PAPER

HEAP-Based Defense Modeling and Simulation Methodology

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SUMMARY This paper proposes an agent-based modeling and simulation methodology for analyzing the tactical and operational effectiveness of warfare environment. To do this, we adopt the advanced agent modeling principle, HEAP (Hierarchical Encapsulation and Abstraction Principle), as well as the hierarchical modeling and simulation framework, SES/MB (System Entity Structure/Model Base). Proposed methodology is differentiated from other conventional agent-based defense M&S approaches in that; (i) it supports an intelligent hierarchical multi-agent architecture, (ii) it provides an efficient mechanism for analyzing the strategic and operational effectiveness of warfare environment between multiple platforms. The proposed methodology is successfully applied to the two by two warships warfare simulation for analyzing the tactical effectiveness.

key words: *HEAP, SES/MB, defense modeling and simulation*

1. Introduction

Increased attention has been paid in recent years to the need for the development and utilization of analysis techniques in advising defense personnel on strategic and operational effectiveness, either as individual platforms or in a wider mission context. Such analysis is conducted primarily for two purposes; (1) to contribute to the development of tactical and operational procedures and (2) to provide advice to defense personnel when new platforms and systems are being considered for acquisition. One means of conducting the above operational analysis is via the use of simulation. Usually such simulations comprise a complexity of interacting physical and human systems. There may be multiple types of military platforms. They might include weapons, sensors, commands and communication systems. Various operating conditions might be manipulated, such as the weather, the geography, the degree to which the naval force is under threat, etc. Human systems might include different numbers of friendly, enemy and a variety of crew roles [1].

An advantage in employing simulation is that it provides analysts and defense personnel with cost, time, and resource effective analysis tools. Unfortunately, the conventional human-based warfare simulation approach is extremely expensive and does not enable analysts to explore all aspects [1]–[7]. To overcome the limitations, agent techniques have been adopted in defense modeling and simulation research. In artificial intelligence, an intelligent agent is an autonomous entity which observes through sensors and acts upon an environment directing its activity towards achieving goals [8]. Agent, in general, can be defined as an entity or asset on battlefield, and it has its own behavior and personality that governs how it acts. The reason why defense requires agent-based modeling and simulation techniques may be summarized as follows; (i) Need to simulate flexible tactics/strategies; (ii) Currently only suboptimal maybe possible since the simulation result depends on the human's skill; (iii) Need faster speed than real time to test various alternative solutions; (iv) Need to minimize the mistake by human intervention.

Currently, there exist several agent-based systems: Irreducible Semi-Autonomous Agent Combat (ISSAC) [2], Enhanced ISSAC Neural Simulation Toolkit (EINSTein) [2], Map Aware Non-uniform Automata (MANA) [3], and Conceptual Research Oriented Combat Agent Distillation Implemented in the Littoral Environment (CROCADILE) [4]. Recently more advanced distillations called Warfare Intelligent System for Dynamic Optimization of Mission (WISDOM-II) [5] and OneSAF [6] has been introduced. They utilize agent-based methods to model combat based on the artificial life approach in which the main focus is to create a global behavior from local interaction between simple agents [7]. They can efficiently support an emergent simulation but not to solve the complex situation needed for the strategic and operational effectiveness analysis of military warship since their agent maintains no internal models and performs no search. To deal with this problem, BattleModel [1] for supporting the tactical decision-making and TAO ITS (Tactical Action Officer Intelligent Tutoring System) [9] for efficient officer training utilize intelligent agents as OPFOR (OPposing FORce or enemy force). However, these systems can only support simple logic-oriented script language or pre-defined state-machine model and so cannot easy solve complex problems such as the systematic analysis of the strategic and operation effectiveness of warfare environment between multiple platforms. To deal with this, we adopt the advanced agent modeling principle, HEAP (Hierarchical Encapsulation and Abstraction Principle), as well as the hierarchical modeling and simulation framework, SES/MB (System Entity Structure/Model Base). HEAP supports a systematic basis to design a hierarchical intelligent agent architecture in which the knowledge is encapsulated in the form of models that are employed at various control layers to solve the predefined system objec-

Manuscript received March 2, 2012.
Manuscript revised October 12, 2012.
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DOI: 10.1587/transinf.E96.D.655

tives [10]–[12]. The SES/MB framework was proposed by Zeigler as a step toward marrying the dynamics-based modeling formalism of simulation with the symbolic formalism of artificial intelligence [13], [14]. By combining both advanced agent modeling techniques, we are able to propose a multi-agent based modeling and simulation system for analyzing the strategic and operational effectiveness of multi-platforms warfare.

2. Review on HEAP

To cope with complex objectives, an autonomous system requires integration of symbolic and numeric data, i.e., reasoning and computation. A pure AI approach is too qualitatively oriented to handle quantitative information very well. For example, classic AI planning approaches [15]–[17] do not consider the timing effects, which should be of primary concern in representing our dynamic world. On the other hand, control researchers have a fairly narrow view-point, so that they mainly focus on refinement rather than robustness of a system [18], and they usually consider only the normal operational aspects of a system. However, autonomous systems have to deal with abnormal behavior of a system as well. Thus, it is crucial to have a strong formalism and an environment that allows coherent integration of symbolic and numeric information in a valid representation process to deal with a complex dynamic world. Approaches to design various autonomous component models for planning, control, and diagnosis have previously been developed in their respective research fields so that there are many overlaps as well as inconsistencies in assumptions. In an integrated system, such components cannot be considered independently. For example, planning requires execution, and diagnosis is activated when anomalies are detected during execution. The HEAP proposed by Zeigler and Chi [10]–[12] provides a framework for developing task models related for autonomous agent systems.

Figure 1 illustrates an autonomous agent development approach based on the HEAP. As shown in the figure, each knowledge base for each agent can be extracted from real world data by using the knowledge mining process. Fuzzy set theory may be suitably adopted to extract the symbolic data for the knowledge base from the numeric data of the real world so that the abstraction-related modeling may be properly accomplished. By attaching the domain independent inference engine model with the domain dependent knowledge base model the intelligent unit is constructed. This means units at each level are encapsulated with the internal knowledge base models that are abstractions of coupled models composed of immediately inferior internal knowledge base models. Based on this hierarchical abstraction relation, the hierarchical execution architecture may be suitably developed [12], [19]–[22].

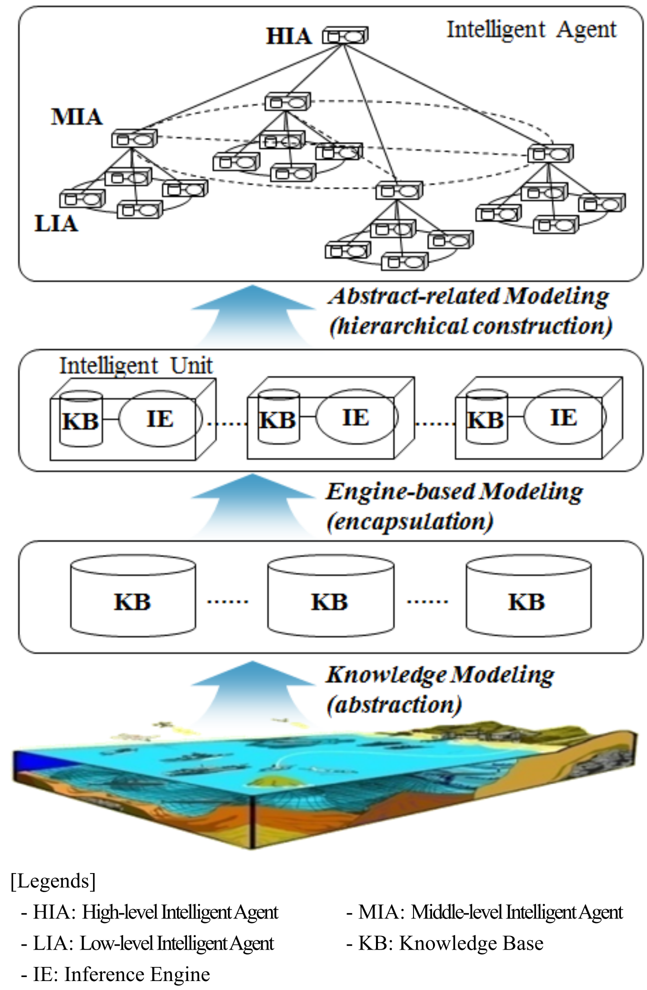


Fig. 1 HEAP concept.

3. Overall Methodology

The overall HEAP-based defense modeling and simulation methodology for analyzing the strategic and operational effectiveness is given in Fig. 2. The structural and behavioral models such as SES (System Entity Structure) models, knowledge base models, inference engine models, platform models and environment models can be developed and stored in the model repository through the Phase 0. Once the model repository is set up, then we are ready to start the goal-driven simulation process. The simulation goals, scope, requirements and constraints can be specified in Phase I. The SES that represents all possible warfare configurations is automatically pruned on the basis of the requirement specification to generate a PES (Pruned Entity Structure), a specific configuration to be simulated, in Phase II. Once the simulation model structure is determined, the next step is to generate the knowledge models based on the abstraction process as in Phase III. Then the inference engine models are attached to the corresponding knowledge models, respectively, resulting in the HEAP-based multi-agent architecture in Phase IV. Then, in Phase V, all component models for warfare simulation are transformed from model repository and attached to the simulation model according to the PES. The discrete event simulation may be

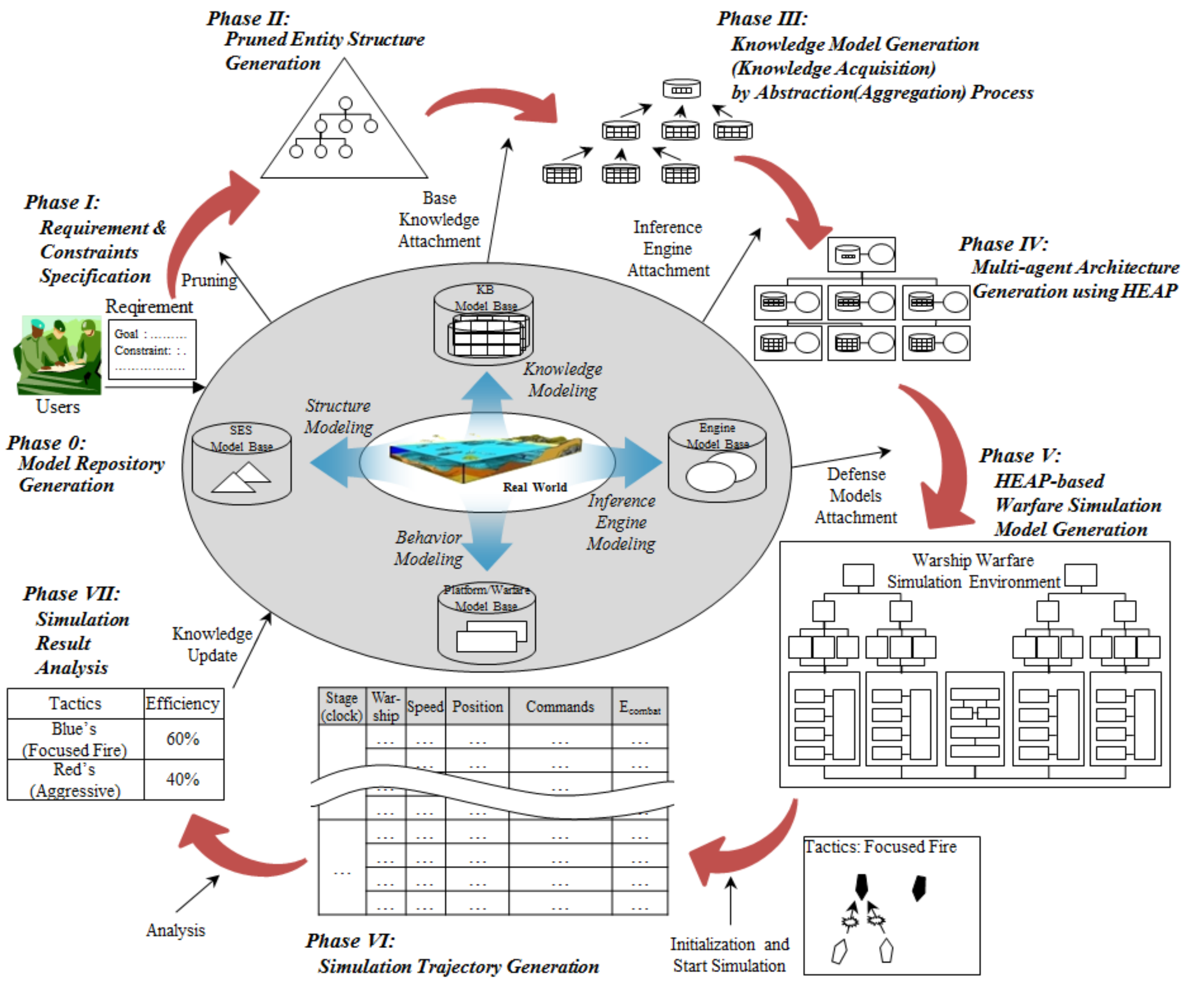


Fig. 2 The overall HEAP-based defense modeling and simulation methodology.

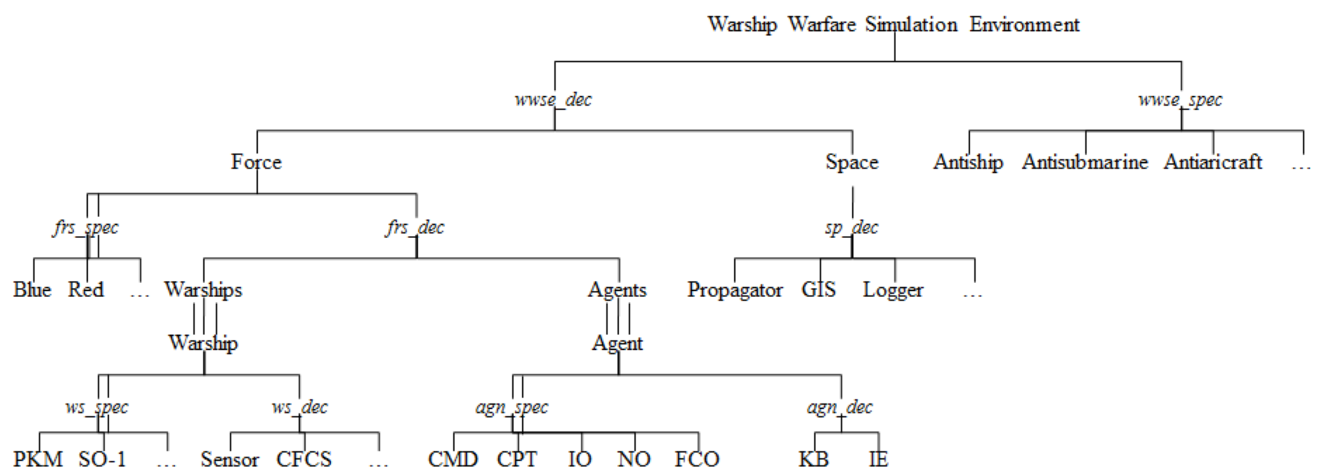
executed in Phase VI. The tactical efficiency analysis of the simulation result can be accomplished in Phase VII. In this way, the tactical analysis cycle using the HEAP-based modeling and simulation may be finally achieved by reporting the analysis result back to users.

· Phase 0: Model Repository Generation

This beginning phase is a modeling phase from the real world so that it requires the structural modeling, platform modeling and knowledge modeling. As a concrete example of structural modeling, consider the SES on Fig. 3. The root entity, warship warfare simulation environment, maybe decomposed into the 2 entities; Force and Space. Now the Force is specialized with Blue, Red, etc. and consisted of Warships and Agents. In this fashion, all possible structural models can be coherently established for later simulation. Every model, which is a leaf entity on the SES, should also be developed in this phase. Every behavioral model, such as warship model, agent model, space model, etc. is implemented by using the DEVS formalism.

· Phase I: Requirement & Constraints Specification

Once the model repository is constructed, the next step is the specification of the requirement and constraints, in which all simulation conditions including goals should be decided. In this case study, the simulation goal is the analysis of Blue's tactical efficiency in two by two warship combat, and other conditions are given in Table 1. Especially, both forces utilize the cooperation tactics; concentrative, consecutive, and parallel firing. The blue force initially takes defensive tactic, however, the red force has offensive tactic. For example, consider two red warships invade the border line. The IO (Intelligence Officer) of the blue warship confirms the invasion based on the sensory data. The IO immediately reports CPT (Captain) to "enemy's attack" message. Upon this report, the CPT decides the "move" command. After being moved toward red ships, the "threat shooting" command is made. In this way, the actual battle is initiated. Both red and blue forces have their own tactics based on their own goal and spec. The main focus of this simulation study is the effectiveness of the combat tactics.



[Legends]
- GIS: Geographic Information System, - PKM, SO-1: a kind of warships, - CFCS: Command and Fire Control System, - CMD: Commander,
- CPT: Captain, - IO: Intelligence Officer, - NO: Navigation Officer, - FCO: Fire-Control Officer,

Fig. 3 A SES example for defense modeling and simulation: Warship warfare simulation environment.

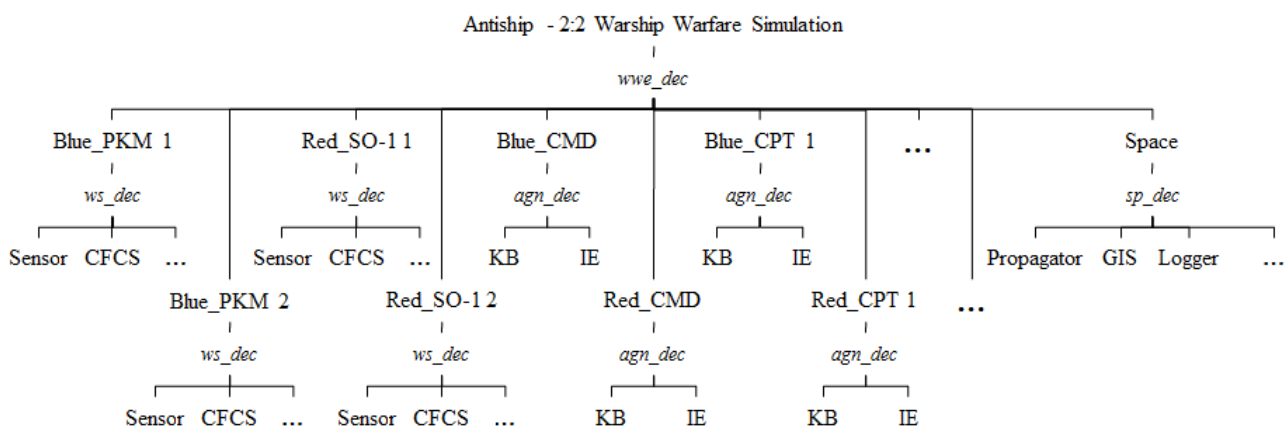


Fig. 4 A PES example from Fig. 4 for 2:2 warship warfare simulation environment.

Table 1 An example of requirement specification.

Requirements		Specification
Goal		Analysis of the Blue's Tactical Efficiency
Constraints	Blue Force	PKM-1, PKM-2
	Red Force	SO-1, SO-2
	Red Force Tactics	Cooperation Tactics (Offensive)
	Accuracy Rate	Full (40%), Half (30%), Fail (4%)
	Average Height of Wave	0.8m
	Combat Area	Western Sea of Korean Peninsula
	Efficiency	$E_{combat} = w_1 \cdot E_{damage} + w_2 \cdot E_{sp} + w_3 \cdot E_{pp}$
Alternatives	Tactics 1	Focused Fire
	Tactics 2	Avoidance

· Phase II: Pruned Entity Structure Generation

In this pruning phase, the structural and behavioral models are selected and constructed on the basis of the requirement specification in previous phase. The PES (Pruned Entity Structure) of given example is represented in Fig. 4, where our (Blue) warships, PKM, and enemy (Red) warships, SO-1, are selected. So that each warship is decomposed into the Sensor Model, CFCS Model, etc. and each agent system is consisted with the CMD (Commander), CPT (Captain), etc.

· Phase III: Knowledge Model Generation

The hierarchical constructions of KB (Knowledge Base) model for the intelligent agent can be achieved in this phase. To do this, the abstraction-related modeling maybe employed to create a higher-level knowledge base model from lower-level knowledge base models. That means the higher-level agent has more abstracted knowledge but the lower-level agent use more detailed knowledge, however, both knowledge have an abstraction-relation. as shown in Fig. 1. In this way, the abstraction-related knowledge base modeling can be accomplished in this phase.

· Phase IV: Multi-agent Architecture Generation using HEAP

In this phase, IE (Inference Engine) model is created and attached to the knowledge base model developed in previ-

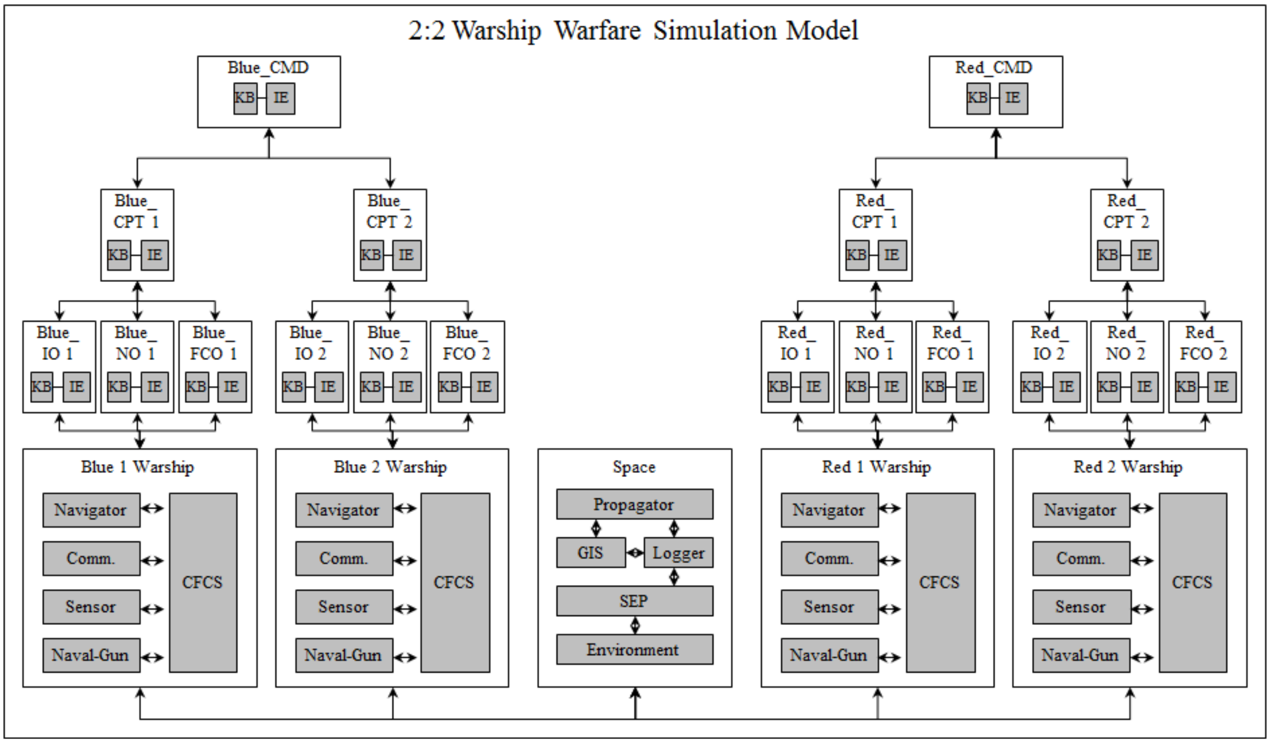


Fig. 5 A simulation model example for 2:2 warship warfare simulation.

ous phase. Basically, the IE model examines the knowledge base and decides the order in which inferences are made. The idea is exactly same as the typical expert systems which comprise a domain-independent inference engine and a domain-dependent knowledge base. Such an engine-based modeling approach provides a clear separation between the domain-dependent model base and the domain-independent inference engine. It facilitates the automatic generation of a model base using abstraction [12]–[14], [19].

· Phase V: HEAP-based Warfare Simulation Model Generation

Once the agent architecture is developed, then the final simulation model maybe accomplished in this phase, as depicted in Fig. 5, by extracting the warship models and warfare space models from the Model Base and attaching them to HEAP agent models (CMD, CPT, IO, etc.) according to the PES as shown in Fig. 4.

· Phase VI: Simulation Trajectory Generation

Now, we are ready to start simulation, in which the initial conditions are the same as in Phase I.

· Phase VII: Simulation Result Analysis

Blue's tactics (Focused Fire) for defending the offensive Red warships is analyzed through simulation as shown in Phase VII in Fig. 2.

4. Case Study: 2:2 Warship Crash in Western Sea of Korean Peninsula

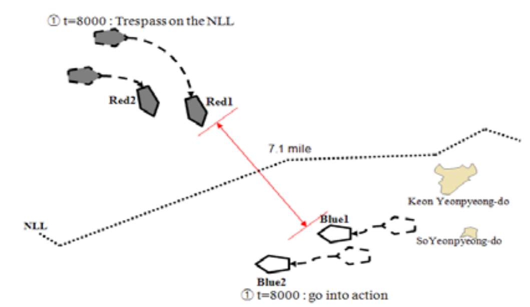
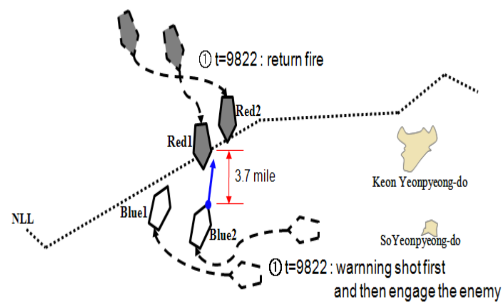
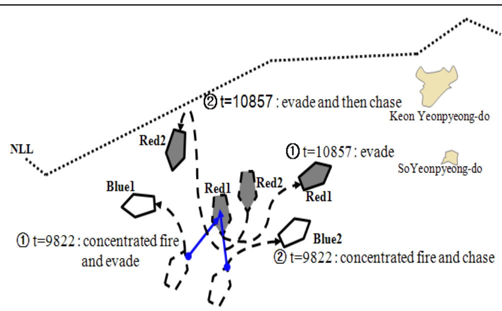
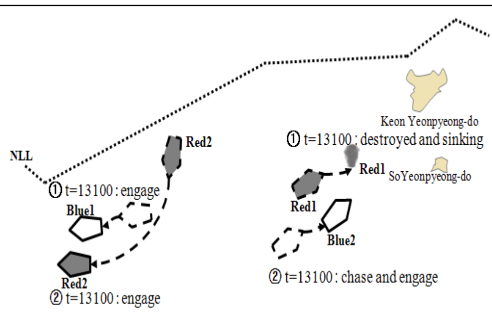
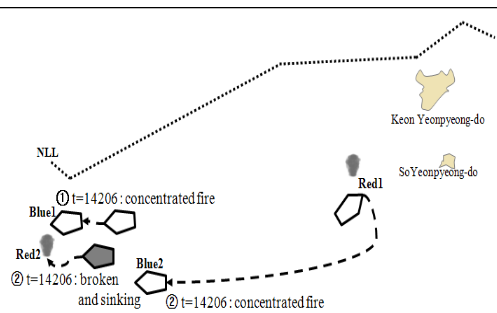
4.1 Simulation Scenario

To verify the feasibility of proposed methodology, we have considered the scenario which is reconstructed the outbreak of naval conflict happened on the west sea of Korean peninsula recently. In this scenario, two red warships (Red 1 and Red 2) invade together across the Northern Boundary Line. The IO (Intelligence Officer) of the Blue 2 warship confirms the invasion upon receiving the numeric sensory data. The IO immediately reports the "enemy's attack" message to CPT (Captain). With this report, the CPT decides to "counterattack" based on its own tactics and sends the "move" command. After being moved toward red ships, the "threat shooting" command is made. In this way, the actual battle is initiated. Both red and blue forces have their own tactics to be tested. The main focus of this simulation study is the effectiveness of the combat tactics. The simulation environment is implemented by using the DeSim++ that is a realization of DEVS framework [13].

4.2 Simulation Result

The simulation progress is summarized in Table 2. In the Table 2, "Stage" is the essential state of warship combat based on the simulation time, "Context Diagram" shows the combat situation graphically based on the "Stage", and the others show the states of each warship. In order to evaluate effectiveness of the combat result in a quantitative manner, we have simply defined the tactical efficiency in Table 1, E_{combat}, which is basically weighted sum of three terms; relative amount of damage (E_{damage}) between our force (Blue) and enemy force (Red), relative amount of spatial predominance (E_{sp}), relative amount of shooting positional predom-

Table 2 A simulation trajectory (partially-shown).

Stage	Context Diagram	Warship	Speed	Position	Commands	E_{combat}
[Stage 1] t= 1 ~ 8000 (*initial*)		Blue1	0.02 0.15	699., -599 -133, -605	Patrol Chasing	50%
		Blue2	0.05 0.15	549,-549 -172, -476	Patrol Warning Shot	42%
		Red1	0.03 0.15	-449, 350 -186, -129	Patrol Invasion	50%
		Red2	0.03 0.15	-749, 449 -174, -227	Patrol Invasion	50%
[Stage 2] t= 8000 ~ 9822 (*attack*)		Blue1	0.15 0.01	-133, -05 -202, -380	Chasing Avoid	50%
		Blue2	0.15 0.02	-172, -476 -168, -339	Warning Shot Avoid	67%
		Red1	0.15 0.15	-186, -129 -214, -335	Invasion Attack(-168, -339)	65%
		Red2	0.15 0.15	-174, -227 -219, -218	Invasion Attack(-168, -339)	65%
[Stage 3] t= 9822 ~ 10857 (*battle*)		Blue1	0.01 0.15	-202, -380 -225, -325	Avoid Attack(-207, -348)	64%
		Blue2	0.02 0.15	-168, -339 -166, -338	Avoid Attack(-207, -348)	64%
		Red1	0.15 0.15	-214, -335 -207, -348	Attack(-168, -339) Attack(-166, -338)	65%
		Red2	0.15 0.15	-219, -218 -186, -155	Attack(-202, -80) Attack(-166, -338)	50%
[Stage 4] t= 10857 ~ 13100 (*chasing*)		Blue1	0.15 0.01	-225, -325 -173, -374	Attack(-207, -348) Attack(-197, -324)	48%
		Blue2	0.15 0.15	-166, -338 -145, -399	Attack(-207, -348) Attack(-138, -449)	47%
		Red1	0.01 0.10	-207, -348 -138, -449	Attack(-166, -38) Avoid	36%
		Red2	0.15 0.02	-186, -155 -197, -324	Attack(-166, -38) Attack(-173, -374)	46%
[Stage 5] t= 13100 ~ 14206 (*ending*)		Blue1	0.01 0.03	-173, -374 -190, -366	Attack(-197, -324) Attack(-281, -446)	48%
		Blue2	0.15 0.05	-145, -399 -225, -411	Attack(-138, -449) Attack(-281, -446)	45%
		Red1	0.10 N/A	-138, -449 N/A	Avoid N/A	0%
		Red2	0.02 N/A	-197, -324 N/A	Attack(-173, -374) N/A	44%

inance (E_{pp}). In this simulation, we assume that a time step is 10 seconds.

Stage 1 in the Table 2 shows the '*initial*' status from t = 0 to 8,000. Both side warships cruise on their own region. That is, the intelligence officer of our ship reports the "clear (rule 1)" message to the captain so as to issue the "patrol (rule 1)" command to the navigation officer. Stage 2 is an '*attack*' stage from t = 8,000 to 9,822. The captain of the enemy warship sends a "NLL attack" command so that the enemy battleship moves toward NLL. Now, the intelligence officer of our force reports "the enemy invasion (rule 2)" to the captain. Then the warship moves to the location where enemy warship is positioned by executing the "action (rule 2)" command from the captain. When it moves close to the place where there are enemy warships, the intelligence officer reports (rule 3) that enemy are within the shooting range. Then the captain confirms the effective shooting range (3.7 mile) and commands "warning shot (rule 3)" to the Gunship officer. However, the enemy doesn't retreat and fights so that the actual battle is started. In this stage, Blue 1 and Blue 2 ships get together to attack the Red 2 ship whereas the Red 1 and Red 2 ships focus on attacking the Blue 1. Thus the E_{combat} of Red 2 is getting reduced from 65% to 40% since the concentrated shooting by Blue 1 and Blue 2. Stage 3 represents the '*battle*' state until t = 10,857. Red 2 ship finally moves to avoid. At the same time, the commander of our force issues a "concentrated attack (rule 2) to Red 1" command to both captains. The E_{combat} of the Blue 1, Blue 2, Red 1 and Red 2 are 55%, 60%, 55% and 70%, respectively. Stage 4 denotes the '*chasing*' state until t = 13,100. The Red 1 warship finally goes down so that the E_{combat} of our force is going up to 70%, however, the E_{combat} of enemy force represent only 40% in this stage. Stage 5 represents the '*ending*' state until t = 14,206. The Red 2 tried to resist against the attack from both Blue ships but to be annihilated.

Conclusively, Blue's collaboration tactic (Focused Fire Tactics) maximized their given specification to defeat the enemy. However, the aggressive collaboration tactic of an enemy (Red) force doesn't work well. The final combat efficiency of Blue and Red is 60%, 40%, respectively as shown in Phase VII in Fig. 2. In this way, the proposed methodology using an HEAP-based modeling and simulation techniques may be suitably applied to the evaluation of tactical efficiency of a complex multi-platform warship warfare environment.

5. Conclusions

This paper proposed a HEAP-based modeling and simulation methodology. We adopt the HEAP principle to design a multiple agent architecture that can support the abstraction-related modeling and hierarchical encapsulation capability. By advanced agent modeling techniques, HEAP, we are able to propose a multi-agent based modeling and simulation system for analyzing the strategic and operational effectiveness of multi-platform warfare. Our approach is differentiated from others in that; (i) it supports an abstraction-related hierarchical multi-agent architecture, (ii) it provides an efficient mechanism for analyzing the strategic and operational effectiveness of warship warfare environment between multiple platforms. A concrete example that copies a realistic situation has been successfully tested to evaluate the tactical effectiveness, as a result, the Blue's collaboration tactics is concluded to be efficient by maximizing our capability and minimizing the damage. The national defense personnel will be able to easily utilize the proposed environment for the analysis of strategic and operational effectiveness of warships, either as platforms or in a wider mission context.

Acknowledgements

This research was supported by DAPA (Defense Acquisition Program Administration) and ADD (Agency for Defense Development) in Korea (UD100004KD and UD110040DD).

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