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IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.Doi Number

Design and Implementation of Data-Based Validation and Evaluation System for Combat System Engineering

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ABSTRACT Combat systems are developed by utilizing standardized frameworks, such as the V process, with testing paired with validation and evaluation (V&E) at every phase. To achieve that, V&E requires the ability to utilize both simulation data and real data generated during development. This article proposes a data-driven V&E system (DVES) that integrates the data types of V&E and can be utilized for all phases of the V process. The proposed system consists of a data collection module and a designed and implemented V&E module. The data acquisition module functions as a file system for simulation data acquisition and a data distribution service interface for interoperation with real systems. The V&E module consists of a mathematical analysis model and a graphical analysis model. To test the proposed system, experiments were performed in scenarios using simulation data and real data and a hardware-in-the-loop simulation of a submarine was conducted. Through the experimental results, tactical analysis and radar performance evaluation indicators optimized for target engagement simulations could be identified and torpedo launch procedures were verified. This is expected to reduce the development period and cost of combat engineering systems by replacing multiple V&E systems with DVES.

INDEX TERMS Data-Based Validation, Data-Based Evaluation, Combat System Engineering, Data Analysis, Validation and Evaluation

I. INTRODUCTION

A combat system, as a type of system-of-systems (SoS), contains computational subsystems to perform a wide range of military functions. In an underwater vessel, for example, an inertial navigation system (INS) enhances the computational accuracy of its orientation and velocity based on data from other subsystems such as electromagnetic log and global position subsystems [1]. For effective development of a combat system, it should be built and integrated using the V process, which is a standardized framework to develop complex systems such as combat systems [2].

The V process, illustrated in Figure 1, provides a structured and systematic approach for combat system development [3]–[6]. The key concept of the V process is that each phase of development is paired with a corresponding verification and evaluation phase. For example, the left side of the V process represents the decomposition of operational requirements into system/subsystem requirements, components design, and production design. The right side of the V process involves validation and evaluation (V&E) of the system at various levels, starting from individual components and subsystems and progressing to the entire system. With the V&E activities, combat system developers [7]–[16] can ensure that each phase of development is properly verified before moving on to the next phase. It also reduces the risk of costly errors in the final system.

To perform the V&E activities for combat system engineering, both simulation data and real-world data should be obtained. Simulation data are mainly used in requirements analysis phases [17]–[23]. Simulations enable the creation of controlled environments where various scenarios can be tested repeatedly. Thus, in the requirement analysis phase, combat system engineers can evaluate the performance of combat systems under different conditions, including rare or dangerous situations that may be impractical to replicate in real-world testing. On the other hand, real data [24]–[28] obtained from development and operational evaluation phases provide a more accurate representation of the system performance in actual operational conditions.

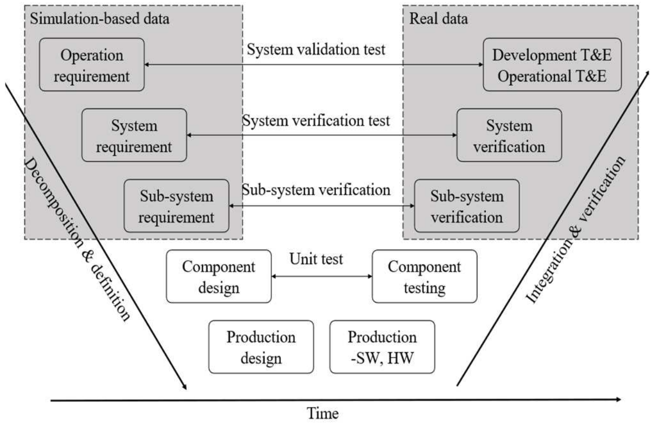

FIGURE 1. V&E application to system engineering

By combining simulation data and real data, combat system engineers can leverage the benefits of both approaches. Simulations enable cost-effective and controlled testing in various scenarios, whereas real data provide validation, realistic assessment, and confirmation of performance in actual operational conditions. This combined approach enhances the overall V&E activities and helps ensure the readiness and effectiveness of combat systems. Because combat systems have complex structures, having a data-based V&E system that can be utilized for all phases of the V process is important [29].

Research in the last decade has focused on data from each stage of the V&E system. Some researchers have studied validation using only simulation data, whereas others have used real data to evaluate the performance of actual systems. This is meaningful for individual phases of the V process, but the overall perspective of SoS requires V&E results from all phases. For the development of a successful combat system, experimental results based on limited information and knowledge from the initial requirements analysis to the operational test phase must be utilized.

This article proposes a data-driven V&E system (DVES) that covers V&E activities in all phases of the V process. The DVES consists of two components: a data collection module and a V&E module. The data collection module has an interface for real data collection and a file system for collecting simulation results. Here, the data collection module interoperates with other systems using data distribution service (DDS) and Transmission Control Protocol/Internet Protocol (TCP/IP) communication interfaces. It also has the support to include modeling information for the integration of simulated and real data.

The V&E module validates and evaluates both simulated and real data. In the validation function, operational validation can be performed by utilizing the *B-spline* method. This approach ensures effective operational validation of the target system. In the evaluation function, performance evaluation metrics can be calculated using the *HARVERSINE* of the target system. The V&E function is designed to be modular, which has the advantage of reusability and easy maintenance even if the target system changes. To make V&E even more effective, we leveraged the Unity 3D engine to visualize the results.

In the experiments on the proposed system, V&E was performed in all stages of the V process in the submarine hardware-in-loop simulation (HILS) environment. The experiments utilized simulation data and real data. First, the simulation scenario utilized data from a simulated torpedo engagement between a submarine and a surface ship to verify the attack pattern of the torpedo and the evasive maneuvers of the surface ship. The engagement simulation was used to perform optimal strategy analysis. The scenario utilizing real data performed V&E of the submarine radar performance evaluation and the launch test of the shipboard torpedo. The proposed system could generate baseline indicators for radar performance evaluation and compare the results of the integrated test phase with the requirements analysis information of the shipboard torpedo. These results confirmed that the proposed system can be utilized throughout the V process, and it is expected to be utilized in actual combat systems.

The remainder of this paper is organized as follows. Section II summarizes related work on V&E systems. Section III describes the design and implementation of the proposed DVES, and Section IV reports the experiments and results. Finally, we summarize the conclusions in Section V.

II. RELATED WORK

System development of V&E uses simulation-based and real data to analyze and test systems [7], [31]. Various studies have been conducted over the past decade to obtain V&E indicators. Table 1 summarizes the previous research related to the present study. This section describes the application of V&E based on data generated by HILS or combat engineering systems.

Most V&E approaches have been applied to systems before development [30], [31]. For example, Ke et al. [32] developed a subsystem that combines an HILS of antiaircraft missiles and used it to conduct simulation training evaluations of antiaircraft missiles. Similarly, Zulkefli et al. [33] developed a subsystem for evaluating and analyzing the fuel consumption and emissions of vehicles in combination with an HILS testbed of connected vehicles. The evaluation items included a real engine, an engine-loading device, and a virtual powertrain model. The above studies developed separate subsystems for evaluating simulation data, similar to the method proposed in this study.

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TABLE 1. **Related works on validation & evaluation systems.**

Related work	System approach	Data-based approach	V&E method	Description
[7]	System engineering	Real data	V&E	- V&E of interoperability data between the SoS
[31]	System engineering	Real data	Validation	- Propose software and protocol for V&E of sensors used in smart buildings
[32]	Data based	Simulation	Evaluation	- Proposal of interface system for evaluation of efficiency of anti-aircraft missiles in HILS environment
[33]	Data based	Simulation	Evaluation	- SW proposal for performance evaluation of connected vehicles in HILS environment
[34]	Data based	Simulation	Evaluation	- Design of guided bomb control system and performance evaluation in HILS environment

Yang et al. [34] built a HILS testbed of a guided bomb and a system to evaluate the control model of the bomb and to analyze the sequence diagram. They focused on evaluating the performance of the target system by establishing HILS testbeds. In addition, they evaluated their solutions through simulations rather than by developing V&E systems. Therefore, researchers [32]–[38] have focused on simulation data and performed V&E, although these works have been limited because performing V&E on various systems is difficult.

From the perspective of real combat system engineering, V&E is performed after developing the target system. For example, Seo et al. [7] proposed an interface validation system for the interoperability of combat systems. The system interfaces during design and after implementation helped verify the corresponding system of systems. Dai et al. [24] introduced a data-based least-squares support vector machine to build a combat effect evaluation model for real combat systems, achieving higher accuracy than conventional combat training evaluation systems. Du et al. [31] and Ding et al. [37] proposed neural-network-based combat evaluation models for cooperative combat between underwater unmanned vehicles. They basically combined a neural network with fuzzy logic to analyze and evaluate cooperative combat patterns of underwater unmanned vehicles to improve the system accuracy. These studies focused on collecting and evaluating data generated by real combat systems to improve their performance. Therefore, they developed V&E systems using real data for evaluation and further improvement.

Our research team has conducted various studies on V&E systems. For the success of the proposed DVES, we studied most activities in V&E for combat system engineering. For example, we performed a requirement analysis of combat systems and studied several methods of data-based V&E, such as data analysis [39]–[43], interoperability between systems [7], [31], simulation modeling [32]–[38], and programming

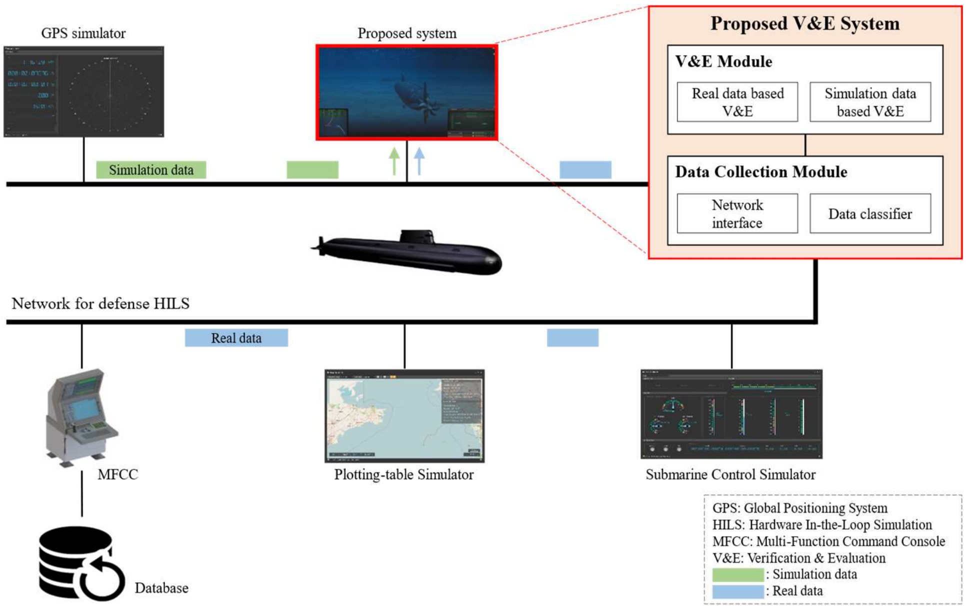

FIGURE 2. **Schematic of the proposed DVES for combat system engineering.**

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based on a 3D Unity engine [44]–[51]. These studies enabled us to collect real and simulation-based data in an integrated environment and improved the effectiveness of V&E through 3D visualization, which is different from previous studies.

III. INTEGRATED V&E SYSTEM

This section details the proposed DVES, system architectures for V&E, and main components.

A. OVERVIEW

Figure 2 shows the configuration of the proposed DVES and target system. It is a HILS system composed of subsystems for simulating real submarines, such as a global positioning system (GPS) simulator, a floating table simulator, a seabed control simulator, a multifunction command console, and databases. The submarine HILS generates simulation data similar to those of the actual system, or the collected real data can be identical to those of the actual system. For example, a GPS simulator can generate both simulation and real navigation data of parameters such as location and speed. The resulting database can transmit the collected real data through the network data bus.

The proposed DVES comprises subsystems of simulators and data collection modules with databases from the actual system and V&E modules. A data collection module has functions of network interfacing and data classification for interoperability with HILS networks, enabling data collection for interoperation with the HILS internal simulators. Thereafter, V&E of simulation and real data can be performed using the V&E module. The DVES is implemented as a modular and hierarchical structure for easy interoperation with other systems.

B. ARCHITECTURE AND METHODOLOGY OF DVES

The DVES has a hierarchical structure comprising the V&E and data collection modules, as shown in Figure 3.

First, the data collection module uses the DDS middleware in the function to collect data for analysis in the actual system or HILS. The collected data are divided into simulation and real data and are classified by preprocessing. The data are then transferred to the V&E module by a data transfer function using TCP/IP communication.

The V&E module sets the parameters to be validated or evaluated by the V&E parameter setup function. The parameters define the appearance of the visualization object, standard coordinate system, standard time, and number of systems to collect data or load scenarios. The data analysis function distinguishes whether the collected data are intended for validation or evaluation for subsequent processing. Validation enables highly effective validation by applying a B-spline interpolation model for missing values between data. Finally, the evaluation function evaluates the system using distance, position, and azimuth performance-evaluation equations.

1) DATA COLLECTION MODULE

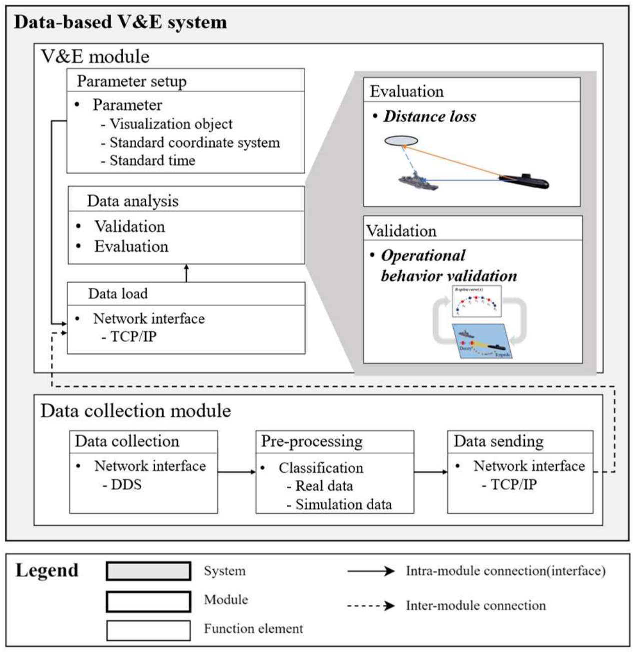

FIGURE 3. Overall DVES configuration.

The data collection module comprises three steps, as shown in Figure 4. The first step is data collection, which consists of DDS interoperation for data collection and message collection logic. For DDS interoperability, messages are collected through connection with the DDS data bus by defining DDS interoperability settings and message modeling. The second step is preprocessing, which includes message parsing, classification, and transformation logic of the collected data. The collected data are divided into simulation and real data, and analysis data are reconstructed according to a specific format. The data collection module may perform preprocessing to reduce the computational load in the V&E module. In the third step, the collected data are transmitted to the V&E module, and interactions using TCP/IP and data transmission logic are performed. If data collection is not complete, steps 1–3 are repeated.

2) V&E MODULE

The main functions of the V&E module are the V&E of data (simulation and collected real data) generated during the system development. Therefore, the V&E module consists of V&E functions. This structure is hierarchical and easy to expand, modify, and use to supplement the interface of the target system.

Figure 5 shows a brief description of a maneuver validation scenario for a submarine. The validation function verifies the system according to the following steps: 1) creation of a validation environment, 2) validation analysis, and 3) result visualization. Specifically, step 1 generates a list of event times in the object and environment settings for validation using messages received from the data collection module.

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Reference coordinate settings, object icons, and initial positions are set for verification. The event time list also includes information about the positions and postures of the main objects and sub-objects by time. After validation is started, time proceeds according to the internal time management module, which extracts events to perform the

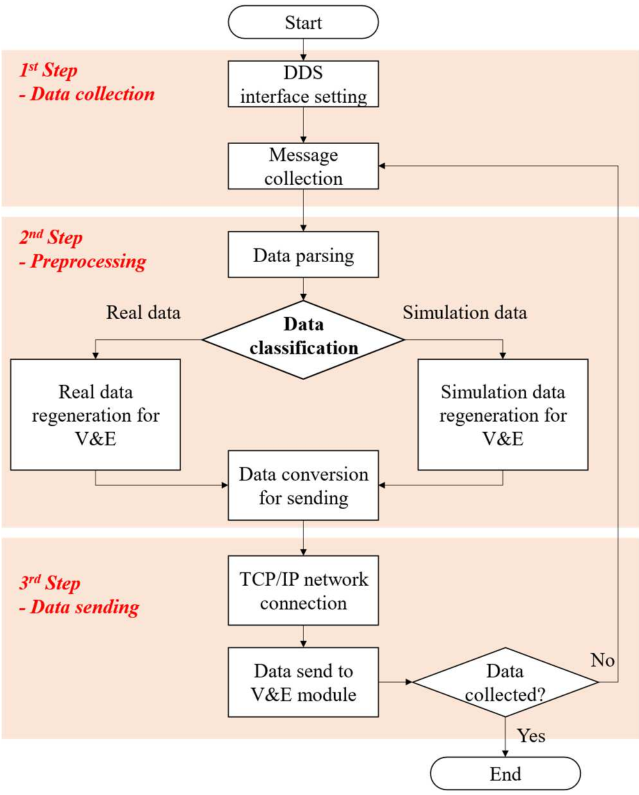

FIGURE 4. Operational flowchart of the data collection module.

validation analysis and result visualization.

In steps 2 and 3, the generated events are sequentially visualized; in this case, the time resolution between the data is highly important. A low simulation resolution or low sampling rate of the data can lead to accurate verification failures, and the operator deduces the empty value between the current and subsequent data. Therefore, the low-resolution problem of the verification data should be minimized via a theoretical background, and in this study, B-spline interpolation [52] was interpolated as empty data.

$$\begin{cases} N_{i,0}(u) = \begin{cases} 1, u \in [u_i, u_{i+1}] \\ 0, u \notin [u_i, u_{i+1}] \end{cases} \\ N_{i,p}(u) = \dfrac{u - u_{i+p}}{u_{i+p} - u_i} N_{i,p-1}(u) \\ \quad + \dfrac{u_{i+p+1} - u_i}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u), \qquad p \geq 1 \end{cases} \tag{1}$$

$$P(u) = \sum_{i=1-p}^{n-1} P_i N_{i,p}(u)\, , u \in [u_1, u_n] \tag{2}$$

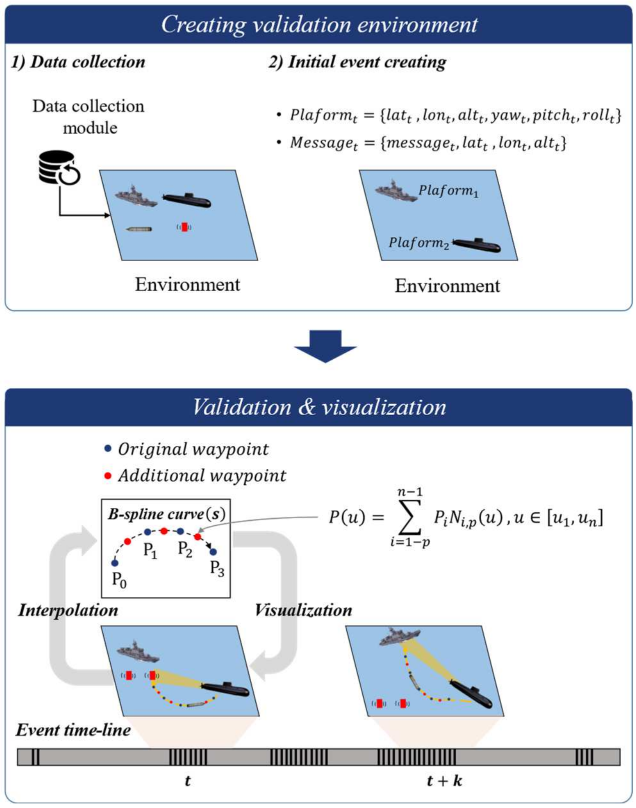

FIGURE 5. Brief description of the scenario for maneuver validation of a submarine.

The B-spline is applied to synthesize reasonable data. Equations similar to that of the B-spline curve include those of the Bezier and Lagrange spline curves. Compared with the above equation, the B-spline curve has no limit on the minimum number of control points for curve generation and can produce a curve closer to the control point. First, we define the subdivided curve as u. Equation (1) is the basic correction of the p-order B-spline equation for u. Then, the basic form of the p-order B-spline equation can be defined through $N_{i,p}(u)$ using (1), as shown in (2). It is easy to implement and has excellent algorithm performance by calling the base function in recursive form.

Figure 6 shows a brief description of a scenario for evaluating the subsystems of a submarine. The evaluation utilizes the HARVERSINE algorithm and consists of three steps: 1) collecting and selecting evaluation data, 2) computing evaluation losses, and 3) evaluation and visualization. Step 1 selects the items to be evaluated from the data received from the data collection module. The evaluation items consist of azimuth-error, distance-error, and position-error evaluation items. Subsequently, the data corresponding to the error calculated based on the evaluated items are collected. First, the azimuth error is calculated from the difference between the azimuth angle of the detection target and that in the actual direction to determine the difference

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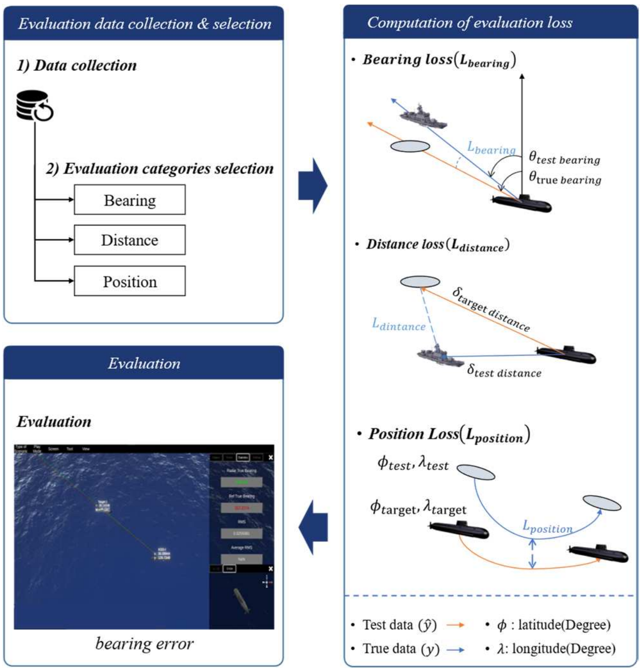

FIGURE 6. **Brief description of a scenario for the evaluation of the subsystems of a submarine.**

between the detection and measurement angles. The distance error is obtained based on the location of the target detected in the test box and the actual location of the target box. The above two items are mainly used to assess radar or GPS detection and navigation errors. Finally, the position error is calculated from the position of the test ship and the actual position error of the test ship, and it predicts the position of the test ship only using an INS without GPS.

The bearing evaluation can be quantified as follows:

$$\begin{cases} f_i = \dfrac{\cos\phi_i \cdot \sin\theta_i - \sin\phi_i \cdot \cos\theta_i \cdot \cos(\varepsilon_i - \lambda_i)}{\sin(\varepsilon_i - \lambda_i) \cdot \cos\theta_i} \\ B_{exp,i} = \tan^{-1}(f_i) \cdot \dfrac{\pi}{180} \end{cases} \tag{3}$$

$$ce_{bearing,i} = |B_{ref} - B_{exp,i}| \tag{4}$$

$$ae_{bearing,i} = \sqrt{\frac{1}{N}\sum_{i=0}^{N} ce_{bearing,i}^2}, \tag{5}$$

where

B_{ref}: Reference bearing.
B_{exp}: Measured azimuth between the target and test ships.
ϕ: Latitude of the test ship.
θ: Latitude of the target ship.
ε: Longitude of the test ship.
λ: Longitude of the target ship.
$ce_{bearing,i}$: Current error of the measured bearing at time i.
$ae_{bearing,i}$: Accumulated RMSE of the measured bearing until time i.

Equation (3) is used to calculate the azimuth ($B_{exp,i}$) from the latitude (ϕ, θ) and longitude (λ, ε) of the target submarine collected by the radar or GPS. It indicates the position of the target ship with respect to the test submarine. For example, if $B_{exp,i}$= 49.8°, the target line is located at 49.8° clockwise from the test submarine. However, as $B_{exp,i}$ is calculated, comparison with the true value (B_{ref}) reveals the error. The error between $B_{exp,i}$ and B_{ref} is calculated as shown in (4), and the radar accuracy is obtained using the absolute value for measuring the target error. Equation (5) is the root-mean-square error (RMSE) obtained from radar data and enables continuous checking of the accumulated errors throughout sensor data collection.

The distance evaluation can be quantified as follows:

$$\begin{cases} g_i = \cos\phi_i \cdot \sin\theta_i + \cos\phi_i \cdot \cos\theta \cdot \cos(\varepsilon_i - \lambda_i) \\ D_{exp,i} = \cos^{-1}(g_i) \cdot \dfrac{\pi}{180} \end{cases} \tag{6}$$

$$ce_{dist,i} = \left|\frac{D_{ref} - D_{exp,i}}{D_{ref}}\right| \tag{7}$$

$$ae_{dist,i} = \frac{1}{N}\sum_{i=0}^{N} ce_{dist,i}, \tag{8}$$

where

D_{ref}: Reference distance.
D_{exp}: Measured distance between the target and test ships.
ϕ: Latitude of the test ship.
θ: Latitude of the target ship.
ε: Longitude of the test ship.
λ: Longitude of the target ship.
$ce_{dist,i}$: Current error of the measured distance at time i.
$ae_{dist,i}$: Accumulated mean error of the measured distance until time i.

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The distance error is calculated by applying (6), which is used to obtain the distance between two points in the WGS-84 coordinate system, based on the latitude (ϕ, θ) and longitude (λ, ε) of the test and target lines. The units of $D_{exp,i}$ are nautical miles. The ratio of the distance error $(ce_{dist,i})$ can be calculated using (7), and the error between the true and measured position values is calculated as to what the error is for the true position value. Equation (8) confirms the accumulated mean error of the distance error rates $(ae_{dist,i})$ calculated using (7).

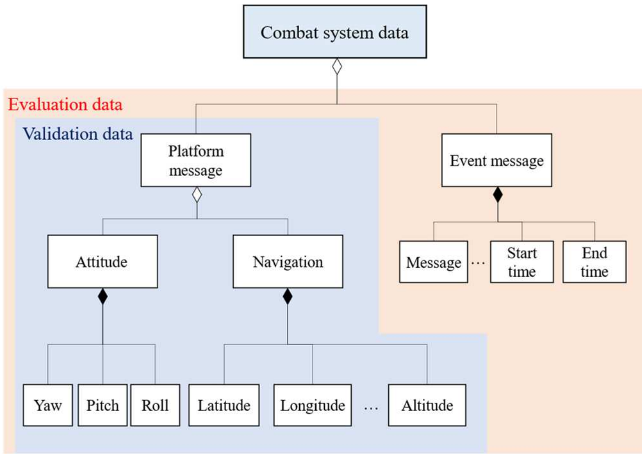

FIGURE 7. Message modeling diagram for combat system engineering.

Figure 7 shows the data used for V&E through message modeling for V&E in combat systems. In this study, platform and event messages were considered. Platform messages contain attitude and navigation data. Attitude data can represent yaw, pitch, and roll of the target object. Navigation data can represent information such as the identification number, location, altitude, and speed of the target object. Attitude and navigation data can be utilized to indicate the behavior of the target system or the detection radius of the sensor. Platform and detection messages update data by identifying platform data and identifiers. Finally, event messages should be displayed on the screen at a specific time and should include phrases mainly employed to analyze the operating procedures of the combat system.

C. IMPLEMENTATION of DVES

Figure 8 shows the architecture of the proposed DVES for implementation. The DVES mainly consists of network interfaces and modules for data collection, visualization, and data-based V&E. The network interface interoperates with actual systems or HILS environments for V&E. We use DDS middleware to connect to many systems in a 1:N connection; however, this approach can cause high message-loss rates. To compensate for the message loss, we applied a quality-of-service policy in the DDS. Consequently, the DVES ensures significantly high reliability in interoperability V&E.

Data collection is conducted using a module that categorizes received messages and a detailed model that loads simulation scenarios. Detailed models for visualization consist of a model, view, and controller, which represent the back end and front end, respectively. The back end consists of detailed models such as objects, messages, and playback speeds. The front end is implemented as a detailed model directly

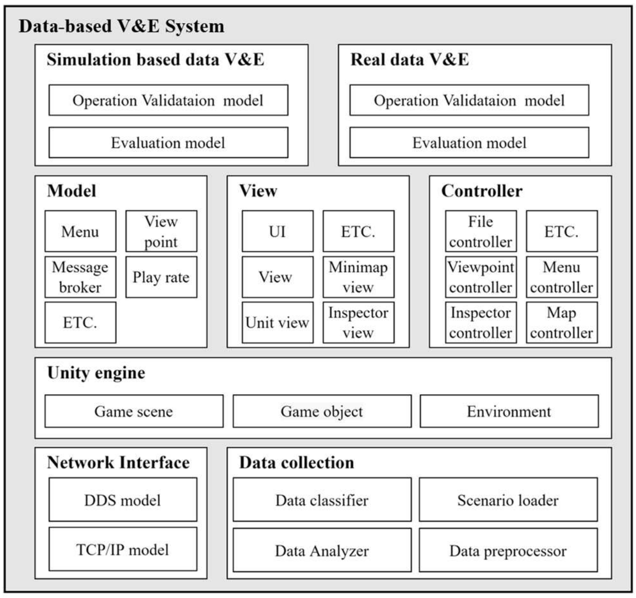

FIGURE 8. Architecture for DVES implementation.

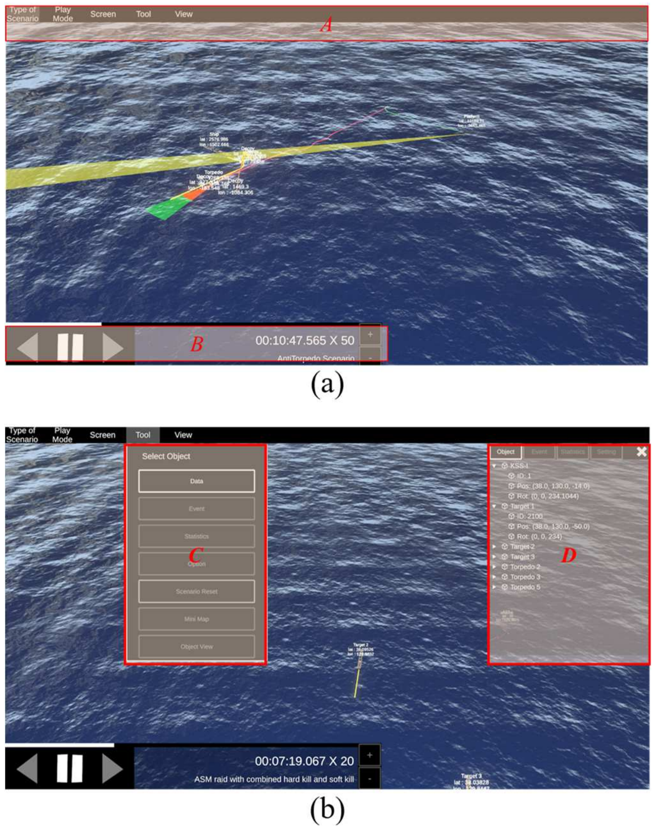

FIGURE 9. Example of DVES menu and data visualization. (a) Main user interface of DVES. (b) Screenshot of a sub-tool.

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controlled by the screen shown to the operator and consists of modules such as mini-maps, views, or file controllers. Finally, the V&E module performs V&E by inheriting the model described above. As described in Section 3.2, DVES facilitates the expansion and maintenance of each model owing to its modular and hierarchical structure.

Figure 9 shows an implementation screenshot based on the design described in Section 3.2. Figure 9(a) shows the main user interface of DVES, where region A represents the main toolbar of the proposed system. The main toolbar allows users to set options for V&E by setting the purpose and type of V&E and the visualization point of view. Region B in Figure 9(a) represents the replay player for data analysis. In this area, you can visualize the overall length and playback time of the replayed scenario and set the playback speed for efficiency in V&E. The information in regions A and B allows operators to gain insights into V&E. Region C in Figure 9(b) represents the sub-toolbar. In the sub-toolbar, the operator can select detailed options for V&E. The operator can set the six degrees of freedom of the platform, whether to visualize event messages, etc. Consequently, the operator can effectively customize the visualization screen of the scenario for each evaluation and validation. Region D visualizes the details set up by the sub-toolbar: it shows the six degrees of freedom of the platform, its identification number, and V&E metrics. The operator can use them to guide V&E.

IV. EXPERIMENTS AND RESULTS

We conducted experiments to collect data generated from complex HILS environments for V&E. The HILS environment of the submarine used for the experiments is shown in Figure 10. The established HILS environment uses a DDS interface for communication between simulators. Each simulator in a HILS environment consists of a database, data publisher, and DVES. First, the database stores information collected from the real submarine data. Then, the data publisher subscribes to the data from the database and republishes it for use by DVES.

A. EXPERIMENTAL SCENARIOS

The experiments conducted in this study aimed to validate and evaluate the data using scenarios with simulation or real data. The detailed scenarios are described in Table 2. In the simulation scenario, the combat effect of the torpedo performance improvement project was also analyzed, and the real data were tested based on the existing data studied by Daewoo Shipbuilding & Marine Engineering (DSME) Corporation [41]. The simulation data compared and analyzed offense and defense-engagement scenarios of submarine surface ships and submarines. The development and operation stages were validated and evaluated using real data, and the development V&E analyzed the detection and measurement accuracy of the subsystems. Moreover, operational V&E validated and evaluated torpedo launch procedure tests.

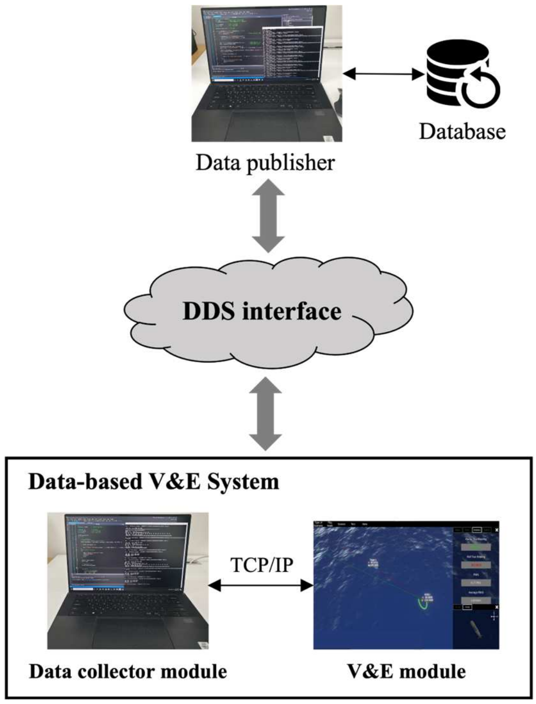

FIGURE 10. Experimental setup for V&E.

Figure 11 shows the diagrams of the experiment scenarios listed in Table 2. Figures 11(a) and 11(b) illustrate torpedo engagement scenarios between a surface ship and a submarine.

TABLE 2. Experimental scenarios for testing DVES.

Data type	Objective	Application phase	Experimental scenario	Operations
Simulation data	Simulation-based validation before system development	Operational requirement, analysis	Engagement scenarios of surface ship versus submarine	- Submarine: attack tactics for launching fire-and-forget and wire-guided torpedoes - Surface ship: defensive tactics containing launching countermeasures and evasive maneuvering
Real data	V&E of the developed system	Development V&E	Performance evaluation of navigation subsystem	- Bearing accuracy evaluation
		Operation V&E	Engagement scenarios against multiple surface ships	- Engagement procedure evaluation using multiple wire-guided torpedoes

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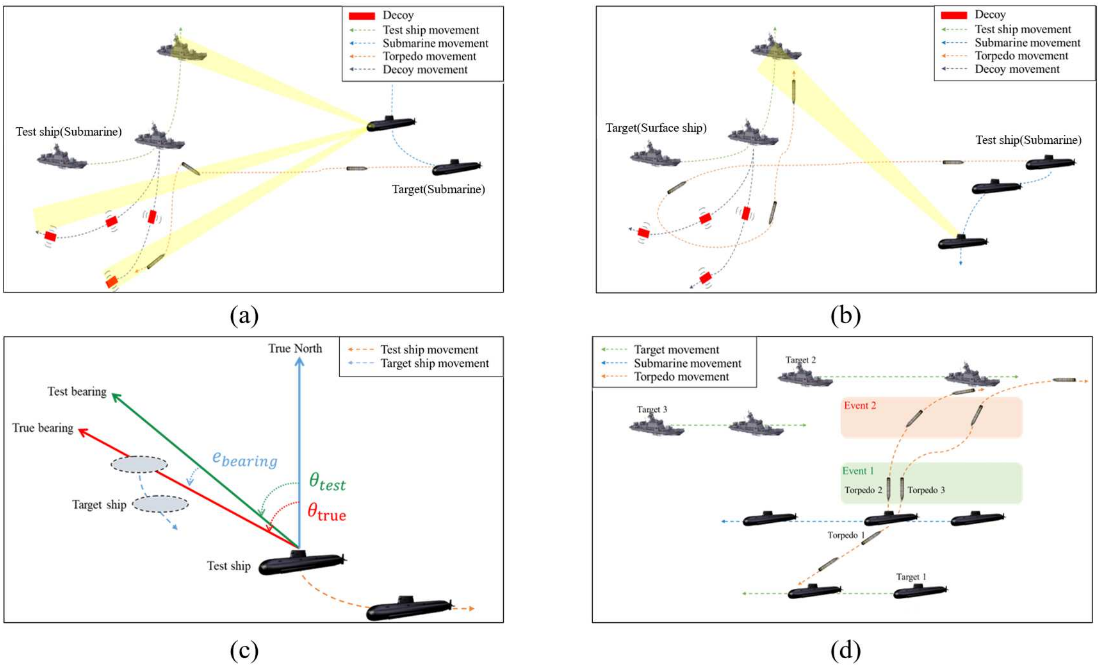


FIGURE 11. Schematics of experimental scenarios. (a) Submarine operation including attack tactics of launching fire-and-forget and wire-guided torpedoes. (b) Surface ship operation including defensive tactics such as launching, countermeasures, and evasive maneuvering. (c) Bearing accuracy evaluation. (d) Engagement procedure evaluation using multiple wire-guided torpedoes.

Torpedoes are classified as straight-running, patterned, and wire-guided according to the induction method. Figure 11(a) depicts the evasive maneuvering of a surface ship for a straight-running torpedo. When the surface ship detects the torpedo, an acoustic decoy is fired to disturb the torpedo target and perform evasive maneuvering. Figure 11(b) illustrates the use of a wire-guided torpedo directed by a sonar mounted in the submarine to outperform the sonar mounted in the torpedo and successfully hit the target. The submarine is connected to the torpedo through a wire, such that it can be tracked without disturbance by the acoustic decoy.

The subsystems used in submarines include navigation and detection sensors, such as a GPS, INS, and radar. Figure 11(c) shows the locations of targets according to radar, the submarine sonar, and the bearing of the target ship evaluated from a test ship. The evaluation provides the error between the true and test bearing. Figure 11(d) illustrates the operation test of the developed torpedo, with the suitability, efficiency, viability, fatality, and safety of the system being evaluated based on the test results. In this experiment, the torpedo launch procedure was tested as an evaluation scenario to determine the correct operation. The procedure test for torpedoes was used to verify that an event was triggered at each stage after the torpedo was launched.

TABLE 3. Experimental parameters.

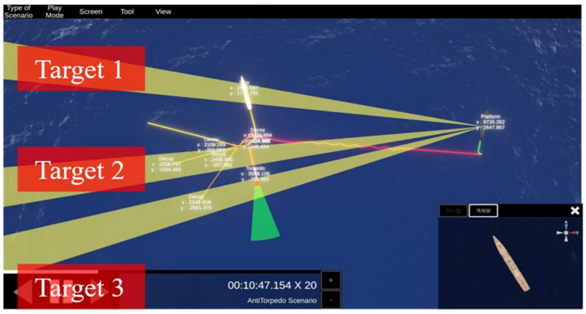
Scenario	Parameters
Operational requirement and analysis	Platform models: surface ship, submarine, torpedo, decoy Sensor model: sonar detection radius
Development V&E	Platform information: submarine Sensor model: radar Mathematical model
Operation V&E	Platform information: surface ship, submarine, torpedo Event message visualization

The parameters for each scenario were defined according to the experiment, as listed in Table 3. The requirements and operational validation scenarios mainly included detailed models to visualize information related to the maneuver model of the object (i.e., surface ship, submarine, torpedo, or decoy) and sensor (i.e., sonar) model. The development V&E scenarios added mathematical models to the existing models to calculate the bearing accuracies of radar sensors. The operation V&E scenarios were used to verify the system behavior according to the procedure designed mainly for testing the launch procedure of wire-guided torpedoes. The existing object model and event message visualization were used to monitor the procedure after torpedo launch to support analysis.

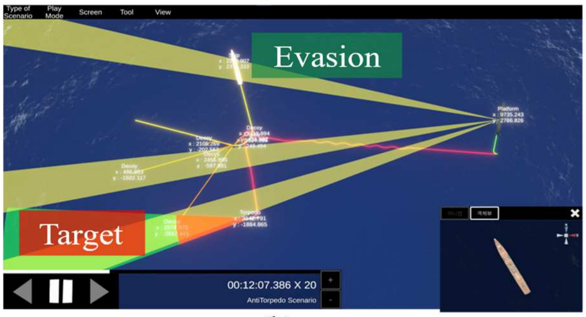
B. SIMULATION DATA-BASED V&E

Figure 12 presents the results of a simulation validation of the evasive maneuver of a surface ship using DVES. Figure 12(a) shows the initial phase of the simulation. The submarine detected the surface ship as a target and fired a sonar-equipped torpedo to detect the target. The acoustic detection system of the surface ship detected the approach of the torpedo and fired a total of three acoustic decoys, which confused the detection system and gave the torpedo three more targets. The torpedo then used target assignment to track the most probable target.

In addition to using acoustic decoys to evade torpedo attacks, surface ships also find it effective to utilize evasive maneuvers simultaneously. Figure 12(b) illustrates the use of acoustic decoys and evasive maneuvers in the middle of the simulation. The evasive maneuver primarily directs the position of the surface ship away from the torpedo; therefore, the surface ship is excluded from the target of the acoustic decoy and is spared from the torpedo attack.



(a)



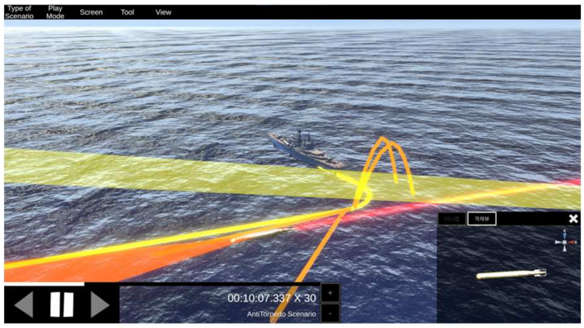
(b)

FIGURE 12. DVES screenshots of surface ship evasive maneuvers. (a) Submarine target detection. (b) Surface ship evasive maneuvers.

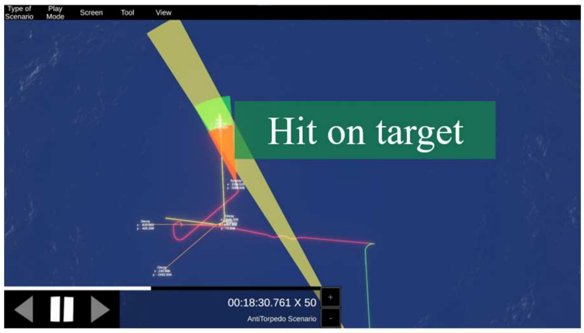
Figure 12 shows that the simulation validated and analyzed the acoustic decoy utilization tactics and evasive maneuvering tactics of the surface ship. For example, questions such as whether the timing of the acoustic decoy launch of the surface ship was appropriate or whether the evasive maneuvering approach was appropriate based on the torpedo position can be analyzed. This is expected to enable operators to analyze tactical simulations more efficiently.

Figure 13 presents the validation results of an attack scenario against a wire-guided torpedo that overcomes the weaknesses of a straight torpedo. Wire-guided torpedoes can utilize the acoustic detection system of a submarine to guide them to the desired target. This is possible because the performance of the acoustic system of the submarine is better than that of the acoustic system of the torpedo.

Figure 13(a) demonstrates that at the beginning of the simulation, the torpedo approached the detection radius of the surface ship and fired an acoustic decoy as an evasive maneuver; however, the torpedo target was wired to the submarine and could not be jammed, assigning the surface ship as the target. After that, the surface ship could not evade the torpedo, even if it utilized evasive maneuver tactics. In the end, the torpedo traced and caught the surface ship, validating the effectiveness of wire-guided torpedoes in jamming.



(a)



(b)

FIGURE 13. DVES screenshots of submarine attack tactics. (a) Evasive maneuvers of suspicious ships using decoys. (b) Attack using a wired-guided torpedo.

C. REAL DATA-BASED V&E

Real data were also used in the V&E of combat systems to obtain experimental results, as illustrated in Figs. 14 and 15. In Figure 14, the test line detects the target line, calculates the azimuth measured through the evaluation model, and displays the measured azimuth and direction (green and red lines, respectively). The lower part of Figure 14(a) shows the V&E scenario measured from time $t = t_0$ to time $t = t_0 + t_1$, and the upper part shows that the same scenario was performed using the proposed system. Figures 14(b) and 14(c) present the results of the radar performance evaluation. The time series shown in Figure 14(b) is the radar performance evaluation obtained using (3) and (4), which reveals the error between the detected and actual values of the radar. The current error is an important factor that can evaluate the performance of the radar at the current moment. However, not only the current performance evaluation error, but also the accumulated performance evaluation error is needed, because it is the performance evaluation indicator for the unit time of the experiment. The accumulated performance evaluation of the radar is depicted in Figure 14(c), showing that the performance

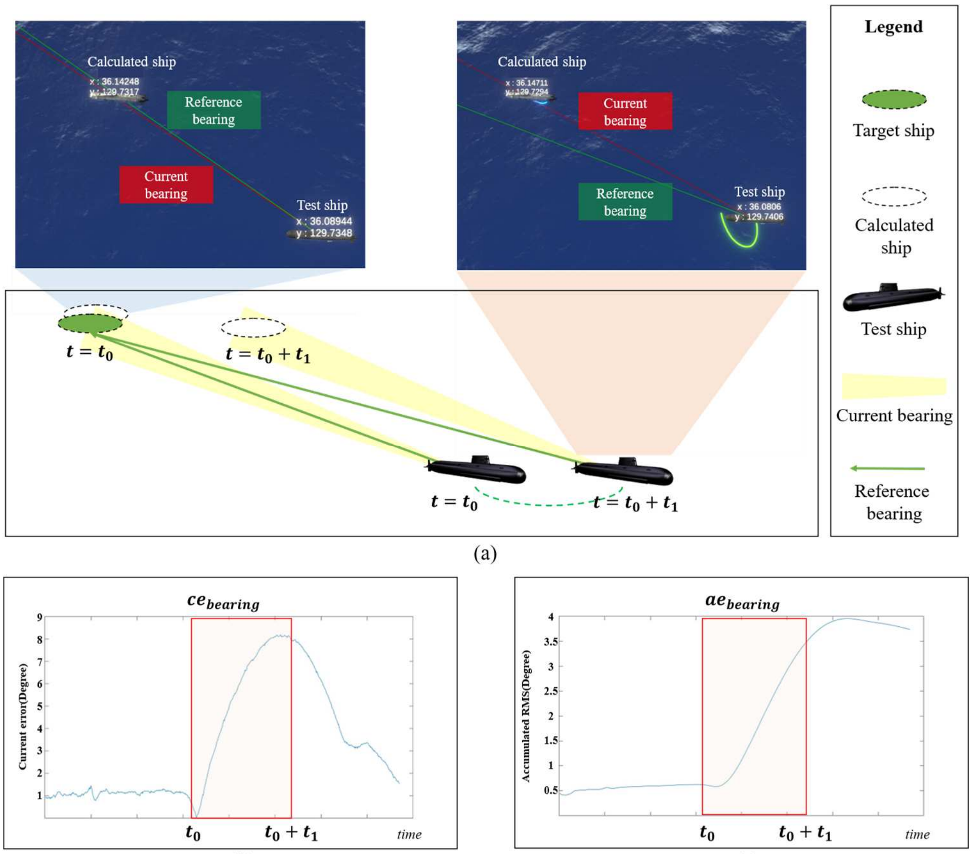


FIGURE 14. DVES screenshots for measuring the bearing accuracy of sensors. (a) Evaluation scenario for radar's accuracy. (b) Measured evaluation loss($ce_{bearing}$) of radar. (c) Measured total evaluation loss($ae_{bearing}$) of radar.

TABLE 4. Experimental results extracted from DVES.

No.	Time (UTC)	B_{ref} (°)	B_{exp}(°)	$ce_{bearing}$(°)	$ae_{bearing}$(°)
1	2021-01-20 04:48:07	351.742	352.2976	0.55561	1.08673
2	2021-01-20 04:48:34	350.821	352.2976	1.4766	1.087078
3	2021-01-20 04:49:02	349.835	352.2976	2.462623	1.128011
4	2021-01-20 04:49:29	349.172	352.2976	3.125618	1.212841
5	2021-01-20 04:49:57	348.471	352.2976	3.826607	1.338115
6	2021-01-20 04:50:25	347.797	352.2976	4.500618	1.496855
7	2021-01-20 04:50:52	347.135	352.2976	5.162605	1.679234
8	2021-01-20 04:51:20	346.725	352.2976	5.572609	1.876577
9	2021-01-20 04:51:47	346.204	352.2976	6.093605	2.078279
10	2021-01-20 04:52:15	345.739	352.2976	6.558601	2.289018
11	2021-01-20 04:52:42	345.285	352.2976	7.012611	2.501643
12	2021-01-20 04:53:10	345.076	352.2976	7.221626	2.705202
13	2021-01-20 04:53:37	344.658	352.2976	7.639625	2.942217
14	2021-01-20 04:54:05	344.44	352.2976	7.857612	3.135889
15	2021-01-20 04:54:32	344.257	352.2976	8.040626	3.321621
16	2021-01-20 04:55:00	344.125	352.2976	8.172615	3.496039
17	2021-01-20 04:55:27	344.163	352.2976	8.13462	3.656807
18	2021-01-20 04:55:55	344.18	352.2976	8.117622	3.803971
19	2021-01-20 04:56:23	344.37	352.2976	7.92762	3.937046
20	2021-01-20 04:56:50	344.426	352.2976	7.87162	4.05527
21	2021-01-20 04:57:18	344.649	352.2976	7.648628	4.159573
22	2021-01-20 04:57:20	344.999	352.2976	7.298622	4.247108

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is good at the beginning and gradually degrades after time $t = t_0$.

To further explain Figure 14, at $t = t_0$, the reference bearing and the current bearing point to the same target; therefore, a slight error can be observed between the detected vessel and the target vessel. If the test line is moved and the reference bearing is updated, the current bearing must also be updated. However, the current bearing has not changed at all, and accordingly, the $ce_{bearing}$ and $ae_{bearing}$ values rapidly increase. Table 4 shows the calculated values and performance evaluation indicators of the radar from $t = t_0$ to $t = t_0 + t_1$, indicating that the current bearing does not change. In Table 4, the largest values of the current and cumulative calculation errors are displayed in red for use in the performance requirements. Moreover, simply by analyzing using the evaluation indies $ce_{bearing}$ and $ae_{bearing}$, it is not possible to know exactly which system is the problem. This information only be obtained by analyzing the raw data of the sensor. However, the proposed system can help operators make decisions by simultaneously visualizing all real, multivariate data.

Furthermore, through the above experiments, the cumulative performance evaluation index of the sensors can be measured using the system proposed in this study, which can be utilized in the system test phase of the V process. Consequently, the proposed system can also be utilized to set the performance criteria required for systems to be developed in the future.

FIGURE 15. **DVES screenshot of engagement procedure using multiple wire-guided torpedoes.**

A launched torpedo may detect the host submarine and attack it. This situation can be prevented by performing the fire-and-forget operation. At some distance, a launched torpedo does not detect any object to prevent self-attack, which is an important procedure to avoid attacking the host submarine. After the torpedo travels a certain distance, it starts detecting the target using its sonar and selects a guidance method. Torpedo induction is divided into collision-path and bearing-rider methods. If the speed and path of the target are known, the collision-path method predicts the foreground angle and induces it to the impact point of the target. The bearing-rider method induces torpedoes to be placed on the target defense line if they know the target direction. In the corresponding experimental scenario, we used the collision-path method for the torpedo to adjust the depth, speed, and guidance modes depending on the target location. Then, the operator selected detection through a wired or internal detection sensor and hit the target.

The above procedure test involved the following items: 1) safety distance passed, 2) torpedo sonar active, 3) guidance with collision path method, 4) desired depth of 5 m, 5) high desired speed, and 6) internal guidance. Figure 15 shows the results of the system evaluation by generating events over the torpedo-launch procedure. In Figure 15, event 1 represents that the safety distance has been passed and the torpedo sonar is active, and event 2 represents the guidance method, desired depth, desired speed, and guidance mode. All steps of the torpedo launch procedure were sequentially and correctly performed.

D. DISCUSSION

This experiment was conducted to confirm V&E for all phases of the V process for a combat system. For this experiment, simulation data for the combat system requirements and real data from a combat system were used. The simulation data validated the torpedo engagement effectiveness of surface ships and submarines. The experiment successfully validated the evasive maneuvering tactics of surface ships and the detection jamming tactics using acoustic decoys, as well as the attack tactics using wire-guided torpedoes of submarines. The experiment utilized the Unity Engine and was more effective because detailed parameters such as the six degrees of freedom of the attitude and speed of the object could be expressed in a 3D environment. The results showed that the requirement analysis procedure of the V process was successfully performed.

Next, the real data were used to evaluate the performance of the radar and the integrated operation system. This experiment had two characteristics. First, by utilizing the interoperable collection module, data from the actual system can be acquired in real time for V&E. Second, both mathematical and graphical analysis of performance evaluation is possible by utilizing the V&E module. The radar performance evaluation experiment simultaneously displayed the computational and graphical results of the HARVERSINE algorithm, enabling the operator to analyze the results of the performance evaluation more intuitively. In addition, the torpedo launch procedure test visualized the behavior of multiple subsystems operating in accordance with the procedure through event messages and guided lines, which has a positive effect on the integrated operation test.

The results of this study are significant because they demonstrate that both simulated and real data can be used to validate and evaluate the V process lifecycle of combat engineering systems. This objective can be achieved not only by validating and evaluating simulation data and real data independently, but also by validating and evaluating combined data. It can also be utilized in all phases of the V process, reducing the overall development time and cost by eliminating the need to configure separate software based on data.

V. CONCLUSION

In this paper, we proposed a DVES that can be applied to all phases of the V process of a combat system. DVES consists of a data collection module and a V&E module. The data collection module consists of a file system for acquiring simulation data and a DDS interface for acquiring real data. By utilizing the DDS interface, various subsystems can be expanded to increase the scope of V&E. In addition, the V&E module consists of a mathematical analysis model and a graphical model using Unity and has the advantage of being extendable to various mathematical models or graphical models by utilizing a hierarchical and modular design.

Simulated and real data from a submarine were used in the experiment. The experimental scenarios consisted of analyzing the impact of a simulated torpedo engagement between a submarine and a ship, evaluating the radar performance of the submarine, and testing torpedo launches. The experiment enabled analysis of items such as the maneuvering strategy, sensor accuracy, and operating procedures of the target system. However, verification of all items was limited because 3D modeling similar to a real scenario was not applied.

Nevertheless, we could intuitively analyze the maneuvering strategies, performance evaluation indicators, and procedural events, which are essential for verifying combat systems. This proved that DVES can be utilized from the requirement analysis step to the system integration step.

In addition, because both simulated and real data can be validated and evaluated, it can be expanded to various V&E scenarios in the future and will be highly valuable for reducing the system development period and cost by helping overcome the existing weaknesses through the integration of data-based V&E systems. Further, because combat systems are part of cyber-physical systems, the proposed DVES is expected to be applicable to large and complex cyber-physical systems.

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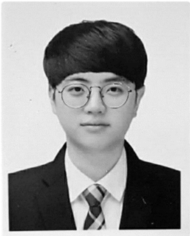

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