Guest Editor's Introduction: Homing Missile Guidance and Control

Neil F. Palumbo

Homing missiles have played an increasingly important role in warfare since the end of World War II. In contrast to inertially guided long-range ballistic missiles, homing missiles guide themselves to intercept targets that can maneuver unpredictably, such as enemy aircraft or anti-ship cruise missiles. Intercepting such threats requires an ability to sense the target location in real time and respond rapidly to changes so that a target intercept can occur. Homing guidance, wherein an onboard sensor provides the target data on which guidance decisions are based, is used to accomplish this intercept. Because of the continually improving quality of target information as the missile closes in, homing guidance provides intercept accuracy that is unsurpassed by any other form of missile guidance. This article serves as the introduction to this Technical Digest *issue on homing missile guidance and control. A number of basic concepts related to guided missiles are introduced in this article to provide the foundational concepts for the subsequent articles. Finally, the flight control and homing guidance concepts that are employed in such systems are discussed in the later articles in this issue.*

INTRODUCTION

The guided missile provides military forces with the capability to deliver munitions rapidly and precisely to selected targets at a distance. This capability establishes an effective means to conduct a wide variety of military missions that range from denying the enemy communications or supply routes, to establishing air superiority, to performing anti-ship cruise missile or ballistic missile defense. Because of this flexibility, guided missiles have attained a remarkable level of importance in military applications and, consequently, in research and development programs. Moreover, the ever-evolving capabilities of enemy systems continue to drive guided missile design toward improved precision, rapid maneuver, and high-speed intercept capabilities.

We begin by defining the difference between an unguided rocket and a guided missile. An unguided rocket is a projectile weapon that (usually) is carrying a warhead and is propelled by an onboard rocket engine.

Like the arrow or cannon ball, an unguided rocket has no ability to change its course once it is airborne. Hence, it flies a ballistic trajectory. It also is notoriously inaccurate, being much more susceptible to targeting errors, wind gusts, and/or other disturbances to its flight path. Examples of unguided rockets include the U.S.-made Hydra-70 family of rockets and the Russian Katyusha.

In contrast to unguided rockets, a guided missile is a projectile provided with a means for altering its flight path *after* it leaves the launching device to effect target intercept. It can do this either autonomously or remotely via a human operator or weapon control system. Thus, a guided missile must carry additional components like inertial sensors, targeting sensors, radio receivers, an autopilot, and a guidance computer. The flight path of a guided missile is adjusted by using movable aerodynamic control surfaces, thrust vectoring, side thrusters, or some combination of these methods. These additions substantially improve engagement accuracy and performance robustness compared with unguided weapons. Examples of guided missiles abound and include the U.S. Navy RIM-66, RIM 156, and RIM 161 Standard Missile variants and the U.S. Army MIM-104 Patriot family of anti-ballistic missiles.

INERTIAL NAVIGATION VERSUS HOMING GUIDANCE

Inertial guidance systems make possible the precision delivery of long-range ballistic missiles for which the target is, for example, a known set of Earth coordinates. However, these systems are not suitable for guiding missiles against unpredictable targets like maneuvering aircraft or anti-ship cruise missiles or against a target whose location is not known precisely when the missile is launched. Intercepting this kind of threat requires an ability to sense the target location in real time and respond rapidly to changes so that a target intercept can occur. Homing guidance, wherein an onboard sensor provides the target data on which guidance decisions are based, is used to accomplish this intercept. Moreover, because of the continually improving quality of target information as the missile closes in, homing guidance provides intercept accuracy that is unsurpassed by any other form of missile guidance.

In this issue, the focus is squarely on guided missiles that make use of an onboard target sensor and, more specifically, on the related flight control and homing guidance concepts employed in such systems.

HOMING MISSILE TARGET SENSORS

The seeker carried on board a homing missile is categorized as one of the following three general types: passive, semi-active, or active. Figure 1 conceptually illustrates the three types of homing missile seekers.

Common examples of passive systems are infrared (IR) and radio-frequency (RF) seekers. IR seekers detect and track the natural heat signature emanating from a target, whereas passive RF seekers detect stray, or otherwise reflected, RF energy from the target. Passive seekers measure the angular direction of the target relative to the missile, but they do not readily provide range-to-target or closing velocity (range-rate) information,

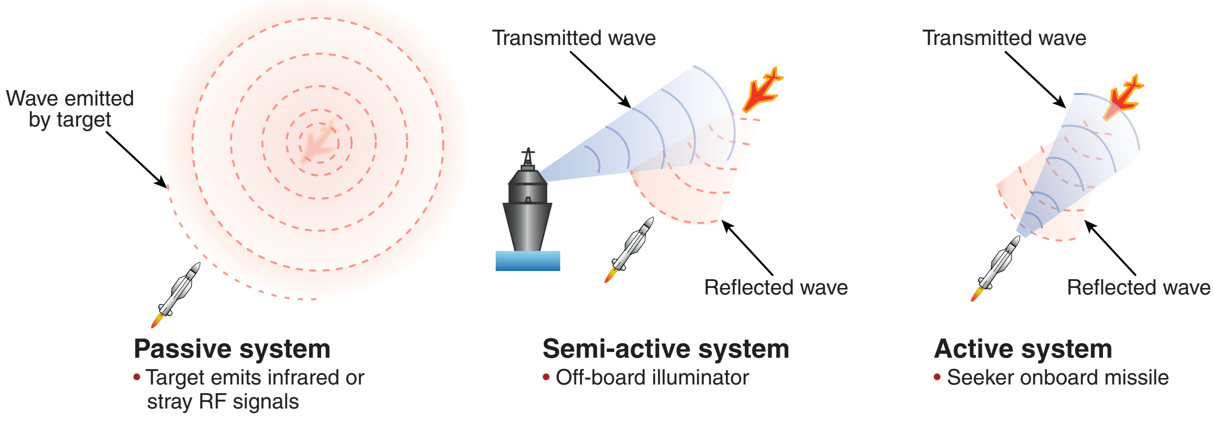

Figure 1. Three basic types of missile seeker systems. A passive seeker does not illuminate the target but, instead, receives energy that emanates from it. Because they do not emit energy, passive seekers make it impossible for the target to determine whether it is being tracked. Semi-active guidance systems illuminate, or designate, the target by directing a beam of light, laser, IR, or RF energy at it. The illuminating beam is transmitted from the launch platform or from an adjacent location. Hence, the illuminating source is largely responsible for target selection in a semi-active system. The passive seeker in the missile then tracks the target using the energy reflected from it. In active seeker guidance systems, an illuminator (transmitter) is added to the missile. Hence, an active guidance system can self-illuminate the target. The addition of an illuminator is costly and adds weight to the missile. However, the missile then is self-sufficient and autonomous after it has locked onto the target.

which is a potential disadvantage in that some guidance techniques require target range and/or range-rate information in addition to azimuth and elevation angles. In these cases, other means of obtaining this information must be employed.

Depending on modality and implementation, semi-active RF seeker systems can provide missile-target closing velocity (range rate) in addition to angular direction of the target. This additional information can help to improve overall guidance accuracy in some instances. Another advantage of semi-active homing is that significantly increased power can be brought to bear on the target without adding to the size and weight of the missile.

Active seeker systems, depending on modality and implementation, can provide missile-target range and range rate in addition to the angular direction of the target. As above, this additional information can be brought to bear in order to improve overall guidance capability. However, power and weight considerations usually restrict active homing to use during the terminal phase of guidance after some other form of guidance has brought the missile to within a short distance of the target.

GUIDED MISSILE PHASES OF FLIGHT

Some guided missiles (usually shorter-range missiles) employ *home-all-the-way* guidance techniques. In these systems, the missile usually sits on a trainable rail launcher (or within a launch canister) that is swiveled to point in a desired direction for launch. The missile must acquire the target (using its own seeker) prior to launch such that, when fired, it can immediately initiate target homing. A variation of this approach is one in which a pre-launch prediction of where the target will be at some post-launch time is provided to the missile. Then, the missile is launched without first acquiring the target organically, and a short inertial boost phase follows. During the inertial boost phase, the missile adjusts its flight path such that it is heading toward the pre-launch prediction of target position. Shortly thereafter, the missile acquires the target using the pre-launch prediction of where to look and initiates target homing.

In the more general case, guided missile flight is partitioned into three phases: boost, midcourse, and terminal guidance phases. Not all guided missiles make use of all three phases.[1,2] However, all precision guided missiles have a terminal phase. Missiles that employ two or more guidance phases are said to execute *multiple-mode* guidance. Figure 2 conceptually illustrates the phases of flight for a multi-mode guided missile.

The need for boost and/or midcourse guidance phases is a function of several factors, including the range at which target intercept will occur (relative to the launch platform) and the types of onboard and off-board sensors available to support the engagement (e.g., off-board radar illuminator and onboard semi-active radar seeker).

During the terminal phase of flight, the guided missile must have a high degree of accuracy and a quick reaction capability. Moreover, near the very end of the terminal phase (often referred to as the endgame), the missile may well be required to maneuver to maximum capability in order to converge on and hit a fast-moving, evasive target. For missile systems that employ a fuze and blast-fragmentation warhead (Standard Missile-2 and Patriot PAC-2 variants are examples of missiles that use a blast-fragmentation warhead), the final miss distance must be less than the warhead's lethal radius. In these systems, the warhead's lethal radius accommodates some lack of guidance precision. On the other hand, a direct-hit missile (Standard Missile-3 and Patriot PAC-3 variants are examples of hit-to-kill missiles) can tolerate only very small "misses" relative to a selected aimpoint on the target body before compromising lethality.

In this issue of the *Technical Digest*, the focus is primarily restricted to guidance techniques related to the terminal phase of flight; however, many of the guidance and control (G&C) concepts that are discussed in the subsequent articles are directly applicable, or can be extended, to the other phases of flight.

FUNCTIONS OF A MISSILE G&C SYSTEM

Many functions must be carried out successfully to intercept and negate the target. Once target detection occurs, a target track must be established by using a tracking sensor, and a decision must be made regarding engageability. If the target is deemed a threat and engageable by the weapon control system, a launch solution is computed, and the missile is launched and boosted to flight speed. Once the missile is launched, the missile G&C system takes over. It must maintain stable flight and converge on the target such that the final distance between the missile and target (the miss distance) is minimized. As mentioned previously, although the missile attempts to minimize the final miss distance, there still can be an appreciable separation between the target payload and interceptor at the closest point of approach. Consequently, a fuzing system and a fragmentation warhead are used to destroy the target. Recent designs for exoatmospheric ballistic missile defense have eliminated the fuze and warhead altogether and rely on body-to-body contact at high closing velocity to achieve a kill. These generally are known as *direct-hit* or *hit-to-kill* systems. In addition to minimizing final miss distance, the missile direction of approach to the target is controlled to provide favorable body-to-body impact or to accommodate fuzing and warhead detonation and to maximize warhead fragments on target. This control of the direction of approach is a key component to

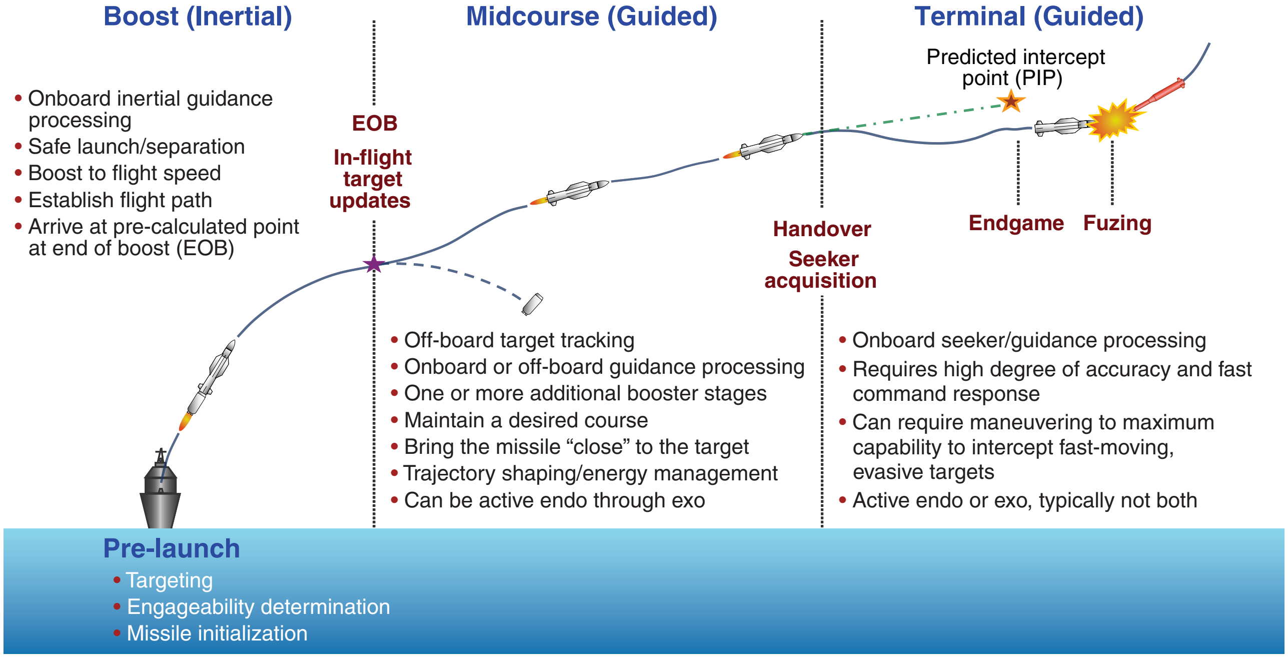

Figure 2. Phases of flight for a multi-mode guided missile. The weapon control system first decides whether the target is engageable. If so, a launch solution is computed, and the missile is initialized, launched, and boosted to flight speed. Inertial guidance typically is employed during the boost phase of flight. Here, the missile is boosted to flight speed and roughly establishes a flight path to intercept the target. Midcourse guidance is an intermediate flight phase whereby the missile receives information from an external source to accommodate guidance to the target. During midcourse, the missile must guide to come within some reasonable proximity of the target and must provide desirable relative geometry against a target when seeker lock-on is achieved (just prior to terminal homing). The terminal phase is the last and, generally, the most critical phase of flight. Depending on the missile capability and the mission, the terminal phase can begin anywhere from tens of seconds down to a few seconds before intercept. The purpose of the terminal phase is to remove the residual errors accumulated during the prior phases and, ultimately, to reduce the final distance between the interceptor and target below some specified level.

maximizing the probability of kill. For homing missiles, pointing to allow seeker acquisition and tracking also is critical. Another important function is to manage interceptor energy to maximize intercept range and maximize missile maneuverability during terminal homing. From this brief discussion, it becomes clear that the missile guidance, navigation, and control (GNC) system must perform a variety of complex functions to enable a successful target intercept.

GNC SYSTEM FUNCTIONAL ARCHITECTURE

The aggregate capability of the guided missile subsystems (inertial measurement unit, target seeker, propulsion, etc.) will define the maximum performance potential of the weapon. It is the role of the missile GNC system to functionally integrate these subsystems to ensure that all requirements are met and that lethality is maximized against the targets of interest. GNC system operation is based on the principle of feedback. Moreover, all fielded guided missile GNC systems are particular examples of the feedback concept in Fig. 3, which illustrates the traditional GNC paradigm that employs a decoupled architecture composed of guidance filter, guidance law, autopilot, and inertial navigation subsystems.

As indicated in Fig. 3, the traditional architecture separates guidance and flight control functions. The inertial navigation system (INS) provides the position, velocity, acceleration, angular orientation, and angular velocity of the vehicle by measuring the inertial linear acceleration and inertial angular velocity applied to the system. The information from the INS is used throughout missile flight to support guidance and flight control functions. The guidance filter receives noisy target measurement data from the homing sensor and estimates the relevant target states, the selection of which are design-dependent.[3–5] For example, a Cartesian guidance filter can provide estimates of target position, velocity, and acceleration with respect to a Cartesian reference frame. Equivalently, relative (target–missile) position, relative velocity, and target acceleration can be estimated. Typically, a linear or extended Kalman filter is used.[3,6–8] The guidance law takes the instantaneous target-state estimates as input and determines what the interceptor direction of travel should be to intercept the

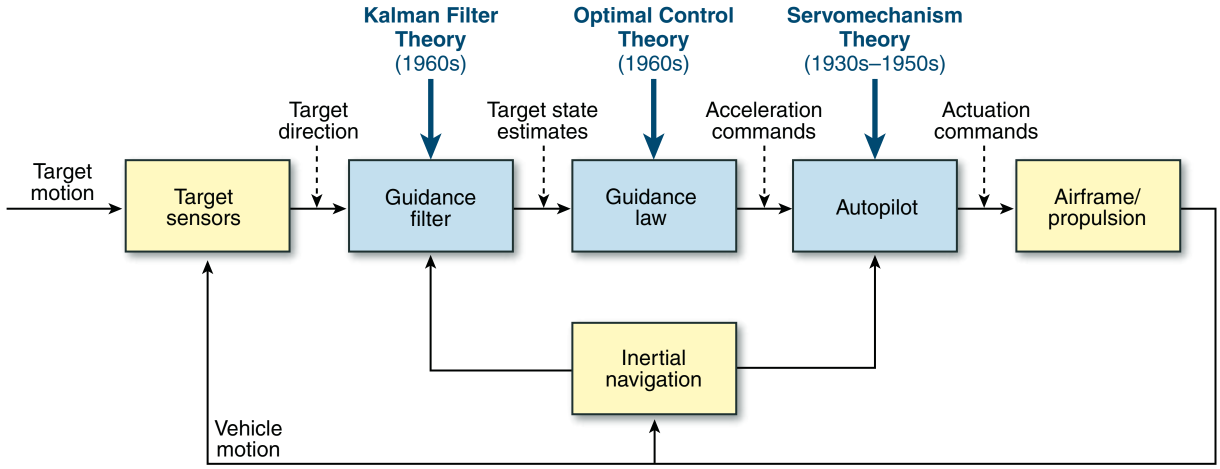

Figure 3. Traditional missile GNC topology. The traditional GNC topology for a guided missile comprises guidance filter, guidance law, autopilot, and inertial navigation components. Each component may be synthesized by using a variety of techniques, the most popular of which are indicated here in blue text.

target. It typically is an anticipatory function in that it generates guidance commands to put the missile on a collision course with the target. One of the oldest and most frequently used guidance laws is proportional navigation (PN).[1,9,10] PN generates guidance commands proportional to the line-of-sight rate between the guided missile and target. (In this issue, the article "Basic Principles of Homing Guidance" discusses PN in some detail. Then, a more comprehensive treatment of modern missile guidance laws and associated synthesis techniques is presented in the article "Modern Homing Missile Guidance Theory and Techniques.") Finally, the autopilot is responsible for stabilization and command following.[1,11–15] The autopilot receives the guidance commands and issues the relevant aerodynamic (e.g., fin), thrust-vector, or divert control commands necessary to achieve the commanded acceleration.

In a decoupled G&C paradigm such as that illustrated in Fig. 3, it is typical to design each component separately and, as suggested by the figure, a variety of synthesis techniques may be adopted for each component design (some dominant techniques are indicated in Fig. 3). Moreover, when designing the guidance filter and guidance law, it is typical to make simplifying assumptions regarding missile response to acceleration commands. These facts can lead to an overly conservative or suboptimal design. In addition, once the individual components are designed, it is typical for the system as a whole to be iteratively tuned, adjusted, and/or modified until satisfactory performance is achieved.

Recent research has led to prototype G&C architectures that consider integration of the guidance and flight control systems. Moreover, modern synthesis techniques are applied to achieve a design that optimally integrates the missile subsystems, thereby leading to a consistently high probability of kill across the threat space.[4,16–20] Figure 4 illustrates a notional integrated G&C (IGC) architecture[12,21–26] and emphasizes the notion that G&C component separation has less meaning in an IGC design.

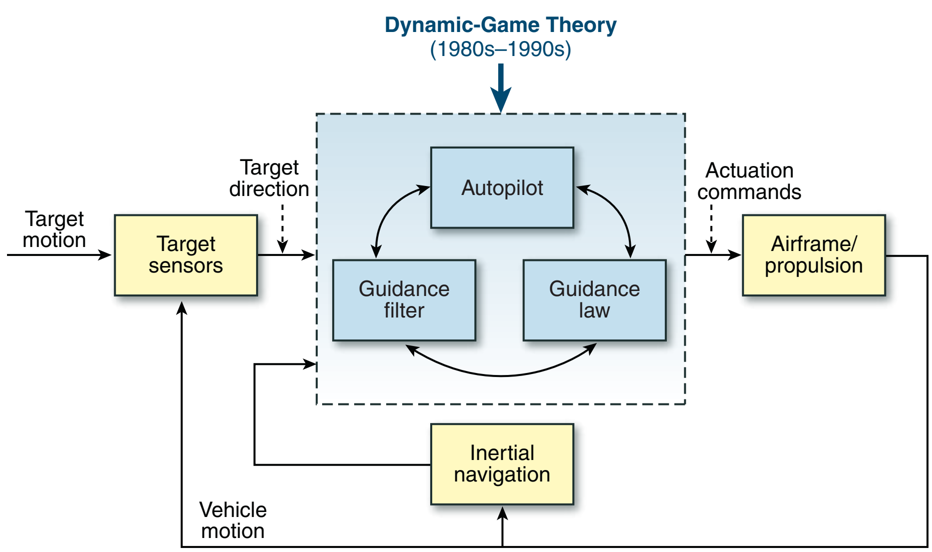

Figure 4. IGC topology. In an IGC system, there is no separation of the guidance and flight control functions.

OUTLINE OF THE ISSUE

This article has discussed a number of basic concepts related to homing missile GNC meant to provide context focus for this issue. In summary, I have defined the difference between guided and unguided weapons, distinguished inertial guidance versus homing guidance, characterized multi-mode guidance, and introduced the feedback structure for missile GNC.

The rest of the articles in this issue of the *Digest* provide more in-depth discussions related to the general concepts introduced here. Referring back to Fig. 3, we see that the flight control function on the right is a key component to achieving the overall mission in that it takes the guidance commands and translates them to achieve the called-for missile maneuvers. This topic alone is quite complex, and a comprehensive treatment of it is far beyond the limited scope of this issue. Thus, the article "Overview of Missile Flight Control Systems" is just as the title implies: it presents a general overview of flight control.

The subsequent three articles address the core focus of this issue, that is, homing missile (terminal) guidance. The article "Basic Principles of Homing Guidance" provides a conceptual foundation with respect to homing guidance. In this article, a basic geometric and notational framework is established, the PN guidance concept is developed from the ground up, line-of-sight reconstruction (the collection and orchestration of the various inertial and target sensor measurements necessary to support homing guidance) is introduced, and many of the challenges associated with designing effective homing guidance systems (noise sources, radome errors, etc.) are discussed.

PN was *the* guidance law of choice (for practical implementation and performance reasons) through the 1970s and beyond. Even today, many guided missiles still employ PN or a close variant. However, by the mid-1970s, it became clear that the types of threats (highly maneuverable aircraft, supersonic cruise missiles, tactical and strategic ballistic missile reentry vehicles, etc.) that were emerging could render PN-guided weapons less effective. That realization, in conjunction with the advancing state of the art in computer miniaturization and computational power, led to a flood of new ideas and synthesis techniques for homing guidance. The preeminent technique centered on linear-quadratic optimization methods. The article "Modern Homing Missile Guidance Theory and Techniques" is a fundamental treatment of guidance laws from this perspective. Here, PN is rederived from the linear-quadratic perspective, and a number of new guidance laws are discussed, compared, and contrasted.

Regardless of the specific structure of the guidance law (e.g., PN versus some other variant), it typically is assumed during the design stage that all of the states necessary to mechanize the implementation are (directly) available for feedback and uncorrupted by noise. In reality, this is not possible; the available measurements require filtering to mitigate noise effects and, oftentimes, other unmeasured states must be derived (estimated) to accommodate guidance law mechanization. Hence, guidance filters take raw sensor data as inputs and derive (estimate) and filter the signals upon which the guidance law operates. The article "Guidance Filter Fundamentals" discusses this topic, and guidance filtering methods are introduced with an emphasis on the discrete-time Kalman filter.

Six-degree-of-freedom simulations are effective tools for cost and risk reduction during the development and deployment of missile systems. The article "Six-Degree-of-Freedom Digital Simulations for Missile Guidance, Navigation, and Control" presents a brief historical review of missile simulations and their practical uses. The authors then examine the requirements of a digital simulation independent of the models and outline current simulation designs. They also characterize the essential models found in a missile GNC simulation and discuss the different levels of detail (fidelity) for these models, while also considering some practical engineering questions that the simulation may help answer based on the level of model fidelity.

G&C algorithms are diverse in type and complexity. However, they all have adjustable parameters that affect their operation and, consequently, guided missile performance. The "tuning" process, whereby optimum values for the adjustable parameters are determined, is a critical challenge in algorithm design. Analytical techniques often are unavailable, and manual "analyze-and-iterate" methods can be time-consuming (and suboptimal). The article "Tuning Missile Guidance and Control Algorithms Using Simultaneous Perturbation Stochastic Approximation" discusses an automated, simulation-based approach to G&C algorithm optimization. Some practical challenges of G&C algorithm tuning, as well as effective solutions to these challenges, also are discussed.

CONCLUSION

For more than 65 years, APL has been making critical contributions to the defense of our naval forces. Within the context of air and missile defense, it is expected that these challenges will continue to mount as threat aircraft and missile systems evolve and become more sophisticated. These evolving challenges, in turn, will continue to drive future guided missile interceptor designs and the associated performance requirements. The articles in this issue should provide the reader with an appreciation for the basic technical and design challenges associated with the missile G&C problem as it is applied to missile interceptor design.

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