineering, and introduces the need to coordinate inter-program activities and manage agreements among multiple program managers (PMs) as stakeholders who may not have a vested interest in the SoS.

Through 2002 as the Navy solidified its programmatic approach to NIFC-CA development the organizational structure depicted in Figure 1 evolved. This picture was completed in 2006 as PEO IWS-7, the NIFC-CA Project Office, established a collaborative Government/Industry Systems Engineering Integration & Test (SEI&T) team that is primarily composed of personnel from the NIFC-CA Project Office, government laboratories, academia and industry team members from each component system.

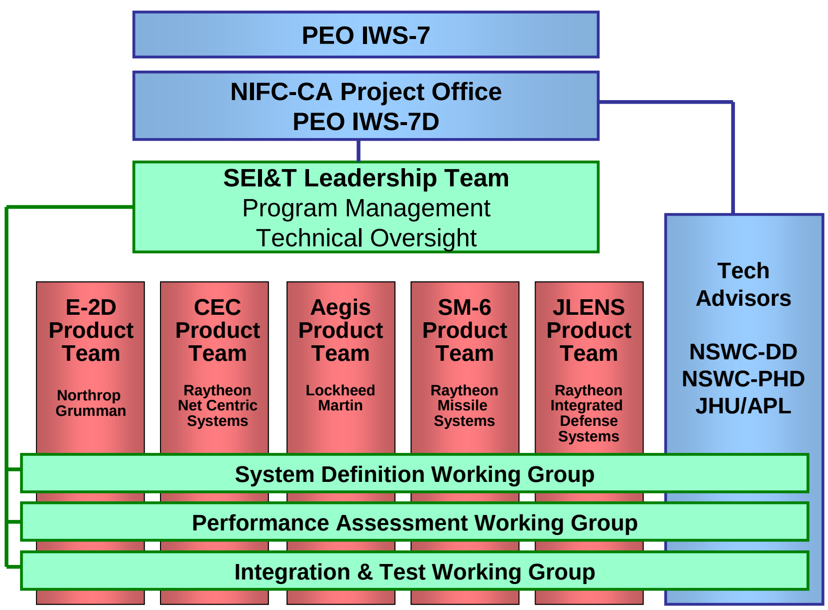

Figure 1: NIFC-CA SoS Management

The task of the NIFC-CA SEI&T effort is to ensure the component programs are integrated to achieve a viable SoS by matching individual system contributions to SoS performance goals. The NIFC-CA capability is not derived from a set of initial requirements leading to component program selection. Rather, the NIFC-CA capability is derived from the SoS performance predictions via analysis and/or SoS models and simulations that describe the expected performance of the component systems.

4.0 NIFC-CA Capability Acquisition and SoS Engineering

Over the past decade, the NIFC-CA government/industry team has made significant accomplishments across the acquisition spectrum both at the FTS SoS killchain level and within the supporting component systems. Figure 2 illustrates the disciplines, processes, tools and products that have been executed throughout the development of the NIFC-CA Capability.

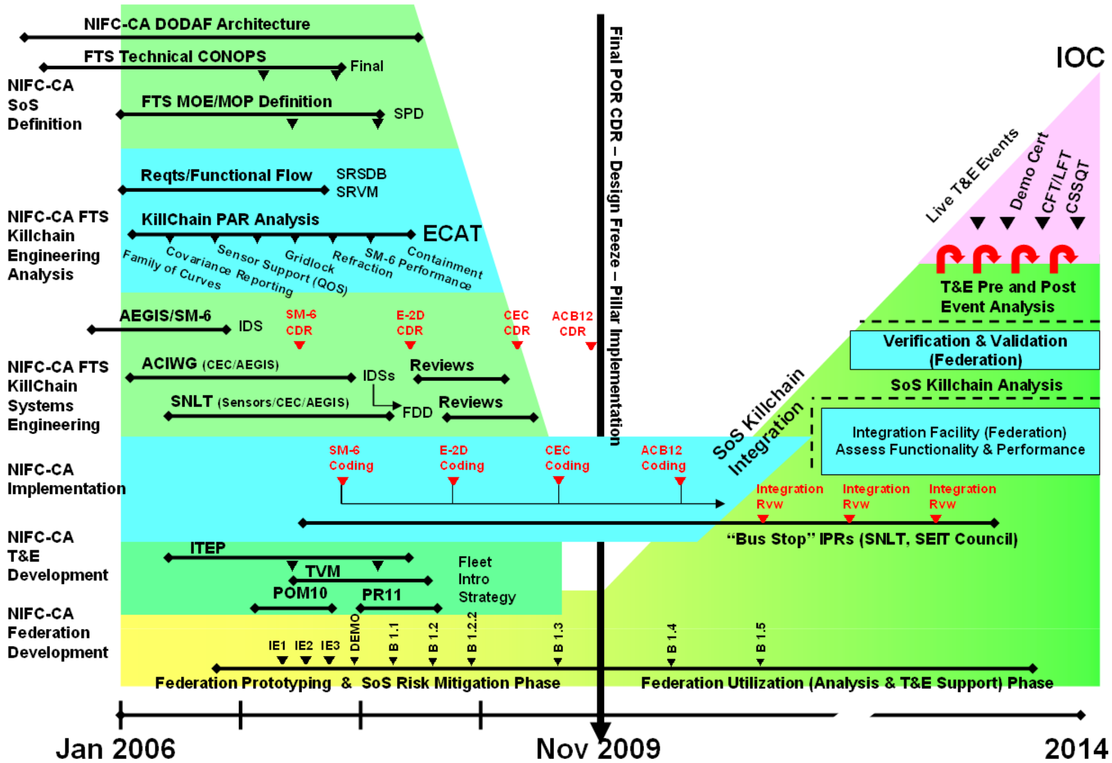

Figure 2: NIFC-CA Capability Acquisition and SoS Engineering

The challenge lying before the SEI&T team working with the component system engineering teams is summarized in the following basic statements:

1) The Aegis combat system was designed in the 1970s and has evolved and expanded dramatically ever since.

2) The Aegis combat system provides a self-contained, highly engineered anti-air warfare system with a dedicated phased array multi-function radar, a robust, time-critical command and decision system and a semi-active interceptor (SM-2) that is tightly controlled all the way to intercept.

3) For IFC engagements, the SEI&T team was charged with uncoupling and distributing this single-system killchain across independent pillar systems consisting of multiple non-organic sensors, connected via the CEC network to the Aegis combat system so that it can control the SM-6 missile until it goes below the horizon, becoming active and independently concluding the engagement.

While Figure 2 takes on the form of the familiar Systems Engineering "V", the individual steps and functions performed within the chart may not seem familiar. Based on a limited budget and the acquisition/engineering management environment described so far, this chart describes the analyses and engineering deemed essential to re-assemble the distributed killchain, automate remote sensor and interceptor management and ensure performance against a wide range of threats in many theaters and scenarios.

The key timeline drivers within this chart are the four CDRs listed that each component system was scheduled to meet within its system acquisition timeline. The challenge for the SEI&T was to execute and finalize all NIFC-CA analysis, functional allocation and design documentation in time to support each CDR for each component system. The transition from analysis and engineering to implementation, integration and T&E is denoted at the bottom of the V when the final component system CDR took place in November of 2009. The following sections of this paper will discuss several of the processes performed on the left side of the V.

4.1 System Architecture Development

For NIFC-CA as an acknowledged SoS type, it became apparent that a good system architecture would be essential to NIFC-CA development. In 2002 NSWC Dahlgren began working with pillar program offices, FTA killchain system engineers and prime contractors to develop a NIFC-CA DoD Architecture Framework (DODAF) architecture.

In 2006, with the establishment of the SEI&T industry team, architecture development drove toward a complete architecture with enough insight at the component systems level to validate NIFC-CA functional allocations and information exchange requirements (IERs) across the entire killchain. Details of the SoS functionality were added as killchain analyses and design were conducted for each Pillar. This effort ensured the allocated design fulfilled the operational architecture.

The NIFC-CA architecture has been utilized as the authoritative source of information to guide system engineering tasking as well as high level discussions with other military services, the Joint Integrated Air and Missile Defense Office (JIAMDO) and other organizations. The NIFC-CA DODAF architecture has proven to be a powerful tool for capturing the functionality, communications and essential information of the NIFC-CA SoS. It has fostered communications across the killchains and within the component pillar systems while documenting the requirements for incorporation of future sensors, weapons and combat systems supporting IFC as well as future functionality and capability spiral evolution.

4.2 NIFC-CA FTS Killchain Engineering Analysis

As described earlier, the key engineering challenge within NIFC-CA FTS has been the decomposition of a tightly integrated real-time killchain and subsequent re-allocation of that killchain across independent component systems. Killchain Engineering Analysis is an essential part of ensuring that the resultant distributed killchain will perform effectively and safely across all SoS component systems.

Within the collaborative environment of the government/industry SEI&T team the entire FTS SoS killchain was reviewed and performance-critical and/or time-critical functions identified for detailed analysis. Performance Assessment Report (PAR) plans were developed and assigned to small teams partnering different prime contractors and government personnel to analyze these critical functions. Two examples illustrate the scope and importance of this analysis:

- The Containment PAR analyzed the maximum size error basket that would be required from the remote sensors via the CEC network in order support SM-6 missile active seeker performance.
- The Sensor Support Quality of Service (QOS) PAR defined the attributes and parameters that would be requested by the weapons control system in order for CEC to find and provide remote sensors meeting that QOS request.

4.3 NIFC-CA FTS Killchain System Engineering

Based on the findings of the killchain engineering analysis and guided by the NIFC-CA DODAF architecture, working groups were formed to address specific killchain systems engineering topics. In order to engage component system program offices and engineers within the broader Navy IFC community, collaborative groups were created to facilitate engineering tasking and information exchange in the form of Interface Working Groups (IWGs) and Technical Interchange Meetings (TIMs).

Due to the staggered nature of the CDRs for each of the component systems and the early CDR date for the SM-6, an Aegis/SM-6 IWG was the first group to gather and develop the specific documentation artifacts for the interface between the Aegis ACB12 combat system and the missile. This is a historic working relationship going back several decades for all variants of the Standard Missile Family. Even so, the SM-6 is a major upgrade in capability and significant design and interface tasking had to be accomplished.

The Aegis/CEC IWG (ACIWG) was established next in order to design and document several CEC to Aegis interfaces. In order to allow many current and future sensor types to support SM-6 engagements, the Aegis WCS is being built to be “sensor agnostic”; essentially it will not know the specific characteristics of remote radars, just the real-time characteristics of their tracking information. To support this uncoupling, CEC was tasked to take on the function of finding and providing remote sensors that are able to meet Aegis Quality of Service (QOS) requirements for each engaged target. Therefore, the ACIWG took on the challenge of creating and documenting a new paradigm for IFC sensor support.

In mid-2006 it became apparent that a larger forum including engineers and leadership from CEC, Aegis and all sensors was needed to discuss and document the detailed engineering that supports the overall NIFC-CA architecture. This forum was established as the Sensor Netting Leadership Team (SNLT). This team, working closely with the ACIWG, took on the challenge of fleshing out the mid-level architecture (IERs, functional allocation, operational sequence diagrams) and, eventually, the low-level integration agreements that are generally invisible outside of contractor development facilities. This latter category basically came down to discussions and agreements between two companies on either side of an interface regarding topics such as 1) data unit interpretations, 2) mathematical matrix transformations, 3) matrix rotation conventions, etc. This function of the SNLT was needed because this kind of coordination historically would have occurred within a single prime contractor. With a distributed SoS killchain, a pseudo-government forum had to be established to enable and capture this kind of discussion between prime contractors on either side of an interface.

5.0 NIFC-CA SoS SE Accomplishments

With the successful completion of the Aegis ACB12 CDR in November 2009, a very capable, flexible and extensible IFC design has been established across the pillars of the NIFC-CA FTS capability. The FTS SoS detailed design is being implemented by each component system as this article is being written. The resultant product will allow the Fleet to engage any target from the near-horizon to the maximum kinetic range of the SM-6 and future interceptors utilizing a variety of sensors.

At a less apparent level, the NIFC-CA engineering teams took the opportunity to apply basic system engineering principles to distribute the NIFC-CA killchain across component systems and establish a solid foundation for rapid evolution of future IFC capabilities. Key system engineering and software engineering techniques including modularity, abstraction, and information hiding were applied during the functional allocation and distribution process resulting in a system that is far more extensible, allowing dramatic evolution and innovation in the future. The following are examples of SoS SE innovations applied during the NIFC-CA design process:

1. Sensor Agnostic WCS: In order to accommodate a variety of remote non-SPY sensors, the ACB12 Aegis baseline was chosen as a point of implementation for a new Reduced State Estimator (RSE) WCS filter design. This design does not rely on hard-coded knowledge of sensor type and performance (information hiding) but is designed to accept basic covariance data describing the sensor track error basket and dynamically apply that data within the filter. This breaks the hard coupling across the interface between WCS and sensors (better modularity), allowing for many different sensors to become providers for engagements without any modification to WCS design or code.

2. CEC Best Sensor Selection (BSS): Early in the NIFC-CA design process the decision was made to institute basic network-centric principles by assigning NIFC-CA remote sensor selection and management to the CEC network. This decision provides full support to the decision to uncouple WCS from remote sensors and moves sensor management closer to the actual sensors while ensuring WCS accuracy and timing requirements are met. Based on a QOS requested by WCS for each target, the new CEC BSS function will find from one to several sensors capable of meeting the QOS and make contracts with each sensor to provide data for the engagement. Per these contracts, CEC will provide one or more sensor track data streams to WCS where final filtering and multi-stream fusion is performed to guide the interceptor flight.

3. Active Seeker Technology: This technology uncouples the hard connection and dependence between the ship and the interceptor. The ship will retain control of the interceptor for the majority of the flight but the ship’s radar and illuminator horizon is no longer a hard floor limiting the flight of the interceptor. Control and illumination from any source is not

required for the final seconds before intercept as the missile goes active and independently finds the target. The entire battlespace from interceptor operating ceiling down to the land or sea surface and from ownship out to interceptor maximum kinematic range is now available to Fleet operators for engagement of all threats.

These are just a few major examples of the system engineering accomplishments during NIFC-CA system development. These accomplishments support higher level DoD acquisition objectives for IFC by enabling a growing diversity of DoD airborne and surface-based sensors to support OTH engagements. This uncoupling and opening of interfaces will lead to industrial innovation of both tracking sensor and active missile capabilities leading to further improvement in overall military capability.

6.0 Conclusion

SoS systems engineering provides great opportunities to leverage national investments in defined-purpose military systems in order to achieve unique and powerful capabilities at the SoS level. It is apparent that most future military SoS acquisition and engineering programs will be of the acknowledged type. Based on this brief overview of NIFC-CA SOS SE it is hopefully apparent that the acknowledged type of SoS SE environment is full of opportunities and challenges. It will require flexible, creative and active program leadership and systems engineering leadership that is mindful of the fundamentals of systems engineering while encouraging and guiding collaborative engineering teams toward SoS-unique objectives. Within that type of leadership framework the collaborative community consisting of SoS systems engineers working with the diversity of the component system engineering teams can produce innovative, extensible and powerful solutions.