Overview of Platforms and Combat Systems

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ABSTRACT

Air and missile defense is a complex process involving the coordinated operation of equipment and computer programs. The most effective defense generally is multiple layers of defense using different technologies in each layer such as long-range hard-kill, followed by hard-kill area defense, followed by both hard-kill and soft-kill (electronic warfare) self-defense. A combat system must merge, fuse, and de-conflict many sources of sensor data to produce a single usable track picture for decision-making. Throughout, sensors are controlled and sensor resource use is managed to meet the overall defense needs. As technical direction agent and technical adviser for many of the combat system elements, the Johns Hopkins University Applied Physics Laboratory (APL) performs the systems engineering, analysis, and experimentation that helps the Navy select the most combat system capability at an affordable cost.

INTRODUCTION

Most Navy warships have combat systems capable of air and missile defense. Those combat systems are well described by the "detect–control–engage" paradigm; that is, the components of the combat system can be notionally grouped as follows:

- Detect components that find and track air and missile targets
- Control components that identify the targets and make the decisions to engage
- Engage components that schedule and perform the engagements with the goal of destroying or otherwise negating the targets

The scope of those components' capabilities varies significantly with ship class, resulting in the variation in overall air and missile defense capability shown in Figure 1.

Aegis destroyers and cruisers are the Navy's most capable air defense units because of their long-range, multifunction phased-array radars; their inventory of many different anti-air warfare, ballistic missile defense, and electronic warfare weapons; and their complex control processes for processing sensor data, making engagement decisions, and controlling those weapons. Aegis destroyers and cruisers can defend large areas against ballistic missiles by defeating them during the midcourse phase of their flight using the Standard Missile-3 (SM-3) family in the exo-atmosphere, as well as closer to impact during their terminal phase using the SM-6 family in the endo-atmosphere. The Aegis Ashore combat system deployed in Europe uses a subset of the

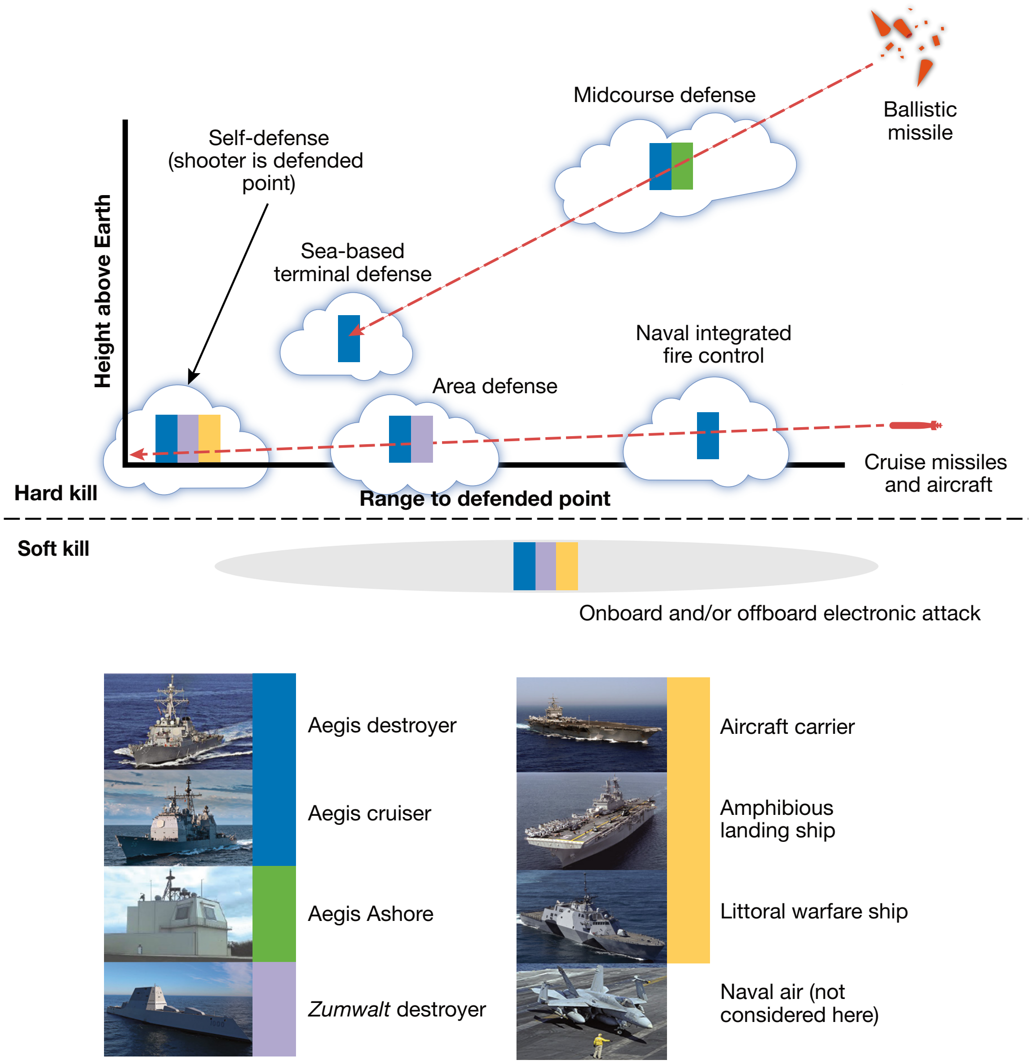


Figure 1. Comparison of the air and missile defense capabilities of different combat systems. (The chart at the top is not to scale.)

same detect–control–engage components on land and provides for exo-atmospheric defense of US-deployed forces, their families, and our allies in Europe. Aegis Ballistic Missile Defense (BMD) ships and Aegis Ashore are part of the larger Ballistic Missile Defense System (BMDS), which is, itself, a global combat system that integrates Navy, Army, and Air Force detect, control, and engage components. Aegis destroyers and cruisers can also defeat attacks from aircraft and cruise missiles. Aegis is capable of extended-range engagements of aircraft and cruise missiles both over sea and over land using the SM-6 surface-to-air missile. With integrated fire control support, SM-6 provides an increased battle space against threats over the horizon. Within the horizon, Aegis can defend both itself (self-defense) and other units (area defense) using the SM-2 missile family and the Evolved Sea Sparrow Missile (ESSM). Aegis also can defeat threats using electronic warfare measures such as jamming and decoys. The Cooperative Engagement Capability (CEC) and Tactical Data Link (TDL) networks enable Aegis and other units to fight as a coordinated force.

The USS *Zumwalt* (DDG 1000) brings to the Navy a unique set of volume firepower and precision strike capabilities and is currently nearing deployment. The *Zumwalt* destroyer has an advanced gun system with a long-range land-attack projectile capable of launching a guided projectile at extended ranges. Its air and missile defense capabilities lie in between those of the Aegis fleet and those of aircraft carriers and amphibious ships. *Zumwalt* has a vertical launching system similar to that of Aegis and the control capability to launch self-defense missiles as well as SM-2 missiles.

Aircraft carriers and amphibious ships are capable of projecting offensive power (Navy air and Marines ashore). The air and missile defense detect–control–engage components on these ships, however, are generally limited to self-defense. Self-defense is achieved either with electronic warfare, with shorter-range missile systems such as ESSM and the Rolling Airframe

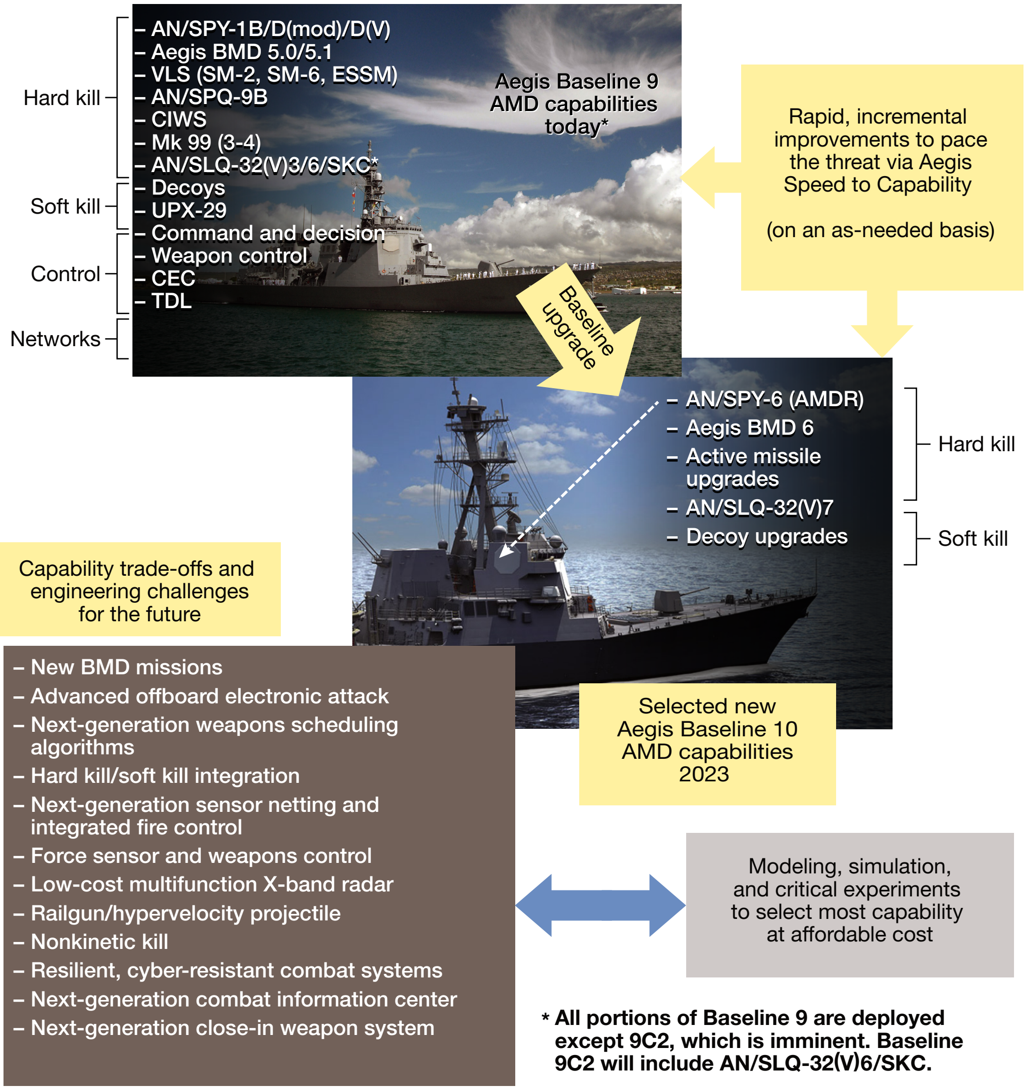


Figure 2. Examples of planned Aegis combat system air and missile defense (AMD) evolution and potential capability trade-offs. VLS, vertical launching system.

Missile (RAM), or with guns (e.g., the Phalanx Close-in Weapon System, or CIWS). The combat system for these ships is the Ship Self-Defense System (SSDS).

Ship combat systems are major investments that evolve over time to achieve new capabilities. Aegis and SSDS ships are undergoing major capability upgrades that include significant new sensor capabilities. The Aegis combat system will evolve from Baseline 9 to Baseline 10 (Figure 2). This evolution features many new capabilities. The AN/SPY-6 Air and Missile Defense Radar (AMDR) will provide multimission capabilities, simultaneously supporting long-range, exo-atmospheric detection, tracking, and discrimination of ballistic missiles, as well as area and self-defense against air and surface threats. For the BMD capability, increased radar sensitivity and bandwidth over current radar systems are needed to detect, track, and support engagements of advanced ballistic missile threats at the required ranges, concurrent with area and self-defense against air and surface threats. For the area air defense and self-defense capability, increased sensitivity and clutter capability are needed to detect, react to, and engage stressing threats in the presence of heavy land, sea, and rain clutter. In the control and engage areas, Aegis Baseline 10 includes functional upgrades to make use of the richer data provided by the AMDR, such as Aegis BMD 6 use of the AMDR's increased radar sensitivity and bandwidth in the engagement of ballistic missiles. Aegis Baseline 10 will leverage ongoing developments in active missiles to provide a more effective defense against evolving antiship cruise missiles. The AN/SLQ-32(V)7, which deploys in Aegis Baseline 10, includes the Surface Electronic Warfare Improvement Program Block 3, which provides onboard electronic attack. The Soft-Kill Coordinator (SKC) capability, an AN/SLQ-32 command and control subsystem, will be expanded to include coordination of

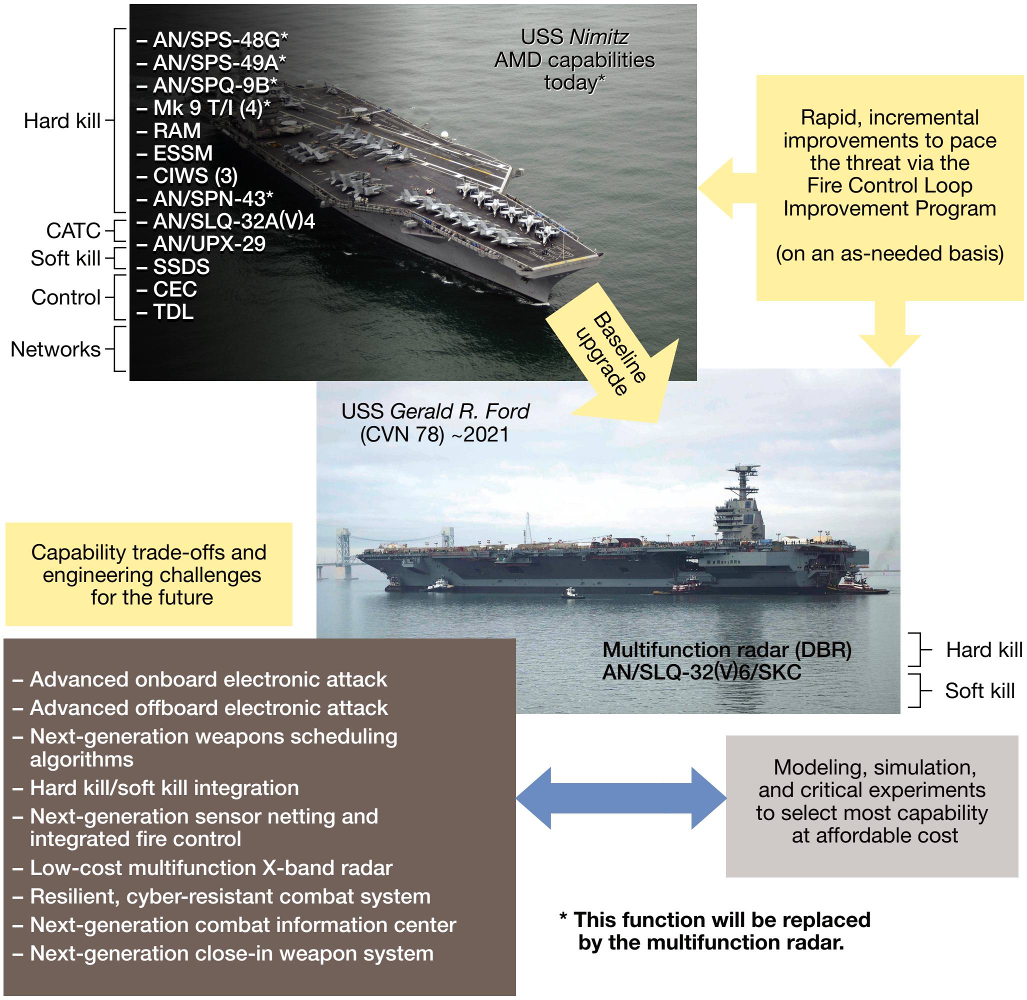


Figure 3. Examples of planned aircraft carrier SSDS combat system evolution and potential capability trade-offs. (Amphibious ships, which also have the SSDS combat system, are also evolving with related improvements and capability trade-offs.) CATC, carrier air traffic control.

onboard electronic attack and an improved inventory of decoys.

The SSDS-based combat system on aircraft carriers and amphibious ships has historically relied on a suite of older sensors (some initially designed in the 1960s) that have undergone periodic modernizations. Radar surveillance and target tracking are provided by the AN/SPS-48G, AN/SPS-49A, and AN/SPQ-9B radars. Additional surveillance and tracking as well as illumination for semiactive missile homing are provided by the Mk 9 fire control system. Carrier air traffic control is supported by the SPN-43. With the new aircraft carrier USS *Gerald R. Ford* (CVN 78), these functions will be replaced by the new Dual-Band Radar (DBR) (Figure 3). This new multifunction radar being developed for the CVN 78 is a combination of the X-band AN/SPY-3 and S-band AN/SPY-4. However, alternative radar designs are being considered for subsequent aircraft carriers CVN 79 and CVN 80 as well as for new amphibious ships. The multifunction radar will accomplish the long-range surveillance and track functions of the AN/SPS-48 and AN/SPS-49 radars, provide data for carrier air traffic control (currently provided by the AN/SPN-43), and provide the horizon surveillance and tracking capability of the SPQ-9B radar and the fire control functions of the Mk 9 tracker/illuminator. The multifunction radar will enable better control of ESSM missile trajectories and more accurate handover to the ESSM seeker, improving ESSM capability against anti-ship cruise missiles.

Selecting the most capability at affordable cost is a challenge in development of any new combat system baseline. Figures 2 and 3 show candidate systems and capabilities for future baselines of Aegis and SSDS, respectively. APL performs modeling and simulation and critical experiments to inform the selection of an affordable subset of these systems and capabilities for new baselines. In addition to the major baseline upgrades, the Navy continues to explore techniques for deploying new capabilities rapidly on an as-needed basis. Aegis and

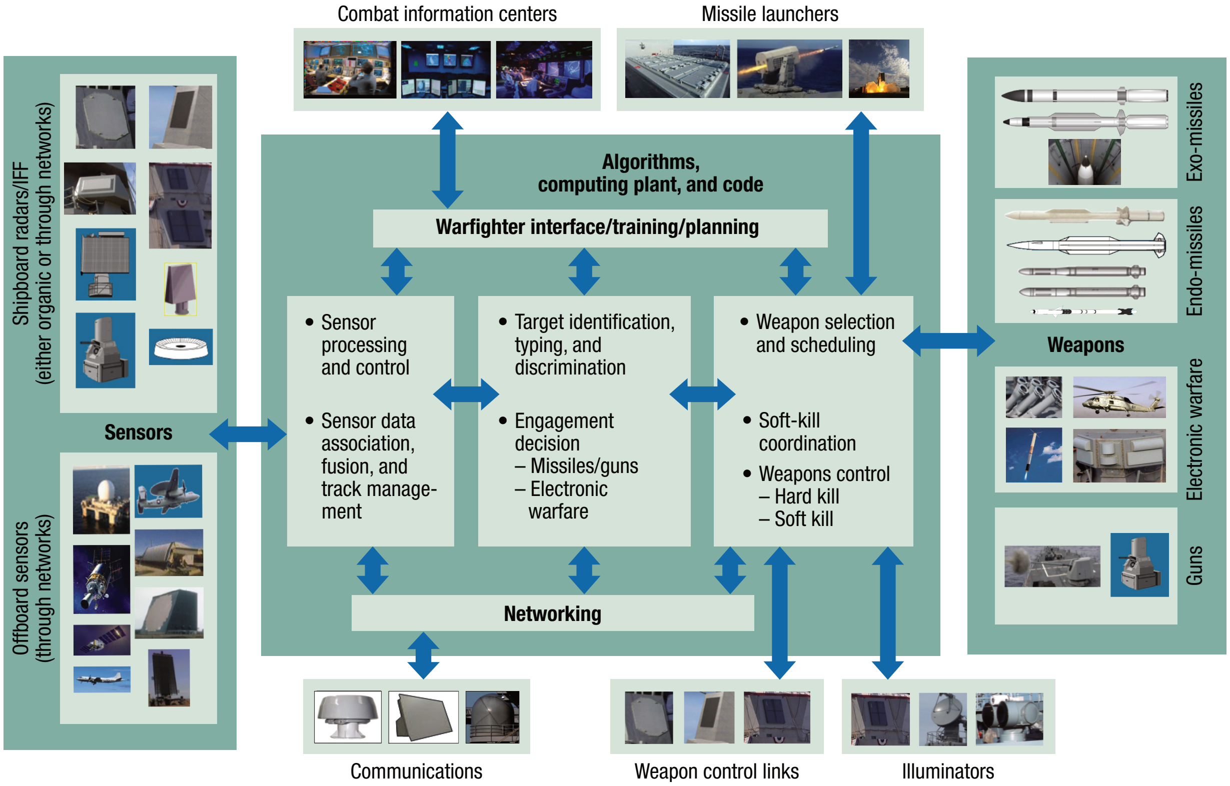


Figure 4. A general combat system. Actual combat systems have a subset of the components pictured. Successful engagements require coordinated operation of many combat system components. IFF, identification friend or foe.

SSDS use the Aegis Speed to Capability and the Fire Control Loop Improvement Program, respectively, to respond to urgent needs in the fleet.

Air and missile defense is a complex process involving the coordinated operation of equipment and computer programs. Figure 4 shows a general ship combat system. The workhorses of sensing on a ship are its shipboard radars—particularly the multifunction radars. These radars are augmented by other shipboard radars serving specific purposes. In addition, ships can access offboard sensors located on other ships, aircraft, land sites, and space via secure communications. Sensors are controlled and sensor resource use is managed to meet the overall defense needs. Individual measurements made by the entire sensor set are associated, and in some instances fused, with other sensor data. In all cases, tracks are generated. Each track should correspond to one physical object. A track is the combat system's sum total knowledge of an individual object, including its kinematics—e.g., vector position and velocity; the classification of the object (aircraft, cruise missile, ballistic missile, clutter, debris, etc.); the type of the object (e.g., if it is a cruise missile, which cruise missile type is it); and when applicable, the identity of the object (e.g., friend or foe).

Figure 5 illustrates the association and tracking problem. In any part of the world on any given day, there is generally a priori context information available to the warfighter. This context will define who the likely enemy is, what sort of threats he has in his inventory, and, in general terms, how he is likely to attack. Within today's combat systems, this information is held as "doctrine," a collection of rules that define how the combat system will respond to sensor information. For example, today's identification doctrine defines, given the context, which additional pieces of sensor evidence are necessary to conclusively identify the target. The next likely input to the combat system is some early indication from ISR (intelligence, surveillance, and reconnaissance) that an attack is coming; this early indication alerts the combat system to the object's presence and often identifies the object, but it does not necessarily provide precise kinematics or low latency. Today, there is little quantitative integration of contextual and ISR data with organic sensors. The quantitative integration of a priori context and ISR is a challenge and growth area for new combat system designs.

Once targets are within sensor range, the combat system receives sensor measurements (e.g., onboard or offboard radar) indicating more precise kinematics at low latency, but these data may or may not include features for identifying the object. One of the challenges is to correctly associate all of these pieces of data into "tracks." As measurements are associated to form tracks,

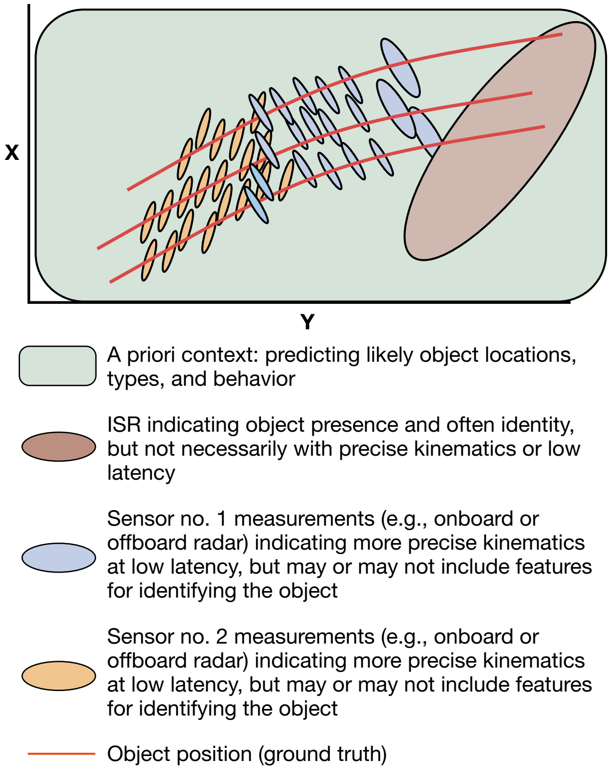


Figure 5. A two-dimensional representation (*x*, *y*) of a multidimensional tracking problem. In this example, three targets are close enough together to challenge association and filtering algorithms.

the track kinematic state is calculated (and used for subsequent associations). Track filtering refers to the algorithms that transform a sequence of measurements into such a track state and is discussed in the article by S. A. Hays and M. A. Fatemi in this issue. Figure 6 shows notional track states that have been calculated by associating and filtering the measurements in Figure 5. In this illustration, the tracking process has worked well. The number of tracks in Figure 6 equals the number of objects, the track states converge over time to the actual object positions, measurements from different sensors have been associated correctly, and the tracks can be extrapolated into the future to accurately predict target position. However, the tracking process can be challenged in all these areas by large sensor measurement accuracies, low sensor update rates, highly unpredictable object motion, and object spacing. In the case of multiple sensors, measurement biases and different sensor measurement dimensions are also challenges. Overcoming these challenges remains a subject of research in combat system design.

A combat system must merge, fuse, and deconflict many sources of track data to produce a single usable track picture for decision-making. This includes all local sensors as well as track data from tactical data links such as Link 16/11 and measurement and track data from sensor networks such as the CEC. The principal challenge is the diversity of the data received and the need to make one unit's track management process interoperable with multiple units' track management processes. For example, each source will generally have a different way of characterizing the accuracy of the kinematic track data, and some sources may provide incomplete characterizations. Similar diversity exists in the characterization of target identity and type. Different units designed in different time frames and with different missions will have different rules and algorithms for supporting the creation of a common track numbering and identification system. In addition, the networks may deliver data with different time delays, biases, and data dropouts. The process by which all these sources are reconciled into a single usable track picture is generally called track management and has been an active area of research and development at APL for many years.

A good example of the metrics for the single track picture is given by the Single Integrated Air Picture Metrics[1] developed by the joint services (Army, Navy, Air Force, and Marine Corps) for air track (vice ballistic missile) tracking (Figure 7). Note that the metrics cover both track kinematics and attributes. In addition,

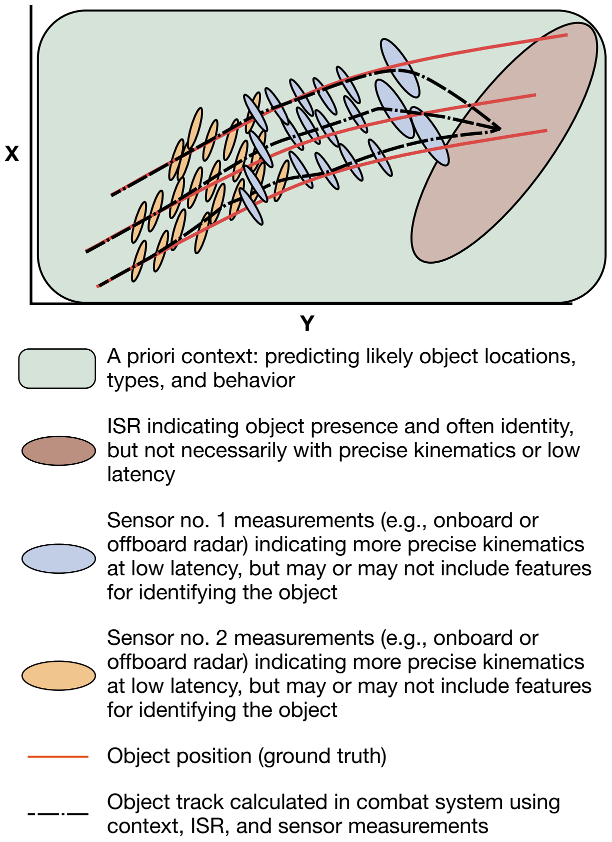
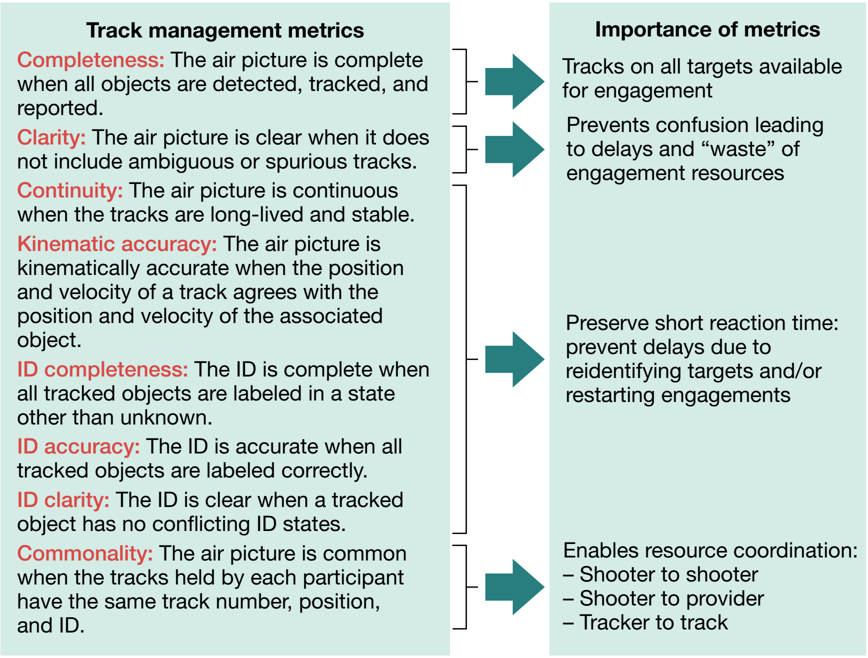


Figure 6. The combat system calculates tracks representing a best estimate of the object kinematics. This figure depicts quantitative integration of contextual and ISR data with organic sensor tracking—a challenge in the design of new combat systems.

the metrics measure the degree of commonality between the track pictures on different ships and aircraft. This commonality is essential for sharing of engagement and identification data.



Track management metrics

Completeness: The air picture is complete when all objects are detected, tracked, and reported.

Clarity: The air picture is clear when it does not include ambiguous or spurious tracks.

Continuity: The air picture is continuous when the tracks are long-lived and stable.

Kinematic accuracy: The air picture is kinematically accurate when the position and velocity of a track agrees with the position and velocity of the associated object.

ID completeness: The ID is complete when all tracked objects are labeled in a state other than unknown.

ID accuracy: The ID is accurate when all tracked objects are labeled correctly.

ID clarity: The ID is clear when a tracked object has no conflicting ID states.

Commonality: The air picture is common when the tracks held by each participant have the same track number, position, and ID.

Importance of metrics

Tracks on all targets available for engagement

Prevents confusion leading to delays and “waste” of engagement resources

Preserve short reaction time: prevent delays due to reidentifying targets and/or restarting engagements

Enables resource coordination:
– Shooter to shooter
– Shooter to provider
– Tracker to track

Figure 7. Typical metrics for the combat system air track picture.[1]

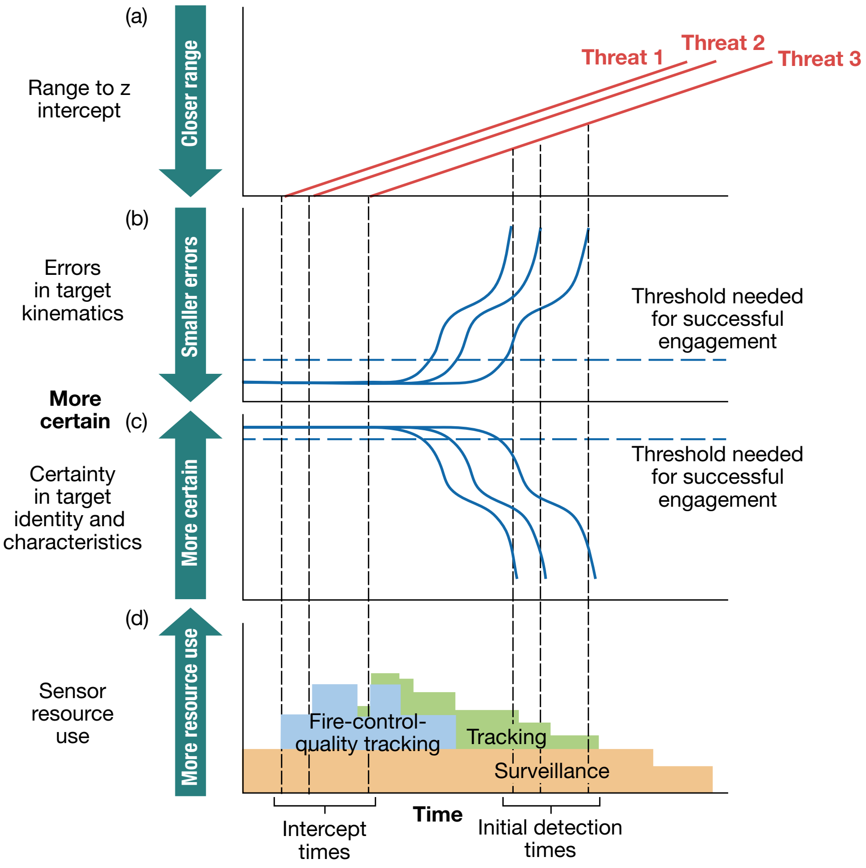


Figure 8. A typical engagement sequence against a raid of threats. Sensor data are gathered beginning as soon as a target is detected, eventually leading to sufficient kinematic accuracy and certainty in identity and characteristics for a successful engagement. Sensor resource needs to meet these thresholds vary throughout the engagement.

Once tracks exist, they become the organizing tool for the engagement sequence. The success of the engagement depends on the fidelity of the track on the target being engaged. As the target closes in range to its objective (Figure 8a), more sensor measurements are made, resulting in continual improvement (Figure 8b) in the accuracy of the track kinematics (e.g., position, velocity, and acceleration) and in the certainty in target identity and characteristics (Figure 8c). However, most weapons require that additional sensor resources (e.g., different radar waveforms, higher update rates, high priority in radar scheduling, or in some instances, additional sensors) be applied to achieve a “fire-control-quality track” (Figure 8d) capable of supporting all or part of the following:

- Determination of intent
- Decision to engage
- Determination of acceptable weapon launch times and intercept points (scheduling)

Combat systems are designed using error budgets for their critical functions. These budgets identify the maximum errors that each combat system function can tolerate, and they allocate a portion of that maximum error to each of many contributing factors. Kinematic track state errors are generally significant contributors to the maximum error. To meet challenging error budget allocations, most combat systems filter measurement data differently for different combat system functions (Figure 9). One example of these differences is the degree of filtering. Heavier filtering (smaller filter gains) will weight new mea-

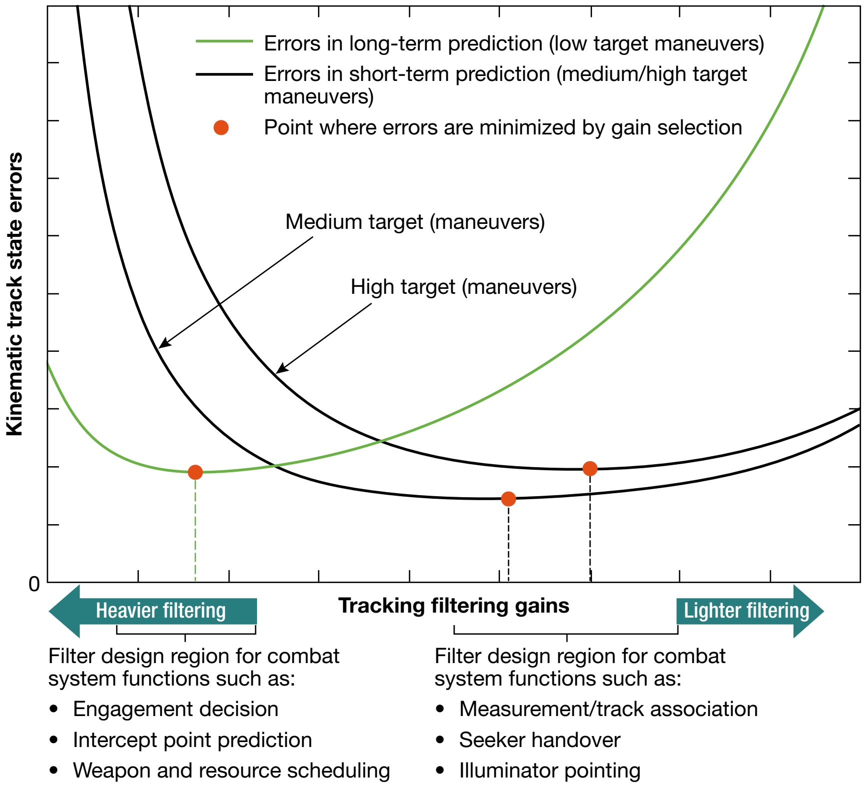


Figure 9. To meet engagement error budgets, most combat systems process sensor measurement data differently for different combat system functions. For example, heavier track filtering (smaller filter gains) will produce kinematic estimates with a smaller variance due to measurement noise and enable longer-term time prediction. Lighter track filtering will produce kinematic estimates more tolerant of unpredictable target motion (maneuvers).

surements less relative to the current track state and produce kinematic estimates with a smaller variance due to measurement noise. However, these filters are not very tolerant of unpredictable target motion (maneuvers). Lighter filtering (larger filter gains) will weight new measurements more relative to the current track state and produce kinematic estimates with a larger variance due to measurement noise. Although these filters are more tolerant of unpredictable target motion (maneuvers), their variances makes them less desirable for functions that require long-term time prediction.

Once tracks exist, they need to be characterized as to their type and identity. Is this target a threat attacking a defended area (which should be engaged) or another object such as a commercial airliner or a nonlethal piece of debris (which should not be engaged)? In addition, the greater number of target characteristics that can be known (e.g., type of threat), the more effective the engagement can be. Both determination of type and determination of identity generally require dedication of additional sensor resources to achieve the confidence necessary for a successful engagement. The identity and characteristics of the track, as well as its kinematics, are compared with operational doctrine to make the engagement decision.

The next part of the engagement decision is to determine which weapons (missiles, guns, and/or electronic warfare) have the capability to negate the threat and to select the weapons to be used based on their inventory and predicted effectiveness. The engagement decision is one of the factors that drives the need for precise track kinematics because the track kinematic state may need to be predicted well into the future (e.g., to account for the fly-out time of a ship-launched missile to a predicted intercept point).

An underlying principle in weapons selection and scheduling is the concept of "depth of fire"—multiple layers of defense in range. The most effective defense generally is multiple layers of defense using different technologies in each layer such as long-range hard kill (e.g., naval integrated fire control), followed by hard-kill area defense, followed by both hard-kill and soft-kill (electronic warfare) self-defense. The ballistic missile defense analogue of this would be midcourse defense followed by sea-based terminal defense.

Consider air defense as an example. Assume a raid of N_T threats. A typical measure of air defense performance is the probability of raid annihilation (P_{RA}). For N_L layers of defense, each with a probability of killing the target (P_K), the mathematical advantage of depth of fire can be easily demonstrated in a very simplified analysis. To annihilate the entire raid, each of the N_T targets must be killed, and there are N_L opportunities to kill each target. The simplified analysis assumes that all these events are statistically independent, in which case, P_{RA} is given by $P_{RA} = [1 - (1 - P_K)N_L]^{N_T}$.

This equation is plotted in Figure 10 for a raid size of five threats. Note that achieving a very high level of defense (high P_{RA}) with only a single layer requires a very high probability of kill in that layer. That high probability of kill can be difficult to achieve with a single technology (e.g., with a single missile type or single electronic warfare strategy) because any defensive technology has weaknesses that could be exploited by the adversary. A layered defense using different technologies in each layer requires a relatively lower probability of kill in each layer and generally makes a high

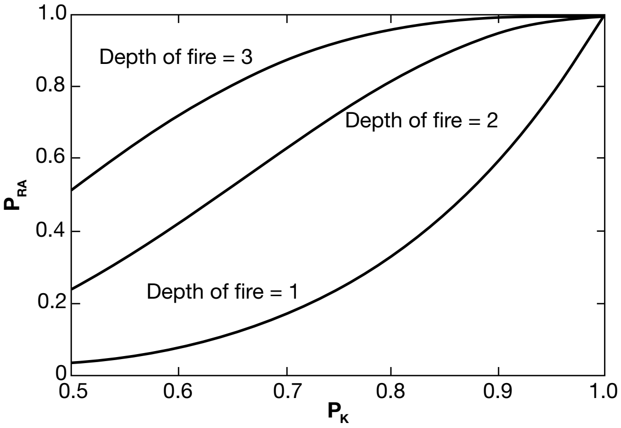


Figure 10. Multiple layers of defense using different technologies generally make a high P_{RA} more achievable. This graph depicts the results of simplified analysis for a raid of five threats and the assumption that all engagements are statistically independent.

P_{RA} more achievable. The different technologies used in different layers make it more likely that the statistical independence assumption is valid and thus more likely that the gains from multiple layers occur. As a result, most ships have a mixture of both hard-kill and soft-kill defensive technologies as well as different types of hard-kill and soft-kill weapons.

In addition, depth of fire can conserve inventory. If the engagement is successful in the first layer, and if that success can be confidently measured, then the resources required for the subsequent layers do not need to be expended on that threat.

As the engagement proceeds, more combat system resources of are generally required for success (Figure 8d). A significant challenge in combat system design is deciding which of these weapons to employ when and how to schedule combat system resources (e.g., sensors, launchers, illuminators) to accomplish the engagements. The schedule is dynamic, changing as new sensor data are provided, additional targets are disclosed, and initially scheduled engagements are executed. These challenges are discussed in the article by M. R. Smouse et al. in this issue.

As engagements are scheduled, the combat system maintains the overall engagement schedule and executes the engagements per that schedule. Most combat systems perform custom filtering of the sensor measurements to obtain a track state that is well matched to individual weapon control requirements (e.g., obtain stable velocities for long time predictions until intercept). The combat system initializes the missile (in the launcher) to set up a common time frame and coordinate frame for communication of data between the combat system and the missile during flight. Once the missile is properly initialized, the motor is ignited. Shortly after launch, the combat system begins communication with a link-capable missile using the weapon control link (Figure 4). Depending on the missile type and phase of flight, it will be controlled (1) autonomously (fire and forget); (2) by providing it with ongoing uplinked target data; or (3) by providing it with acceleration commands. Target data from the combat system will be used by the missile to acquire the target with its seeker (generally active radio frequency [RF], semiactive RF, passive RF, or infrared), after which the missile can begin homing on the target.

REFERENCE

[1] E. Byrd et al., “Single Integrated Air Picture (SIAP) Attributes Version 2.0,” Single Integrated Air Picture (SIAP) System Engineering Task Force (SE TF), Arlington, VA, Tech. Rep. 2003-029, Aug. 2003.

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