Simulation-Based Undersea Warfare Assessment

Tina M. Higgins, Arthur E. Turriff, and David M. Patrone

Simulation has long been an important tool in developing tactics and evaluating system performance for the U.S. Navy submarine force. The Object-oriented, Rule-Based Interactive System (ORBIS)—a simulation tool that enables systematic identification of critical submarine capabilities—has been used to provide key insights to APL sponsors over the past 15 years. ORBIS allows the operations research analyst to readily determine "what matters most" to perform the mission at hand effectively. A sample application is a wartime avoidance scenario in which a U.S. submarine detects a threat submarine and maneuvers according to a prescribed rule set to prevent counterdetection. This article provides an overview of ORBIS, a brief description of its history, its application to tactics development and systems assessments, and its underlying passive and active detection models.

OVERVIEW

The Object-oriented Rule-Based Interactive System (ORBIS) is a time-stepped Monte Carlo submarine engagement simulation that has been used extensively to develop submarine tactics and applied in the evaluation of a variety of submarine systems. The Monte Carlo feature allows for random variations in certain parameters and simulated events to develop probabilistic assessments of system performance. Multiple runs for each combination of scenario, sensors, signature, tactics, etc., provide the statistical basis for the measures of effectiveness and measures of performance used to evaluate mission success.

The scenario is the overarching description of what is to be simulated and comprises the submarines' locations, missions, operating profiles, and tactics as well as the prevailing environmental conditions. Submarines are placed randomly within the scenario guidelines and, as the engagement progresses in time, move and react as governed by their tactics. Tactics are emulated using an "expert system" that represents the tactical doctrine of U.S. and threat submarines. The rule base consists of simplistic "if…, then…" rule sets as well as advanced mathematical techniques (e.g., geometric constraint-based reasoning) to resolve complex decision criteria.

Systems in ORBIS are represented as objects. A submarine is a top-level object and its sensors, signatures, and other subsystems are subobjects whose state, and hence performance parameters, depend on the state of the associated top-level object. For each time step, the sonar equation is used to determine when detection occurs, and is calculated for each sensor, frequency, and submarine platform combination. Based on the results of these calculations, the level of knowledge (i.e., contact, detection, or classification) that a given submarine has regarding the target submarine is evaluated, and the governing tactics effected based on the prescribed rule base. Sonar equation parameters are derived from the current state of each submarine as defined by its speed, aspect, and range to the threat submarine; tactics are typically derived from the detection state and operating profile.

HISTORY

ORBIS originated in the late 1980s when Ernie Holmboe, then CNO OP-213C, sponsored the development of a new simulation system for tactics development to be based on state-of-the-art programming practices. Existing simulation tools were large, cumbersome FORTRAN-based systems. Changes to the simulations were generally difficult to make, and there was no means to view the simulated engagements as they evolved—real impediments to developing tactics. In addition, it was difficult to understand the "why" behind the results from the batch-mode Monte Carlo statistics. That is, the simulation results would indicate the overall outcome of a batch of simulation runs, but they did not provide insights as to the conditions under which a success or failure had occurred or the behavior or rule that might be changed to produce a different result. Specifically, an engagement simulation system was desired where the rules (i.e., tactics) that governed the behavior of the simulated entities could be easily changed and the impact of those changes could be observed directly on a per-run basis (in addition to the Monte Carlo mode) as the simulated engagement evolved.

APL provided the submarine systems and tactics-domain expertise for ORBIS to Physical Dynamics, Inc. (PDI), who implemented the new simulation as a Lisp-based expert system. In the early 1990s, PDI was disestablished and APL became the technical direction agent, also undertaking the responsibility of software development. The Laboratory continues in this role today, most recently upgrading the representation of the complex undersea warfare domain in a true object-oriented programming language. The challenges posed by representing advanced systems with a high degree of fidelity, and by capturing complex, multilevel behaviors in these operational studies, suggested that it was time again to modernize the simulation system.

ORBIS has been used through the years in a variety of assessments and demonstrations. Figure 1 shows the system's evolution and applications. In the early 1990s, ORBIS was used in cost and operational effectiveness assessments (COEAs; now called "analysis of alternatives") of the Submarine Off-board Mine Surveillance System (SOMSS) and the AN/BSY-1 High Frequency Active Sonar for the New Attack Submarine (NSSN; now the Virginia class). An operator-in-the-loop capability was added to ORBIS in the mid-1990s to support the Submarine Combat Information Laboratory (SCIL).[1] When connected to the Defense Simulation Internet (DSI), the SCIL supported distributed simulations for the Advanced Research Projects Agency. During that agency's Maritime Simulation Demonstration, ORBIS and the SCIL supplied both U.S. and foreign simulated submarines with operators in the loop in a large, multisite, distributed simulation using the DSI. In the late 1990s, ORBIS was used to perform simulation-based operational studies. Throughout this time period, ORBIS was applied extensively to tactics development.

APPLICATIONS

Tactics Development

ORBIS is used to test candidate tactics for effectiveness and robustness prior to their evaluation in exercises

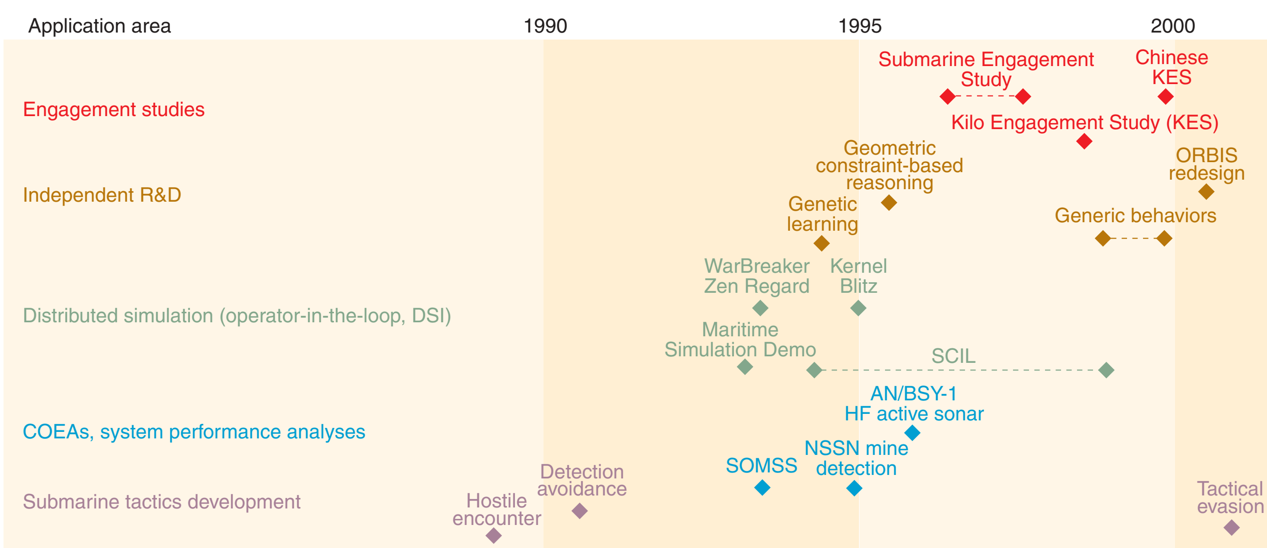

Figure 1. History of ORBIS.

at sea with actual submarines. Post-test, the results observed at sea are compared with simulation results. This comparison is first used to validate sonar detection performance by identifying and adjudicating differences between sea test results and those produced by the simulation. When the differences are resolved or at least understood, ORBIS can then be used to resolve outstanding issues and examine the robustness of the tactics. This is possible since ORBIS is able to run a large number of replications under a variety of conditions, whereas runs conducted at sea are limited in number.

In addition, certain inevitable artificialities associated with exercises can be "erased" in the simulation. For example, a friendly submarine may play the role of a threat submarine, but safety requirements dictate that they operate in different depth zones to provide separation during the test. The differences in acoustic signature and sonar systems between the role-playing friendly submarine and an actual threat submarine, and the differences in acoustic propagation that might be caused by the requirement for depth separation, can be erased in the simulation to examine the likely outcome in actual engagements.

A simulation playback feature of ORBIS enables the analyst to review the status of the simulation and evaluate the tactics employed for the given operating conditions. Submarine track histories, course and speed, target relative bearing, and current tactical guidance are displayed.

System Performance Assessment

Submarine systems are evaluated to determine the capability of a given submarine—comprising its sensors, signature, kinematics, tactics, etc.—versus a given threat. Typical information of interest in a system performance assessment includes the detection performance of the U.S. submarine, the counterdetection capability of the threat, the ability of the threat to reach an engagement-ending criterion, and the ability of the U.S. submarine to successfully complete its mission. Figure 2 shows a sample event results tree for an avoidance scenario involving the submarine that detects first, the counterdetection capability of the threat submarine, the classification capability of the threat submarine, and the ability of the U.S. submarine to successfully avoid the threat submarine.

Once a baseline system capability is established, the impact of system improvements can be determined. This is often referred to as the so-called what-if capability of ORBIS. Figure 3 shows a sample results detection range graphic, where the vertical bars of the box represent the 25th, 50th, and 75th percentile detection range, and the end points of the horizontal lines are the minimum and maximum detection ranges observed in the Monte Carlo series of runs. The baseline detection range performance for a given scenario is shown in the upper left graphic. Improvements in red and blue system capabilities are shown along the horizontal and vertical axes, respectively. The lower right graphic shows the detection range performance for both systems with enhanced capability.

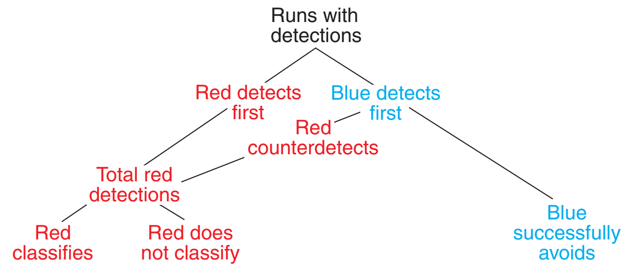

Figure 2. Sample ORBIS event results tree.

The sonar equation is the primary means of determining when detection occurs in ORBIS, and will be examined in detail below. Alternatively, the simulation can apply more simplistic detection models, such as "cookie-cutter" detection ranges. That is, submarines located within a predefined range are considered to be detected and submarines outside this range are considered to be not detected.

DETECTION MODELING

Because submarine tactics—and hence changes in ordered course, speed, or depth—are prescribed by their detection state versus the threat submarine, the passive and active acoustic detection models are the underpinning for ORBIS. Although the models are described to a certain degree of fidelity, the level of fidelity can be adapted to the needs of a given assessment.

Passive Acoustic Detection Modeling

Passive acoustic detection modeling is ORBIS's primary detection method. In the passive sonar equation,

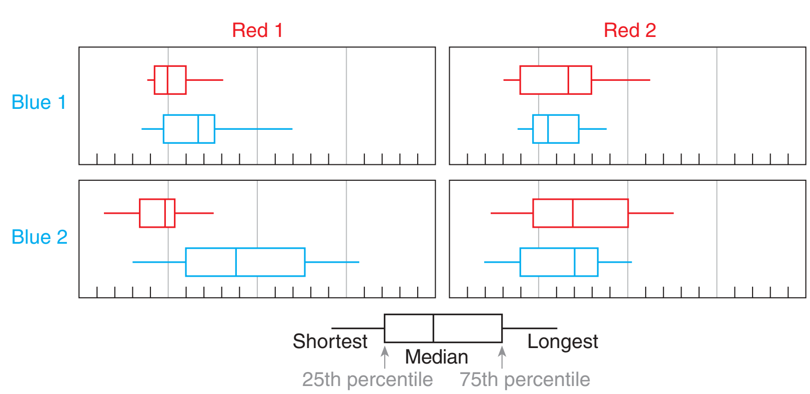

Figure 3. Sample ORBIS detection range quad chart.

the signal terms, i.e., target source level (*SL*), transmission loss (*TL*), sonar system losses (*Loss*), and environmental variability (*Fluct*), are compared to the interference terms, i.e., the total noise as seen at the receiver (*TN*) and the detection threshold (*DT*). The effective noise component of the sonar equation is dependent on the directionality of the receiver. The effects of the horizontal beam pattern on the total noise are explicitly modeled, whereas the vertical beam pattern is incorporated into the transmission loss input.

Because all inputs are measured in decibels, the passive sonar equation is a simple addition or subtraction of equation terms:

$$SE = SL - TL - Loss + Fluct - TN - DT \ ,$$

where signal excess (*SE*) is the amount of energy by which the target signal exceeds the sum of the total noise at the receiver and detection threshold level for desired probabilities of detection and false alarm.

If the signal excess is positive, there is contact with the target submarine. For each time step of the simulation, the signal excess value is calculated for each sensor, frequency, and platform combination. A single contact or a series of contacts denotes a detection. Sonar equation parameters are derived from the current operating state of each submarine as defined by its speed, its aspect and range to the threat submarines, and the environmental characteristics of the region of interest.

In the ORBIS detection model display, the values of all elements of the sonar equation are listed for each sensor at each time step. In addition, submarine state information (e.g., speed, depth, bearing) is provided so that the analyst can review the cause of specific values for sonar equation parameters.

For broadband calculations, the sonar equation is evaluated for discrete sub-bands. The sub-band signal and interference values are power-summed separately and then combined to determine signal excess for the entire band. Note that frequency-dependent data (target signature, transmission loss, directivity index, etc.) must be input for each sub-band. Also, in each sub-band, performance for the band is estimated using a single reference frequency.

The passive detection model has the flexibility to determine the value for any parameter of the sonar equation via methods ranging from a table lookup to a calculation using a complex model. In addition, when simulating advanced sonar systems, this ability to change a specific parameter dynamically is essential. For example, ORBIS has historically modeled advanced sonar performance via the application of a series of detection threshold values. As the operator changes from one mode to another, the detection threshold value is updated. The logic for switching among the various operating modes is incorporated in the detection model or the tactics that govern the use of the sensor.

Each term in the passive sonar equation is described below (most of the terms in the remainder of this article are defined in Ref. 2).

SL: Target source level is the amount of sound radiated by a projector. This variable is input as a function of frequency, aspect, speed, and operating mode.

TL: Transmission loss is the diminishing intensity of sound energy as the underwater sound signal travels through the sea. This variable is input as a function of frequency, azimuth, range, location, season, target depth and type, and receiver depth and type. The effects of the vertical beam pattern must be included in the transmission loss.

Loss: Losses attributed to clipping, scalloping, defocusing, spreading, etc., may be grouped together as system losses. Although grouped for the sonar equation, the analyst can review them and identify loss levels by type. This variable is input as a function of frequency and receiver type, as well as loss type.

Fluct: Fluctuations are random variations in the observation of sound in the sea. This term is described by two independent Gauss-Markov processes, which account for fluctuations that are both platform-dependent and platform-independent. The standard deviation of the fluctuation value (in decibels) and associated decorrelation time are input as constants, but managed for multiple frequency bands. This requires additional inputs: the number of bands and the band limits for each. Fluctuations are then calculated separately for these user-defined bands. When applying the sonar equation, fluctuations associated with the closest frequency are used.

TN: Total noise is the effective noise as seen by the receiver and is typically computed as follows:

$$TN = EN \oplus LE \oplus DS \oplus JN \oplus OS \ ,$$

where

EN = effective ambient noise,
$\oplus$ = power sum,
LE = receiver self-noise,
DS = discrete shipping noise,
JN = jammer noise, and
OS = ownship noise.

However, the total noise parameter may also be a simple lookup in a precomputed table or a calculation by a high-fidelity noise model. Total noise is determined for each receiver as a function of frequency. Each parameter of the total noise computation of the simulation is detailed next.

EN: The ambient noise level is a composite of several components that may be described as the noise of the sea itself, whereas the effective ambient noise level also considers the effects of the receiver directionality via either the receiver's beam pattern function or an input directivity index value. The beam pattern function is an explicit model of a receiver's response for a given target direction, whereas the directivity index is the improvement in signal-to-noise ratio produced by using an array of hydrophones rather than a single hydrophone for an isotropic noise background.

Ambient noise is input as a function of frequency, azimuth, location, time of year, and sea state. The directivity index is input as a function of frequency, aspect, and receiver type. Beam pattern function inputs are receiver type, frequency, beam broadening coefficient, and array-specific parameters such as the length of the towed array or the planar aperture of the sphere. For example, the horizontal beam pattern function for a continuous line array is[2]

$$b(\theta) = 10\log\{\sin[(\pi L/\lambda)\sin(\theta)]/[(\pi L/\lambda)\sin(\theta)]\}^2 \ ,$$

where L = length of the array in meters, λ = wavelength in meters, and θ = target angle measured relative to broadside in radians.

LE: Sonar self-noise is attributed to the array/platform configuration, which is limiting to the sonar performance. This variable is input as a function of frequency, aspect, and speed.

DS: The discrete shipping noise is attributable to ships in the main beam and the mirror beam of the receiver. It is calculated as follows:

$$DS = \bigoplus_{i=1 \ldots n}[DS_n - TL_{\text{Ship-R}} + b(\theta)] \ ,$$

where

DS_n = signature level of the nth ship,
$TL_{\text{Ship-R}}$ = transmission loss from the nth ship to the receiver,
θ = receiver-to-target angle, measured relative to broadside,
$b(\theta)$ = receiver beam pattern, and
n = number of discrete ships considered in the calculation.

Discrete ship signature data are input as a function of frequency, location, and season. Transmission loss is as described earlier, except the acoustic model calculation is based on the transmission from the keel depth of the discrete ship to the receiver depth.

JN: Jammer noise is the component of the total noise at the receiver attributed to a noise-making countermeasure. The jammer noise calculation is similar to the discrete ship calculation and is computed for each countermeasure as follows:

$$JN = [JL - TL_{\text{CM-R}} + b(\theta)] \ ,$$

where JL = radiated noise level of the countermeasure, and $TL_{\text{CM-R}}$ = transmission loss from the countermeasure to the receiver. The jammer radiated noise level is input as a function of frequency. Also, note that the transmission loss input is from the employment depth of the countermeasure to the receiver depth.

OS: Ownship noise for towed array calculations is the contribution to the total noise attributed to the radiated noise from ownship. This variable is input in tabular format as a function of frequency and speed.

DT: The detection threshold is the signal-to-noise ratio required for an operator to detect the target signal in an interfering noise background for a specified probability of detection and probability of false alarm. This variable is input for each receiver and may be updated dynamically, depending on the number of contacts in the most recent series of contact opportunities.

Active Acoustic Detection Modeling

The active detection model is similar to the passive detection model, as echo terms are compared to interference terms to determine if contact occurs. Sonar equation parameters are derived from the current operating state of each submarine and the environmental characteristics of the region of interest. Active model capabilities include detection capabilities of the passive model for system directionality, flexibility in parameter evaluation (lookup table or call to detailed model), and ability to dynamically change input parameters.

As with the passive model, all the inputs are measured in decibels and the sonar equation is a simple addition or subtraction of the parameters. The active sonar equation is as follows:

$$\begin{aligned} SE = ESL - TL_{\text{S-T}} - TL_{\text{T-R}} + TS - Loss_{\text{R}} - Loss_{\text{S}} \\ + Fluct - TN - DT \ . \end{aligned}$$

Signal excess (SE) is the amount of energy by which the target echo exceeds the sum of the signal masking effects and detection threshold level for desired probabilities of detection and false alarm. The transmission environment determines which detection threshold value to apply (i.e., noise-limited or reverberation-limited). The active total noise calculation is based on the passive model. However, active target strength values replace radiated noise values for discrete ships, and the reverberation of the active energy is included in the computation.

In bistatic geometries, the target echo may be masked by the direct transmission of energy from the source to the receiver, where the receiver is unable to discern the target echo from the energy that is received directly from the source. This occurs if the time for transmission from the source-to-target-to-receiver is less than the time for transmission from the source to receiver plus a direct blast mask time. That is, a target is masked by the direct blast if the following evaluates to true:

$$\tau_{\text{S-T}} + \tau_{\text{T-R}} < \tau_{\text{S-R}} + \tau_{\text{b}} \ ,$$

where $\tau_{\text{S-T}}$ = transmission time from source to target, $\tau_{\text{T-R}}$ = transmission time from target to receiver, and $\tau_{\text{S-R}}$ = transmission time from source to receiver. The direct blast mask value τ_{b} is typically determined empirically for the given acoustic propagation conditions and is a function of source operating mode.

Each parameter in the active sonar equation is described below.

ESL: The energy source level is the sound energy radiated by a projector. This variable is input as a function of frequency, source type, and operating mode and may be computed from the source level and pulse duration, *t*, as follows:

$$ESL = SL + 10\log(t) \ .$$

TL: The transmission loss parameter for target to receiver is the same as for passive detection modeling. However, in the active case, transmission loss is also required for source to target transmission. The source to target transmission loss is a function of the source depth and operating mode, target depth, frequency, azimuth, range, location, and season. The dependence on operating mode is required because the vertical directionality of the transmission may vary for the different operating modes.

TS: Target strength is a measure of the reflectivity of a submarine target at which active sound energy is directed. This variable is input as a function of frequency, aspect, and target type. In the case of bistatic detection, the equivalent monostatic aspect is computed prior to accessing or computing target strength values.

$Loss_{\text{R}}$, $Loss_{\text{S}}$: System losses are considered as in the passive detection model, except the source and receiver loss terms are managed separately. This partitioning of values allows for the multistatic evaluation of the sonar equation.

Fluct: Fluctuations for active systems may be calculated using the Gauss-Markov model as in the passive case, or for impulsive sources, using an exponential distribution. In either case, the fluctuations vary about a mean value and are managed for multiple frequency bands.

TN: The active model total noise computation is based on the passive model calculation, but also includes the reverberation of the sound energy reflecting off elements other than the target of interest:

$$TN = EN \oplus LE \oplus DS \oplus JN \oplus OS \oplus RL \ ,$$

where RL = reverberation level and all other terms are defined as before.

For the discrete shipping noise (*DS*), active target strength values replace the radiated noise values in the calculation. The variable is not likely to affect the overall total noise as seen at the receiver. However, it is left to the analyst to determine which components of the active noise model are of interest. Factors for consideration are the purpose of the simulation or the frequency regime of the simulated systems. Therefore, all parameters are retained in the total noise calculation for completeness.

RL: The reverberation level is the reflection of the transmitted active sound off the ocean bottom and surface as well as scatterers within the ocean volume. Typically, only the reverberation attributed to the ocean bottom and surface are considered in the reverberation calculation. However, the option to also include the effects of volume reverberation is available. Reverberation is computed as a function of frequency, source type, receiver type, and source-to-target-to-receiver geometry. Inputs required are the energy source level, transmission loss parameters to each bottom and surface reverberating patch on the equal-time ellipse (source and receiver side), the bottom scattering coefficient, horizontal ranges, the speed of sound in water, the pulse width of the active source, and the angular width of the reverberating patch.

While reverberation is derived for bistatic geometries, it is also valid for monostatic calculations. Reverberation rejection is the reduction in reverberation that is achieved by acoustic processing. This processing is based on the Doppler frequency shift and can be modeled via Q-functions. (A Q-function is implemented by a table lookup that lists reverberation reduction levels as a function of relative speed.)

DT: In the active detection model, unique detection threshold values may be applied, depending on whether the environment is noise- or reverberation-limited. That is, if the effective ambient noise is higher than the reverberation, DT_{N} is applied. Otherwise, the reverberation is higher than the effective ambient noise and DT_{R} is applied.

CONCLUSION

ORBIS, a time-stepped Monte Carlo submarine engagement simulation, has been used extensively in support of U.S. Navy tactics developments and system performance assessments. The system enables the operations research analyst to readily determine “what matters most" in order to perform the mission effectively. In addition, ORBIS can be easily adapted to the requisite level of fidelity for a given assessment. Passive and active acoustic detection models are the underpinnings for tactics evolution in the simulation.

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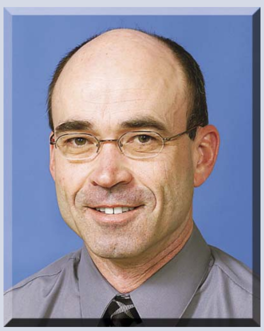

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