Simulator Environment Configuration for Integrated Threat Response and Evasive Maneuvers of Aircraft

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ABSTRACT

Novice pilots in formation flight operations often struggle with low mission success rates and survivability, emphasizing the need for an effective training solution. This study presents survivability, emphasizing the need for an effective training solution. This study presents the development of an advanced virtual training simulator designed to enhance pilot performance through an immersive and interactive environment. The proposed system integrates a high-fidelity flight simulator, tactical threat scenarios, and electronic warfare (EW) signal modeling.

Utilizing Mixed Reality (MR) technology, the training system combines virtual and real-world elements to provide a realistic and engaging experience. Pilots train with actual flight controls and instruments within a simulated cockpit, accurately replicating aircraft behavior, flight dynamics, and tactical maneuvers. The system enables pilots to improve formation flying, threat response, and decision-making in complex operational environments.

A key component of the simulator is EW integration, which allows pilots to experience realistic radar threats, jamming signals, and electronic countermeasures. By leveraging commercial modeling and simulation (M&S) software, the system generates adversary scenarios that closely resemble real combat situations. Additionally, tactical threat scenarios analyze enemy threat levels and operational areas, providing critical mission planning data. The system also prepares pilots for unavoidable in-mission events, ensuring effective decision-making under high-risk conditions.

The simulator records flight operations, tactical decisions, and EW threat responses in a structured database. This data-driven approach enables adaptive training by tailoring threat scenarios to individual pilot performance, addressing specific strengths and weaknesses.

This study presents the methods and processes for modeling adversary threat scenarios. By incorporating tactical and EW threat data, the proposed simulator improves mission success rates and pilot survivability, providing an effective training solution for modern air combat operations.

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INTRODUCTION

In modern military operations, Electronic Warfare (EW) and Electromagnetic Spectrum Operations (EMSO) have emerged as critical operational elements for achieving military objectives in complex battlefield environments, alongside the rapid development of advanced weapon systems based on electromagnetic technology. The Republic of Korea Armed Forces are accelerating the introduction of electromagnetic spectrum operations concepts across all services—Army, Navy, and Air Force. This transformation stems from the reality that enemy missiles, air defense networks, electronic warfare systems, and communication systems, as well as conventional combat assets, are becoming increasingly sophisticated through the application of advanced technologies, requiring corresponding defense systems to utilize diverse electromagnetic spectrums. The Korean military is actively pursuing integrated management and optimization activities for electromagnetic spectrum across all weapon systems, including communications, navigation, and sensors, to ensure freedom of action for friendly forces and expand operational domains in complex electromagnetic spectrum environments.

Particularly for the Air Force, numerous airborne and space-based weapon systems with high dependency on the electromagnetic spectrum are emerging. Unlike past weapon systems focused on standalone functions, integrated weapon systems connected through the electromagnetic spectrum are now competing across all domains, making them a critical factor determining the success or failure of air operations. The Republic of Korea Air Force needs to transition from traditional electronic warfare concepts to integrated electromagnetic spectrum operations. To achieve electromagnetic spectrum superiority, new approaches applying advanced technologies such as artificial intelligence (AI), big data, and data-link connectivity are required, moving beyond the conventional collect-distribute-use procedures. If the development of operational systems and operations applying electromagnetic spectrum operations concepts is delayed, manned fighter aircraft of the Republic of Korea Air Force during peacetime and wartime may face increased exposure to complex aerial threats, including detection risks from enemy air defense systems, enemy surface-to-air missiles, and air-to-air attacks from enemy aircraft. This could lead to an increased operational burden on mission pilots and reduced survivability.

BACKGROUND

Wargames and analytical tools are utilized as needed during mission execution to provide reliable data for decision-making purposes. However, these analytical tools have limitations in that they require considerable time and effort when adequate preparation is lacking. While situations requiring analysis can arise at any time, it is practically difficult to immediately construct and deploy analytical models suitable for emerging situations. To address these constraints, the effectiveness of wargames can be maximized by pre-defining wargame scenarios and their corresponding models, then analyzing them through minimal adjustments to fit actual situations. The importance and role of wargames are clearly presented in Lantto's (2022) research. The configuration and utilization of wargames have also been discussed in terms of Course of Action (COA) development. DeBerry (2021) presented more efficient COA development methods using automated COA analysis approaches compared to traditional human resource-based methods. When existing wargame tools are appropriately utilized according to purpose and timing, they can provide beneficial results through efficient situation construction and offer significant assistance in decision-making processes.

However, initial modeling and scenario construction consume substantial time and resources, limiting practical field applications. Therefore, wargame operations must be constructed rapidly and accurately, and personnel participating in operations must contribute based on accurate information from their respective areas of expertise. Through this approach, COAs, combat power analysis, and operational plan validity can be analyzed and utilized as reference materials in decision-making processes (Lantto, 2022). Hagley et al. (2021) analyzed historical battles between the United Kingdom and Argentina using Monte Carlo methods with Command: Professional Edition®(CPE). Through this study, they derived meaningful results by analyzing the effects of aircraft loadout configurations during combat scenarios.

Interest in electronic warfare has recently increased, and electromagnetic spectrum operations require a transition from existing operational concepts to modern warfare concepts, as mentioned in the introduction. Zhang and Xie (2024) conducted research on utilizing wargame tools for electronic warfare. Their research proposed a framework for battlefield support decision-making in electromagnetic spectrum environments, presenting rapid evaluation of action plans and military operation support methods in complex electromagnetic spectrum situations.

In such complex modern warfare situations, practical threat assessment and response capabilities are essential for the successful execution of electromagnetic spectrum warfare. Threat assessment of enemy threats during mission execution is a critical factor in determining mission execution sequences. Particularly for missions conducted in multi-domain operational environments under complex electromagnetic spectrum situations, threat assessment should be prioritized, and courses of action (COAs) should be determined based on analysis results. This requires preliminary weapon system threat models and electronic warfare models for mission execution. Criteria and methods for scenario and model construction are presented in Roux and Van Vuuren (2008), which also provide guidelines that must be followed during model construction. The most important guideline for model construction is to start with small and simple threat categories when configuring systems, and to configure resources deployed for scenarios and missions as simply as possible. Complex system configurations make wargame models and electromagnetic analysis models complex and impractical.

Research is actively being conducted to maximize the capabilities of mission personnel by applying analytical data to 3D environments. Particularly for the Air Force, training in virtual environments has shown significant effects due to special training environment requirements (Team Orlando News, 2025). Schaffernak et al. (2022) analyzed the validity and effectiveness of training methods in 3D environments through three approaches and verified their effectiveness. Wang (2022) researched the application methods of virtual reality/mixed reality in flight training and analyzed appropriate approaches for flight training between virtual reality and mixed reality environments through experiments. He suggested that mixed reality-based flight training could be a better alternative as it provides immersion and enables highly focused training.

This paper discusses methods for effectively addressing situations where novice and intermediate pilots performing missions in electronic warfare and AI collaboration scenarios face difficult-to-control situations within the cockpit, expanding from existing traditional air force battlefield concepts. Additionally, this study aims to explain equipment configuration methods for mastering such coping methods. As shown in Figure 1, the necessary components for implementing functions to meet requirements were divided into three categories: (1) input/output environments accessible to pilots and flight simulation, (2) effects on equipment operating in threat radio frequency environments, and (3) effects on equipment operating in threat weapon environments. Literature reviews were conducted on methods for analyzing each situation to address each requirement. Flight simulation programs were used as technical tools to meet requirements, constructing mixed reality cockpit environments. The cockpit environment was configured with systems for external threat detection, including Radar Warning Receiver (RWR) and Multi-Function Display (MFD), which can obtain information about external threats. Ansys Inc.'s STK® (Systems Tool Kit), an electromagnetic environment analysis tool, was used for threat radio frequency environment analysis, while CPE (Command Professional Edition), which can utilize databases for various weapons, was used for threat weapon system analysis.

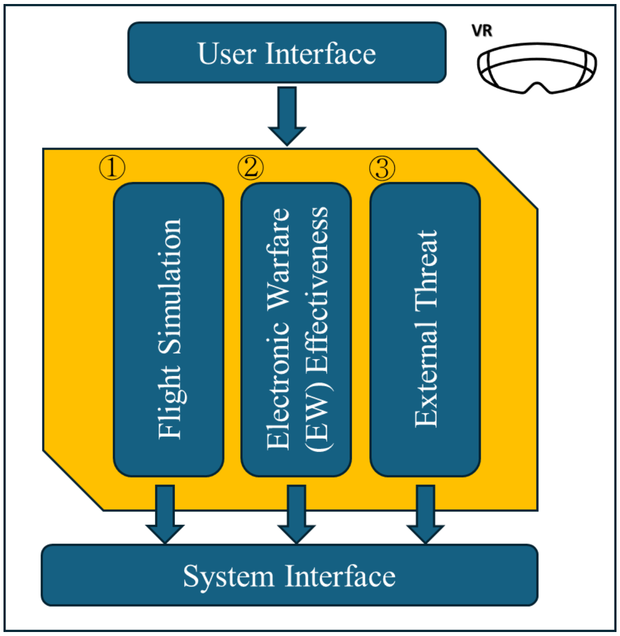

Figure 1. Integrated Training System Architecture

SOLUTION APPROACH

System Configuration

The Mission Engineering Guidebook was referenced as a method for evaluating impact in each component (Office of the Under Secretary of Defense for Research and Engineering, 2023). The interpretation and analysis processes of complex domains were decomposed into individual domains and classified as independent functions or analysis areas. Each functional component was designed with six elements: user input, external threat information, flight simulation, electronic warfare effectiveness, threat equipment information, and system interface. These components can be categorized into three modules that represent their functions. The first module, "User Interface," is responsible for receiving control input from users and operates by constructing a cockpit environment using Mixed Reality to create an environment similar to actual training processes. The second module, "Electronic Warfare (EW) Effectiveness," is responsible for evaluating the impact of electronic warfare environments during mission execution. This module is designed to examine detection effects from enemy radar systems, using STK to model radars for mission environment configuration and simulating the electromagnetic environment that friendly aircraft encounter during mission environments and mission duration. The third module, "Threat Equipment Intelligence," analyzes the degree of damage that threats can inflict when adversaries create threatening situations using weaponry, with models constructed using CPE. Each model is configured to evaluate threat levels that friendly assets may encounter in electromagnetic environments and weapon system environments when penetrating enemy territory by deploying enemy threat assets in identical positions and assessing their impact.

Building Scenarios

An identical scenario was constructed with the mixed reality simulator to assess the impact of threat weapons and threat radio frequency propagation in mission environments where pilots participate. The mission used for analysis is as follows: A scenario was constructed where friendly (BLU team) fighter aircraft depart from an arbitrarily defined starting point A on the map, pass through threat equipment, and arrive at target point B. A simplified scenario passing through threats was designed to verify the functional validity of pilot assistance devices.

Figure 2 consists of ground threat positions, belt areas representing arbitrary departure points, and target points located in the rear. The configuration of Surface-to-Air Missile (SAM) sites can be examined in detail in Figure 3. Each SAM battery possesses one missile, and six batteries were modeled to constitute one SAM site. The total number of available missiles from the SAM site was limited to six. This configuration was designed to be similar to the weapon system operations of actual SAM sites in operation.

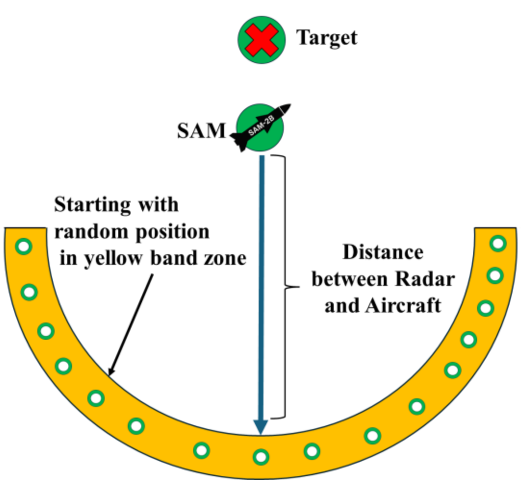

Figure 2. Initial deployment and threat configuration of the scenario

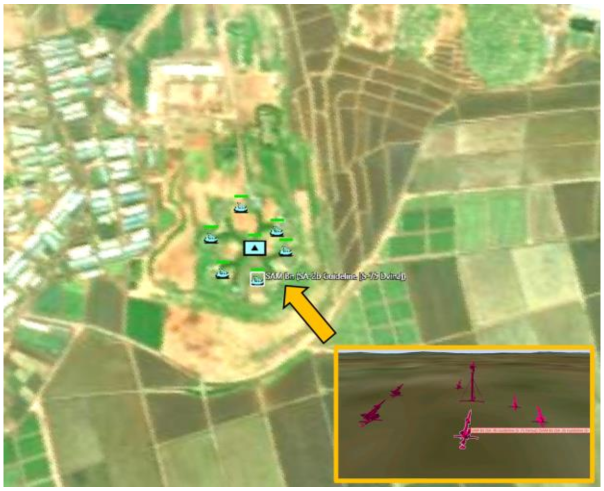

Figure 3. Deployment of threat weapon systems

Threat radio frequency environment analysis models and threat weapon system analysis models were constructed based on the layout configured in the scenario. As described by the Office of the Under Secretary of Defense for

Research and Engineering (2023), system metrics must be established to evaluate functions and performance of the overall system. The baseline operational environment is maintained consistently, with environmental settings applied uniformly across all function and performance evaluations. However, separate programs and tests were used to conduct analyses in respective areas according to the specific functions and performance being evaluated.

Flight Simulator

The flight simulator possesses the capability to receive user inputs and share data with analytical tools that perform other functions. As the sole interface through which users can interact, the flight simulator must be configured to closely resemble the actual user environment. Programs that constitute the piloting environment have achieved significant recent developments, enabling the construction of environments that implement mixed reality using various VR equipment. Visual and tactile elements were emphasized to maximize user immersion when using the device.

Components that pilots can contact visually or tactilely were designed to consist of products as similar as possible to actual aircraft to provide immersion. Considering functional and cost aspects, the control stick (grip) component adopted the F-16 Side Grip component from Real Simulator. Multiple VR headset products were also reviewed for the same reasons. To conduct this research, products incorporating field of view, refresh rate, and eyeball tracking functions were required. The VIVE Focus Vision product was selected to configure the system for implementing mixed reality. Additionally, products including passthrough camera functionality were selected to implement the mixed reality model. As mentioned in Wang's (2022) research, mixed reality training processes were determined to provide greater immersion and enhance learning effectiveness.

For the flight simulation program, a program with compatibility that could effectively represent F-16 flight characteristics was selected to configure the system.

Weapon System Threat Environment

Figure 4. Layout of threats and aircraft

Models were constructed using wargame tools to examine the impact of threat weapon systems. The tool used in this study was CPE, which provides a reliable database for weapon systems and was determined to be a useful program for wargame analysis. The deployment of F-16 and threat weapon systems was configured based on the constructed scenario. Positions were placed at arbitrary locations without establishing special assumptions. As shown in Figure 3, the friendly force (BLU team) was organized with one F-16 aircraft, while the enemy force (RED team) was organized with six SA-2b missiles, including search/track radar and tracking radar. The distance between the F-16 and the radar site was positioned at approximately 23 nm. In Figure 4, the red line represents the anti-aircraft firing range of the missile site, and the yellow line indicates radar detection area of F-16. This scenario defines a mission where the aircraft must proceed from a specified origin to a target destination while penetrating hostile radar and missile defense systems. The scenario aims to analyze available evasion strategies and quantify the extent of potential casualties incurred during the mission. The F-16 was modeled for two cases. BLU 1 was configured as a model with the F-16 equipped with chaff/flare dispensing equipment. BLU 2 was configured as a model without countermeasures. Detailed model configurations are presented in Table 1.

Table 1. System components assigned to each force

	BLU1	BLU2	RED
Aircraft	F-16 x 1 unit with DECOY	F-16 x 1 unit	-
Facility	-	-	- SA-2b x 6 rounds - Search/Track Radar x 1 station - Tracking Radar x 1 station

Electromagnetic Threat Environment

Enemy threats were configured into two major categories: one search/track radar capable of long-range detection and one tracking radar capable of acquiring targets within weapon system engagement range. The enemy threat phases consist of three major stages. The first stage involves examining the approach speed and direction of objects as unidentified objects approach. The second stage involves preparing for engagement with tracking radar when penetration occurs within self-defense range. The final stage involves executing engagement after target identification. The performance characteristics of radars used for electromagnetic environment modeling are summarized in Table 2. The radar performance data were compiled based on data described in CPE's weapon database.

In this study, the long-range search radar was configured as the previously mentioned search/track radar, and a radar with an effective detection range of 150 nautical miles was selected. The radar system used for analysis consisted of one search/track radar capable of aircraft detection and one tracking radar capable of aircraft tracking.

Table 2. Data for Radar System Configuration

	Search/Track	Tracking
Frequency	150-170 MHz ("A" Band)	5.01-5.06 GHz (G-band)
PRF	360 Hz, 310-400 pps	1656-2880 (track) pps
Power	350 kW (peak)	1.5 MW (peak)
Range	150 nm	80 nm

To verify the actual effective detection range of the radar, targets and radars were modeled to calculate the effective radar detection range. The search/track radar achieved initial detection at approximately 70 nautical miles upon approach of friendly F-16 aircraft, while the tracking radar detected at 7 nautical miles. Although the tracking radar detection distance specifications presented in CPE indicate long-range detection capability, the modeling reflected actual radar operational methods that operate actively after recognizing approaching targets according to Rules of Engagement (ROE) in real operational environments, detecting approaching aircraft at shortened detection distances compared to design specifications.

Figure 5 shows the F-16, search/track radar, and tracking radar modeled for electromagnetic environment analysis. The purple area represents the detectable range of the search radar, while the yellow area represents the state where the tracking radar has initiated tracking and detected the aircraft. When aircraft enter within the weapon system's engagement range, the tracking radar activates and was modeled to immediately track aircraft according to fire control ROE. The blue line represents the F-16's flight path. After the F-16 penetrates within the tracking radar's operational range and passes through the area where both radars are activated, it follows fire control procedures according to ROE.

Figure 6 shows Radar Cross Section (RCS) calculations that were computed and input for detection value calculations when the F-16 is detected. Through this process, when the F-16 is detected while moving near the radar, the Probability of Detection increases. Consequently, conditions for missile launch are established through the process of object recognition and detection.

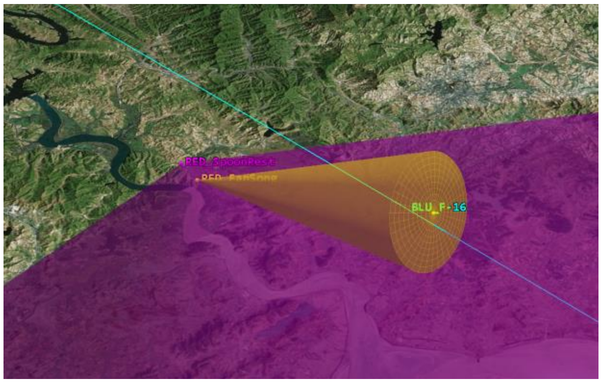

Figure 5. Two radars detect the BLU team aircraft in flight

Figure 6. F-16 with RCS pattern

ANALYSIS RESULTS

Flight Simulator Analysis

An Evasive Guidance System (EGS) was configured in the flight simulator to support evasion when missiles are launched. Survival times were compared and analyzed between cases where the EGS was used and not used for three groups: civilians with no prior flight experience (NOVICE), individuals with flight experience of less than 100 hours (JUNIOR), and pilots with more than 1,000 hours of flight experience (ACE). This analysis aims to verify the effectiveness of Evasive Guidance System usage.

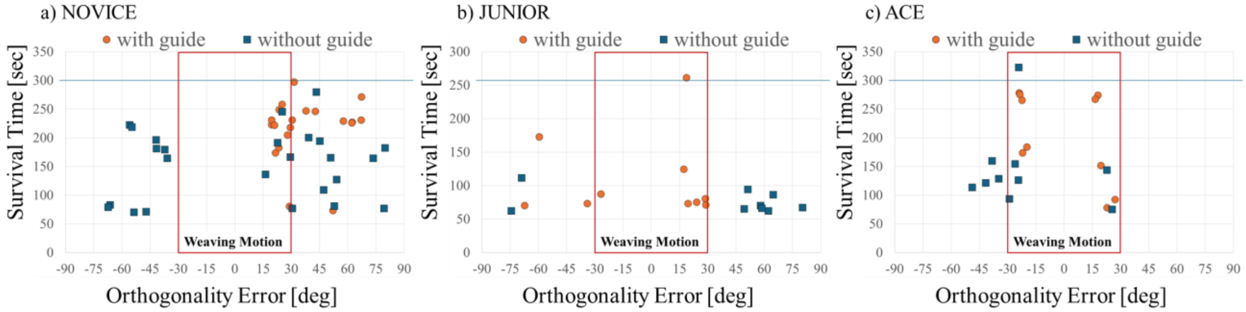

Figure 7. Analysis of Average Survival Time Performance with/without the EGS by Flight Experience a) NOVICE, b) JUNIOR, c) ACE

Figure 7 compares survival times when the EGS was applied and not applied according to flight experience. The weaving motion areas indicated in each chart represent sections where the aircraft is flown while evading threats by shaking the aircraft left and right when threats are detected or encountered during flight. In the case of NOVICE, there is an overall tendency to evade to the right during flight, and it can be observed that flight time increases when the EGS is provided. This is because the missile base is located on the left side in the scenario setup, and the missile approach direction is from the left, resulting in a tendency to evade to the right during evasive maneuvers. JUNIOR shows overall short survival times, which was identified as being due to insufficient adaptation to the simulator and VR environment. However, when the EGS was used, it can be observed that appropriate threat evasion maneuvers were performed in the weaving motion areas. In the ACE case, survival time is clearly extended when the EGS is used. Additionally, when the EGS was used, threat evasion was conducted in appropriate weaving motion areas.

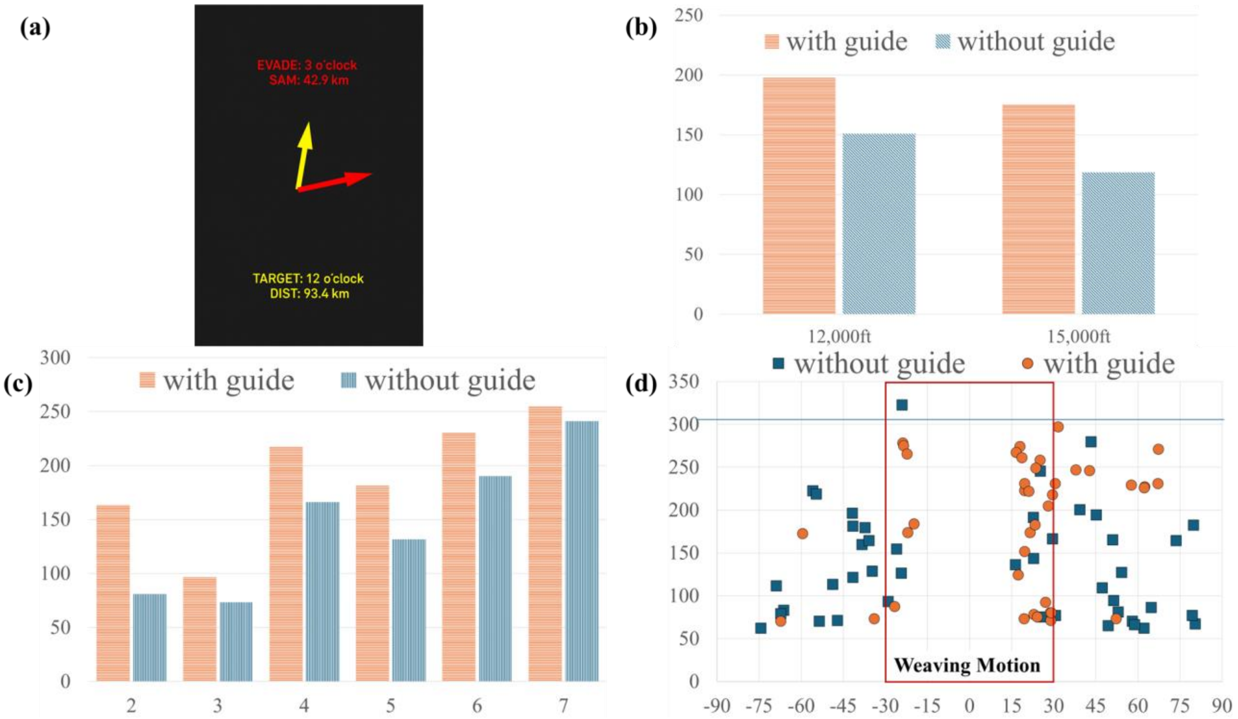

Figure 8. Analysis of performance with/without EGS to Average Survival Time(a) EGS, (b) Analysis of Altitude and Average Survival Time with/without EGS, (c)Analysis of Missile Expenditure and Average Survival Time with/without EGS, (d) Analysis of Orthogonality errors and Average Survival Time with/without EGS

Figure 8 consists of four diagrams. (a) The EGS was configured and displayed in VR to enable pilots to find evasion routes when missiles approach. (b)-(d) present comparative results of average survival time differences between using and not using the EGS. The execution results for NOVICE, JUNIOR, and ACE shown in Figure 7 were compared to using initial altitude value, number of missile evasions, and orthogonality errors. Figure 8(b) shows average survival times according to aircraft initial altitude. Comparison of average survival times confirmed that the evasive guidance system was effective in extending average survival time. Figure 8(c) shows average survival time relative to the number of missiles launched, similarly confirming significant differences when using the guidance system. Figure 8(d) represents the angular difference between the angle guided by the evasive guidance system and the heading maintained by the pilot. Most extended average survival periods can be observed within the orthogonality error range of 50 degrees or less. The red box area represents the -30 to +30 degree range where appropriate weaving motion occurs during threat evasion. When the EGS is used compared to when it is not used, the data points are displayed inside the box. This indicates that the EGS is effectively guiding pilots.

Electromagnetic Systems Threat Analysis

Threat weapons against Air Force fighter aircraft are predominantly composed of guided weapons, necessitating concurrent impact assessment of Electromagnetic environments, specifically threat radio frequency environments. The threat radio frequency environment model configuration was established in an identical environment to the model configured in CPE to maintain consistency in model construction. Electromagnetic environment configuration was performed using STK. A radar system with identical configuration to CPE was constructed to evaluate the impact of electromagnetic environments. For fire control, STK was also configured to enable threat weapon launches under the same conditions. Figure 9 presents graphs analyzing detection signals when search/track radar and tracking radar are activated and deactivated.

Figure 9(a) shows the process of search/track radar initiating detection as distance decreases. The solid line represents search/track radar signals, while the dashed line represents tracking radar signals. Figure 9(b) presents a graph showing how long the aircraft was exposed to search/track radar and tracking radar during approach. Tracking w/Threat waits for the aircraft to approach within an effective launch range and activates when the aircraft approaches within a certain distance.

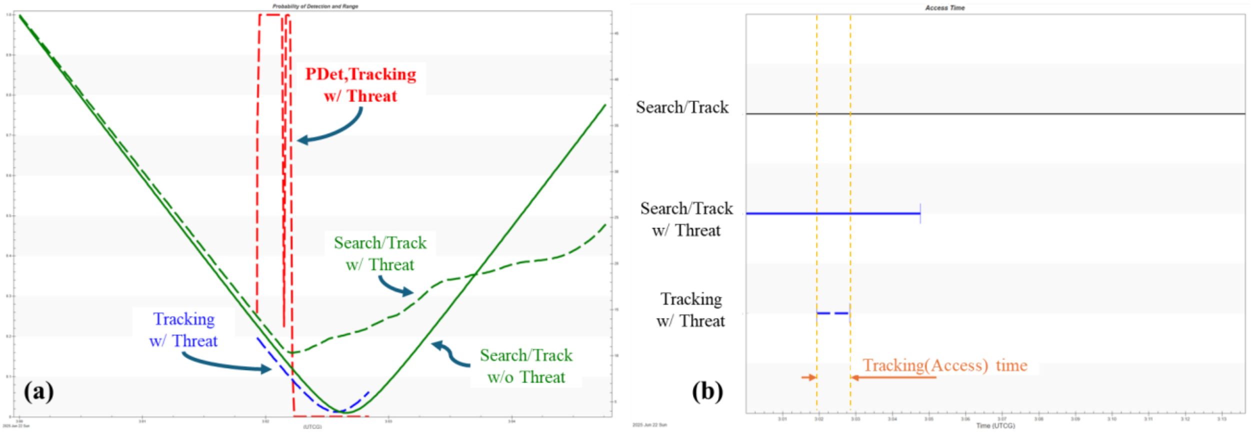

Figure 9. Computational Example: Electromagnetic Environment Assessment and Probability of Determination/Access Time Analysis

The Probability of Detection (PDet) ranges from 0 to 1. As the value approaches 1, the probability of aircraft detection by radar increases. As shown by the red dashed line in Figure 9(a), the detection probability value approaches 1 as the tracking radar activates. This indicates that the tracking radar has detected the aircraft and completed launch preparations. Consequently, the aircraft performs evasive actions, which can be observed in the green dashed line. After tracking radar activation, the aircraft initiates evasive actions and can be observed gradually increasing distance.

Weapon Systems Threat Analysis

One advantage of CPE, a wargame tool, is its support for tools that can statistically determine the validity of scenarios once conditions and environments are configured. Statistical approaches to evasive maneuvers in configured scenarios require conducting and processing numerous trials. This study aims to identify the extent of losses and damage based on the presence or absence of countermeasures by selecting a small number of sample cases. Two scenarios were configured for this purpose: one with countermeasures implemented and one without countermeasures. The configured scenarios utilized Monte Carlo analysis to identify losses and consumption of BLU team and RED team forces during scenario execution. Based on these findings, this study aims to establish methods for effective mission execution and procedures for analysis.

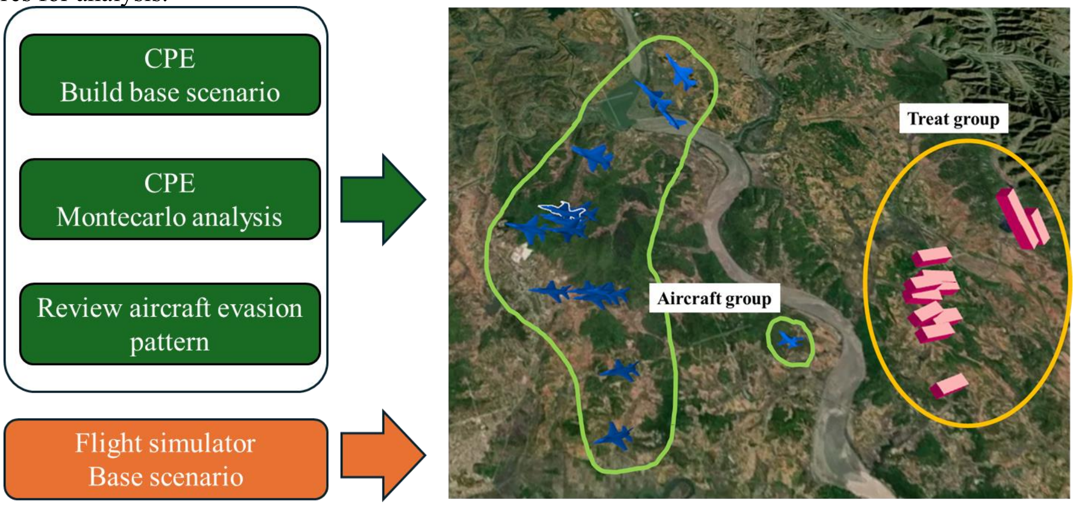

Figure 10. Aircraft evasion path against SAM missiles

The green-highlighted blocks in Figure 10 represent the process of conducting Monte Carlo analysis to assess the validity of equipment configuration environments between scenarios. The right screen displays Monte Carlo analysis results from multiple trials conducted within a single scenario. The Aircraft group represents the point at which evasive maneuvers are initiated to avoid missiles from the Threat group.

Table 3 Losses and expenditures of each force

	BLU		**RED**	
	w/o CM	**w/ CM (Chaff)**	**w/o CM**	**w/ CM (Chaff)**
LOSSES	**Fighter casualties: 1**	**-**	**-**	**-**
EXPENDITURE	**-**	**Chaff deployments: 39**	**SA-2b Missiles: 58**	**SA-2b Missiles: 60**

The results of the Monte Carlo analysis conducted in Figure 10 are summarized in Table 3. The RED team was configured with identical settings as established in Table 1, while the BLU team was differentiated to examine the effects of countermeasure implementation. Using identical scenario parameters, 20 simulation trials were conducted with 10 trials in each condition: without countermeasures (CM) and with CM equipped. In the non-CM condition, one fighter aircraft was destroyed during scenario execution. In contrast, the CM-equipped condition resulted in 39 CM deployments with zero fighter aircraft losses.

Notable findings include that 58 missiles were used when countermeasures were absent, resulting in fighter casualties. Conversely, when countermeasures were present, 39 chaff rounds were deployed by friendly forces without fighter casualties, while enemy missile usage reached 60 rounds, exhausting all missiles from the configured SAM site. Increasing the sample size for analysis is expected to yield statistically significant results that could demonstrate the effectiveness of countermeasures.

SUMMARY AND CONCLUSION

This study discussed methods for effectively addressing situations where novice and intermediate pilots performing missions in electronic warfare/AI collaboration scenarios face difficult-to-control situations within the cockpit. This system was designed with the purpose of training inexperienced pilots or pilots who have difficulty processing large amounts of information instantaneously to implement appropriate functions, and with the goal of improving survival rates by incorporating evasive capabilities. To implement a system for training these coping methods, system modules were configured into three components: (1) input/output environments accessible to pilots, (2) effects on equipment operating in threat radio frequency environments, and (3) effects on equipment operating in threat weapon environments. Each module was configured according to design intentions. For aspects that could not be perceived or attended to during actual piloting, learning about environments encountered during mission execution was implemented through debriefing. For mission execution based on given scenarios, it was confirmed that analysis functions for survival time increases, tracking radar tracking effects, and proper evasive routes were effectively configured.

This system has been developed to perform individual analysis processes. Future development plans include flight path selection, threat intensity indication, and synchronization of interactive programs. Therefore, it is anticipated that the completed system will be able to provide pilot evasion route evaluation and evasion route recommendation functions.

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