Evaluation of Submarine`s Tactical operations using heterogeneous models

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ABSTRACT

For high fidelity, Interoperation of heterogeneous levels of models could be suggested as one of the reasonable methodologies in defense modeling and simulation. Engagement-level model can be supported by engineering-level models representing the detailed functionality of its composites to increase the accuracy of Measures of Effectiveness (MOE). This paper presents a case study of anti-surface warfare (ASuW) simulation from the perspective of submarine to analyze MOE of Bearing-only Target Motion Analysis via heterogeneous models. Tactical decisions are built as engagement-level based on DEVS formalism and few physical behaviors of participants that have significant impact on the result such as maneuvering of submarine are built as engineering-level. By variant of tactics, thousands of experiments are conducted. Decision maker can select one among tactics that leads to high effectiveness. This case study shows that interoperation of heterogeneous models can serve as a sophisticated approach for evaluation of tactics with high fidelity.

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INTRODUCTION

To make a decision what to purchase in defense domain, decision makers are considering lots of criteria; cost, time, and resource. The goal is to select the most a cost-effective one, which creates synergy effects with existing forces, among alternatives. They need reasonable evidences to select a proper solution. Therefore these alternatives should be evaluated under certain combat conditions where the platform will be operated.

Modeling and Simulation (M&S) is sophisticated and affordable tool for evaluating the effectiveness of a defense system. Not only can it make various conditions for evaluating systems, but it can only allow us to test a system repeatedly in same condition with varying parameters. Therefore, M&S can reduce costs, resources and development time across acquisition phases than conventional approaches such as prototyping and so on. Moreover, M&S can support to evaluate defense systems performance depending on operation.

Modeling and simulation of defense domain

M&S is applied on all levels of military operations, from the strategic level to the technical level. These differences in military operations cause different representation of models, which build a model hierarchy: Theatre, Mission, Engagement and Engineering (Figure 1) (Tolk, A. 2012).

Sometimes, there are needs to take the strengths of two different models simultaneously when more fidelity is required on the simulation. Hybrid or Heterogeneous modeling approach is introduced at this moment. Hybrid model means that simulation model is consisted of different level models based on single implementation or tool, versus Heterogeneous model means its consisted models are built on different implementation or tool.

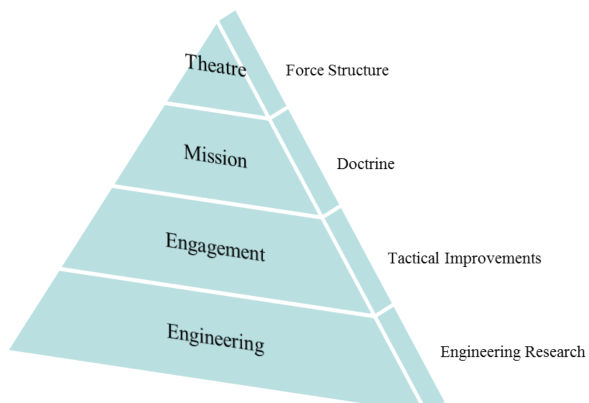

Figure 1 a hierarchy of defense simulation

Multi-modeling approaches: hybrid and heterogeneous modeling

It is more efficient to utilize the existing models than to make a huge model newly in order to model a complex system in defense domain. The utilization can be performed by hierarchical composition of existing models. This is called multi-modeling approach (Brooks, 2008). Moreover, it is more explicit and efficient to use composition of small, loosely coupled models than one giant model (Warmer, 2006).

Most simulations in defense domain were developed as discrete event based approach that is the DEVS (Discrete Event System Specification) formalism or the continuous approach that is system dynamics. The discrete event based approach and continuous approach respectively have advantages of solving its concerns. For example, continuous approach is interesting in the change of value according time change, whereas discrete event model is concerned about state transition by events. For high fidelity simulation, there are needs to accumulate the strengths of two different models simultaneously. So the study of utilizing different models in one simulation, called hybrid or heterogeneous modeling, has been investigated.

There are two approaches to implement an interoperation of multi-method models. First approach is building a simulation infrastructure, called simulation engine, to execute multi-method models in a single simulation engine (praehofer, 1991) and , as its defense domain application, there is a research for submarine diving and surfacing simulation (Cha, et al., 2010) (Ha, et al., 2013). Second approach is interoperation between multi-method models without modification of existing models via a simulation interoperation middleware, even though they are working on different simulation engine. For example, the interoperation between hybrid models, which consists of continuous and discrete event models, was introduced (Sung, et al., 2009). Those models were implemented with the DEVSim++ toolset for discrete event models and MATLAB/Simulink for continuous models, respectively. And their interoperation was implemented on HLA/RTI that is an interoperation standard for distributed simulation. Additionally, there is a research that reported new insights from interoperating heterogeneous level models in battle experimentation (Kim, et al., 2012). The lessons from a conventional battle experimentation could be limited its model representation that missed its details which might slightly change the simulation results.

This paper presents submarine tactical operation simulation which is composited of engagement-level discrete event models in which operator`s decisions are implemented, that might cope with uncertainties of human decision, and engineering-level continuous models in which its physical behaviors (such as maneuvering, detection of target) are implemented to evaluate submarine's tactics.

BACKGROUND

Brief description about typical anti-surface ship warfare

In anti-surface warfare (ASuW) of submarine, submarine takes advantage of its long-range passive detection. When received signals exceed the detection threshold of its passive hydrophone arrays. The operator will recognize that a counterforce exists within the maximum detection range of the detector. After target recognition, submarine will conduct complex maneuvers, which are required for Bearing-Only Target Motion Analysis (BOTMA), to estimate target parameters such as target position, speed and heading and try to take a good position to launch a torpedo after TMA maneuvering done (Coll, 1994). In these attack procedures, Accuracy of predicted target parameters is significant factors for success of attack. To obtain more accurate result, time varying position of submarine should be obtained from mathematical equation. Besides, sequences of maneuvering, which are thought as approach tactics, should be carefully chosen considering its effect on TMA result.

Target motion analysis from perspective of submarine

Target motion analysis (TMA) is defined as the estimation of a detected target`s range, course, and speed. In Bearing-Only TMA, particular importance is attached to range estimation. This is because knowledge of range is equivalent to knowledge of target position, since bearing is presumed known. And Bearing-Only TMA is very important because bearings may be obtained passively, without disclosing own ship presence (Wagner, et al., 1999).

The best known of TMA ranging techniques is the Ekelund method of bearings-only ranging. It requires a maneuver by own ship and uses observed bearing before and after a turn by own ship to estimate range of the target. It is an assumption that target is on a linear track. A vessel`s track will be said to be linear if its course and speed is constant. The Ekelund range is obtained by dividing the difference between submarine speeds (V_a) across the line of sight by the difference between bearing rates ($\dot{B}$):

$$R_e = \frac{V_{a2} - V_{a1}}{\dot{B}_1 - \dot{B}_2} \quad (1)$$

In Ekelund`s derivation, range was assumed constant over the ranging maneuver, but in practice range depends on time, so it is necessary to find when the Ekelund estimate is in some sense most accurate. The Time Correction Procedure is employed for this purpose obtaining the best range time (T_*) (Coll, 1994).

$$T_* = \frac{t_1 * \dot{B}_1 - t_2 * \dot{B}_2 + B_1 - B_2}{\dot{B}_1 - \dot{B}_2} \quad (2)$$

In this paper, The Time Corrected Ekelund estimation (equation 1, 2) is employed to determine the range between target and own ship. And course and speed of target are calculated with two different Ekelund estimations.

Target detection in underwater warfare

To detect target existence without own ship detected, submarine employs acoustic sensors named as SONAR that measures the acoustic signal that is radiated by the target. The target signal can be caused by its machinery, propeller noise, hull flow noise, and so on. But the acoustic signal is delayed, distorted, and weakened in traveling through the sea. Its decreased amount mainly depends on the distance between target and own ship. These phenomena are formulated by the sonar equation (Payne, 2010).

$$SL - TL - NL + DI \geq DT \quad (3)$$

The sonar equation (equation 3) is based on a relationship or ratio that exists between the desired and undesired portions of the received energy when some function of the sonar equipment is performed. If the target radiates an acoustic signal of SL (target source level), the sound intensity is diminished while traveling to the receiver. The decrease in intensity level due to this is TL (transmission loss). And noise (NL) acts to mask the arrived signal and is not wanted. And DI (Directivity index) is employed to give reduction in noise level obtained by the directional properties of the transducer array of sonar. DL (detection threshold) indicates the level for target to be detected with the specified probability of detection, normally 50 percentages.

Actually, the task of detecting a sonar signal is a chance process for several reasons, one of which is that a human operator is involved. If received acoustic signal exceed detection threshold, its detection result is determined by a random value generated from probability distributions that model the phenomenon. Therefore, detection of target is implemented with probability in discrete event model, but calculation of the sound propagation, which is mainly depend on geographical position of the participants, is modeled as continuous model.

Representing motion of marine vehicle such as submarine, torpedo and surface ship

Measured bearings, time varying directions of acoustic signals that are emitted from target and received at passive sonar of submarine, are taken into account for TMA estimation. So correct geographical positions of target and own ships should be required to calculate correct bearing.

To get geographical position of them more accurately, this paper employs 6 degree of freedom (DOF) equations formalized as non-linear differential equations with hydrodynamic coefficients that depends on hull shape of the submarine and type, position of installed hydroplane and rudder of the submarine (Gertler, 1967). These hydrodynamic coefficients can be obtained by planar model test of the submarine. With inaccurate hydrodynamic coefficients, 6 DOF equations cannot represent motion of submarine accurately. So it is one of major challenges to obtain right coefficients for estimating motion of marine platform. Fortunately, due to the previous project, right coefficients are applied at the equations. Hence, right motion and trajectory of the submarine and torpedo are calculated in the maneuver model. Additionally, the motion of surface ship is also represented in same manner. By simplification of the 6 DOF equations, reducing 3 DOF (pitch, roll, and heave) from 6 DOF, the equations of motion for ship is obtained (Abkowitz, 1969). For representing the motion of target surface ship, the equations are employed in this simulation.

CONFIGURATION FOR SUBMARINE TACTICAL OPERATION EVALUATING SIMULATION

Scenario

In typical ASuW scenario, the submarine is assumed to be conducting a barrier patrol against surface targets. The target will be a military ship with constant course and speed that has been detected by the submarine using its hydrophone array. Assuming that hostile ASuW units may be present in the area, the submarine will conduct the approach and attack avoiding the use of any active arrays. At the same time, target motion will be estimated in order to find firing point (Figure 2). And this bearings-only Target Motion Analysis (TMA) requires complex maneuvers (Coll, 1994).

When a submarine commander conducts an approach, he is trying to achieve the following objectives: first, closes the target within torpedo range, seconds, remains undetected at least until torpedo release, and third, generates a TMA result accurate enough to place the torpedo within its target acquisition. And he makes final attack decision based on tactical, operational area restrictions and weapons and sensors characteristics.

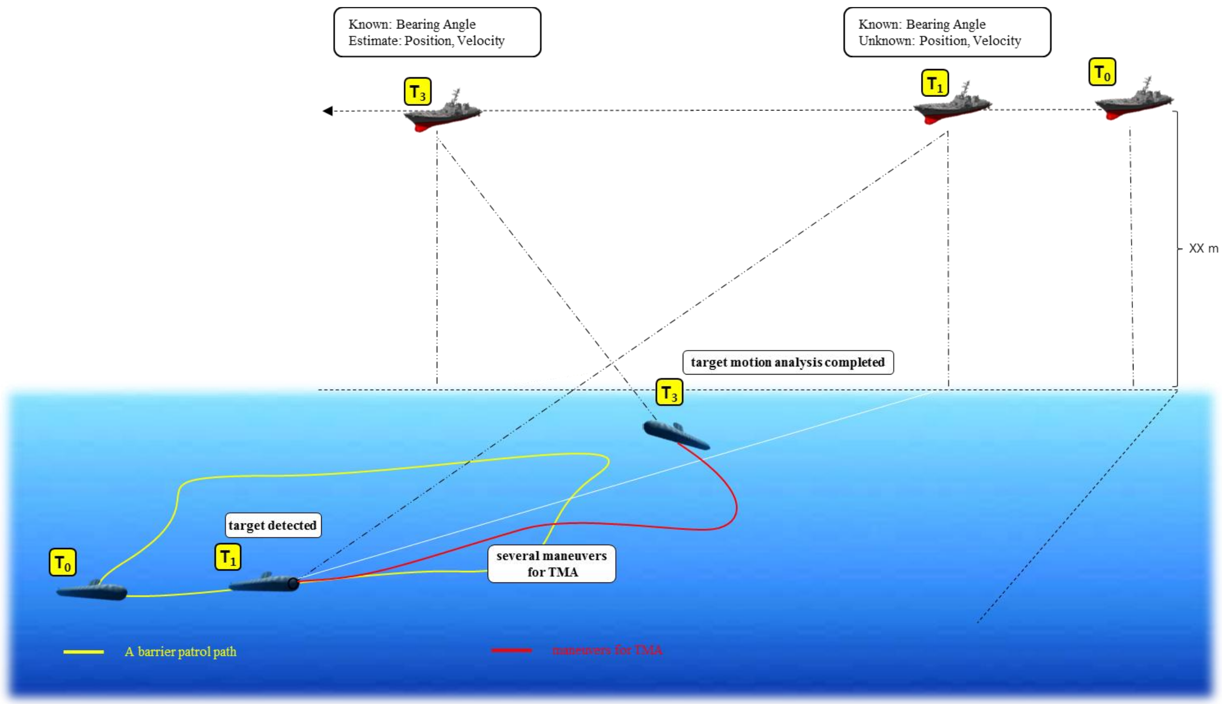

Figure 2 A scenario of anti-surface ship warfare of diesel submarine

In TMA procedure, several maneuverings of own ship are needed for calculating TMA estimation. Selecting a combination of maneuverings is considered as operator`s tactical decision. In this paper, four different approach tactics are evaluated its effectiveness for Bearing-only TMA to hold a proper position for attack as following Bakos`s research (Bakos, 1995): Point– Lead–Point, Point– Lag–Point, Point– Lead–Lag, Point– Lag–Lead. The first approach is always a Point, submarine course and target bearing are opposite, which is necessary to estimate target bearing rate. Second approach is either lead or lag. Third approach depends on the second approach.

Objectives

The three objectives of this paper are listed as below:

- The primary objective is to evaluate probability of a successful attack from the perspective of submarine by changing operator`s tactics about selecting maneuvering-type during approach and calculating TMA.
- The second objective is to determine what combination of maneuvering-type results in high performance on probability of a successful attack.
- The Third objective is to build an environment for interoperation between discrete model and continuous model.

Methodology

This paper is focusing on evaluating probability of a successful attack from the perspective of submarine by employing interoperation between engagement model, which is a discrete event model, and engineering model which is a continuous model. This Measure of effectiveness (MOE) may be partially affected by operator`s tactical decisions such as selecting a maneuvering-type. Therefore, operator`s tactical decisions and commands are built as engagement-level based on DEVS formalism and physical behaviors of participants that have significant impact on the result are built as engineering-level based on mathematical equations. To implement the simulation, DEVS Sim++ for discrete event models and MATLAB/Simulink for continuous models are employed. DEV Sim++ supports to simulate DEVS based model by communicating hierarchical abstract simulator and MATLAB/Simulink supports to execute continuous model by solving mathematical equation.

Discrete event model base on DEVS Formalism for Submarine Operator`s decisions

The DEVS formalism specifies discrete event models in a hierarchical and modular form. With this formalism, one can perform modeling more easily by decomposing a large system into smaller component models with coupling specification between them. There are two kinds of models: atomic model and coupled model (Zeigler, 2000). An atomic model is the basic model and has specifications for the dynamics of the model. And a coupled model provides the method of assembly of several atomic models or coupled models to build complex systems hierarchically.

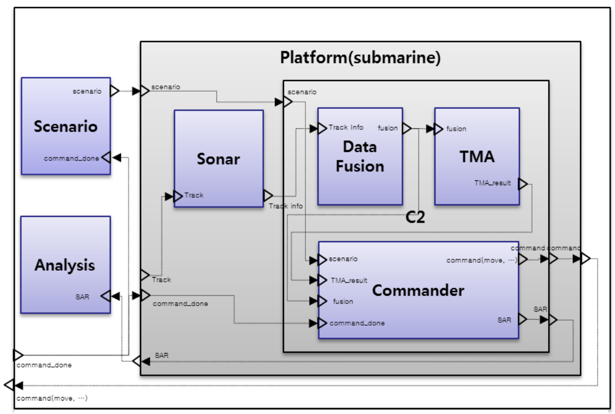

Figure 3 Structure of submarine tactical operation simulation

In this paper, Submarine model is represented as discrete event model following DEVS formalism. The overall structure of Submarine model is depicted in Figure 3.

Submarine coupled model has sonar model, which is charge of measuring acoustic signals emitted from target platform, and Command Control (C2) model that represents operator`s decisions.

To support decision-making of C2 model, data fusion and Target Motion Analysis atomic models respectively give detection result and estimated target information such as location, velocity and course. Consequently, commander atomic model makes decisions and sends a command message that indicates which type of maneuvering should be taken at specific heading angle to maneuver models which is continuous model.

Additionally, Scenario and Analysis atomic models give an experimental frame for repetition of the simulation. Scenario atomic model sends geographical location information that is scheduled submarine’s patrol routes capsulated in scenario message to submarine model and Analysis atomic model receives results of the simulation and display a proper format.

Overall simulation flow of the submarine tactical operation simulation is depicted in Figure 4. At the initial, submarine conducts a barrier patrol against surface ship. If a target is detected, next procedure is to check whether the submarine exists inside Submersible Approach Region (SAR) to attack the target or not. And one approach tactic is conducted among four different tactics: Point– Lead–Point, Point– Lag–Point, Point– Lead–Lag, and Point– Lag–Lead and TMA is simultaneously calculated. After TMA calculation, SAR constraint is reconsidered. If the submarine exists inside SAR region and distance from the target is within maximum torpedo range, a torpedo is launched to the target. After torpedo firing, the attack will be evaluated to success or failure according to whether the torpedo is contacted at the target or not. Then one replication of the simulation is finished.

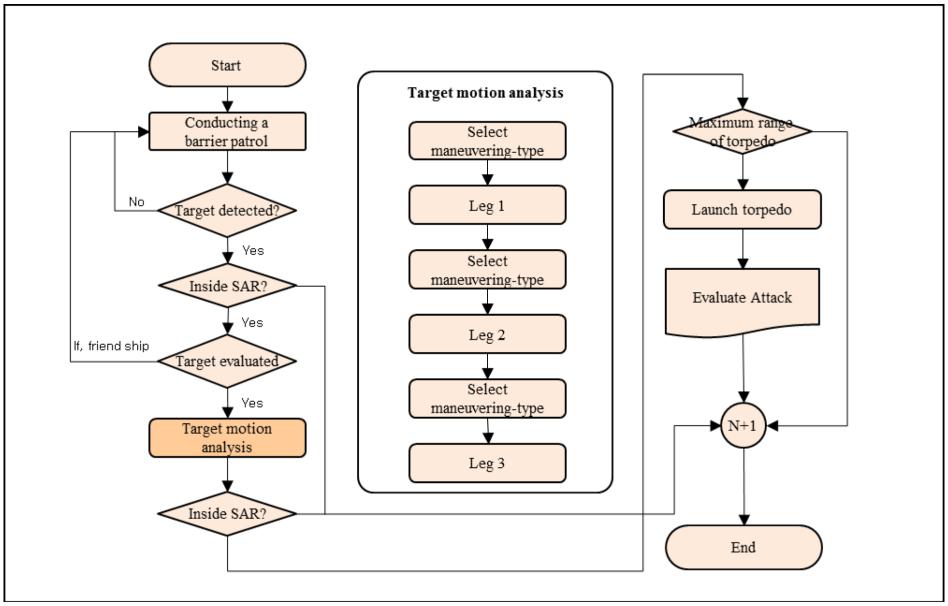

Figure 4 Simulation flow chart of submarine tactical operation simulation

Continuous model base on Mathematical Representation of Submarine and its target`s behaviors

In this submarine tactical operation simulation, two continuous models are involved: First is maneuver model that represents motion of submarine, torpedo and its target, and second is sound propagation model that represents the sound propagation equation used for calculating acoustic signal power (as decibel unit) received at passive array sonar in underwater.

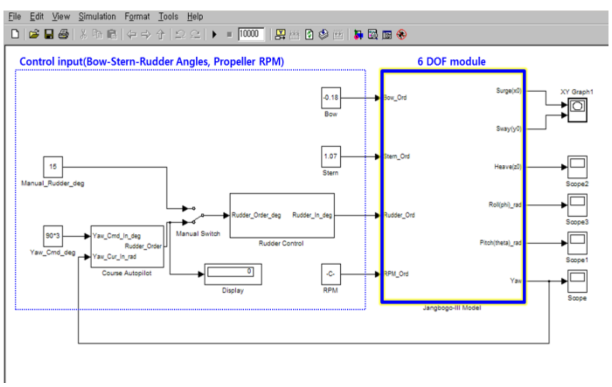

Figure 6 Maneuver model on MATLAB/SIMULINK.

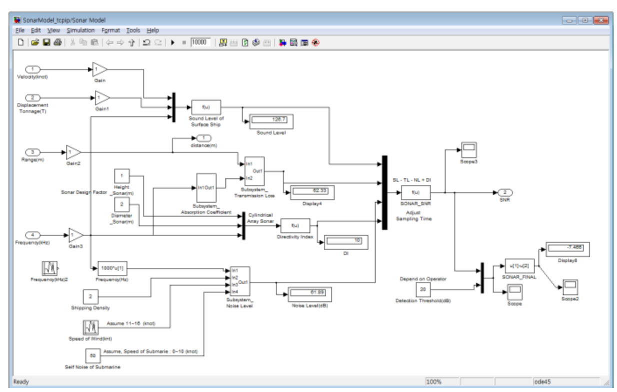

Figure 5 Sound propagation model on MATLAB/SIMULINK

Maneuver model employs 6 degree of freedom (DOF) equations (Gertler, 1967). Therefore, right motion and trajectory of the submarine are calculated at the maneuver model. The maneuver model is not only a reusable continuous model but also a continuous simulator working independently. And, this maneuver model can represent 6 DOF motion of other type of submarine or even torpedo by changing its coefficients easily by changing hydrodynamic coefficients.

Sound propagation model are also implemented as continuous model as engineering level using the sonar equation (equation 3). Each terms of sonar equation (equation 3) are employed as following: The target source level can be parameterized by target`s properties such as installed engine, its running speed. So if target changes its speed in the simulation, the target source level is also changing. Transmission loss is calculated with positions calculated from each maneuver models. Noise level can be obtained by Wenz Curve that can be used to estimate noise levels from a variety of sources within the frequency range of interest. And Directional index is known value from properties of passive sonar equipment.

Interoperation between Discrete event model and Continuous model

The interoperation between heterogeneous models is implemented on HLA/RTI environment. The architecture of the evaluation of submarine`s tactical operations is described in Figure 7. The evaluation simulation consists of one discrete event model and set of continuous model that is managed by the coordinate model. A concept of space model as coordinate model is employed to manage continuous variables such as position, speed and received acoustic signal level diminished by traveling through the sea. It is a benefit of the space model to add new platform or remove the platform destroyed by attack during the simulation. The space model is connected to maneuver model of participants and knows positions of participants at any time. And it passes those positions to sound propagation model for calculating transmission loss in sonar equation. In a conventional configuration of the DEVS formalism based simulation, information among participants is exchanged by model to model. So if the number of participants of the simulation is increasing, the number of interfaces among models should be increasing proportionally (Sarjoughian, et al., 1999) (Ha, et al., 2013).

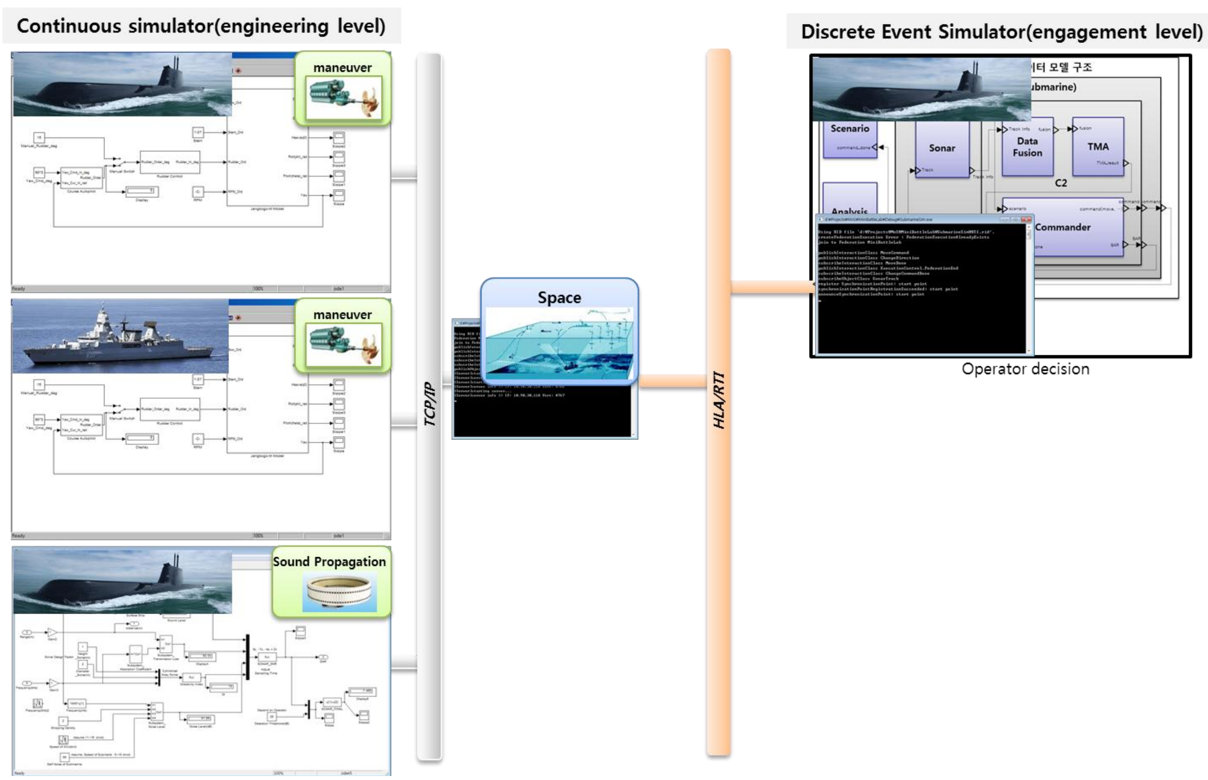

Figure 7 Architecture of simulation for evaluation of submarine`s tactical operations.

RESULT

Four different approach tactics are simulated using heterogeneous models assuming a target speed uniformly distributed between 10 and 24 knots, with combination of each approach tactic and own speed (2, 4, 6, 8 knots) consisting of 250 trials (totally 4 by 4 by 250). Figure 8 shows that probability of successful attack generally increases as own speed increases for all tactics. Except point-lag-lead tactic, other tactics have a similar tendency but the probability value slightly different. In fact, those differences don’t mean that there is a significant difference between tactics according to stochastic analysis using the significant level (0.05 significant level used). So the submarine officer can choose one of the alternatives expect point-lag-lead even though point-lead-point tactic shows highest probability of successful attack over all speed range.

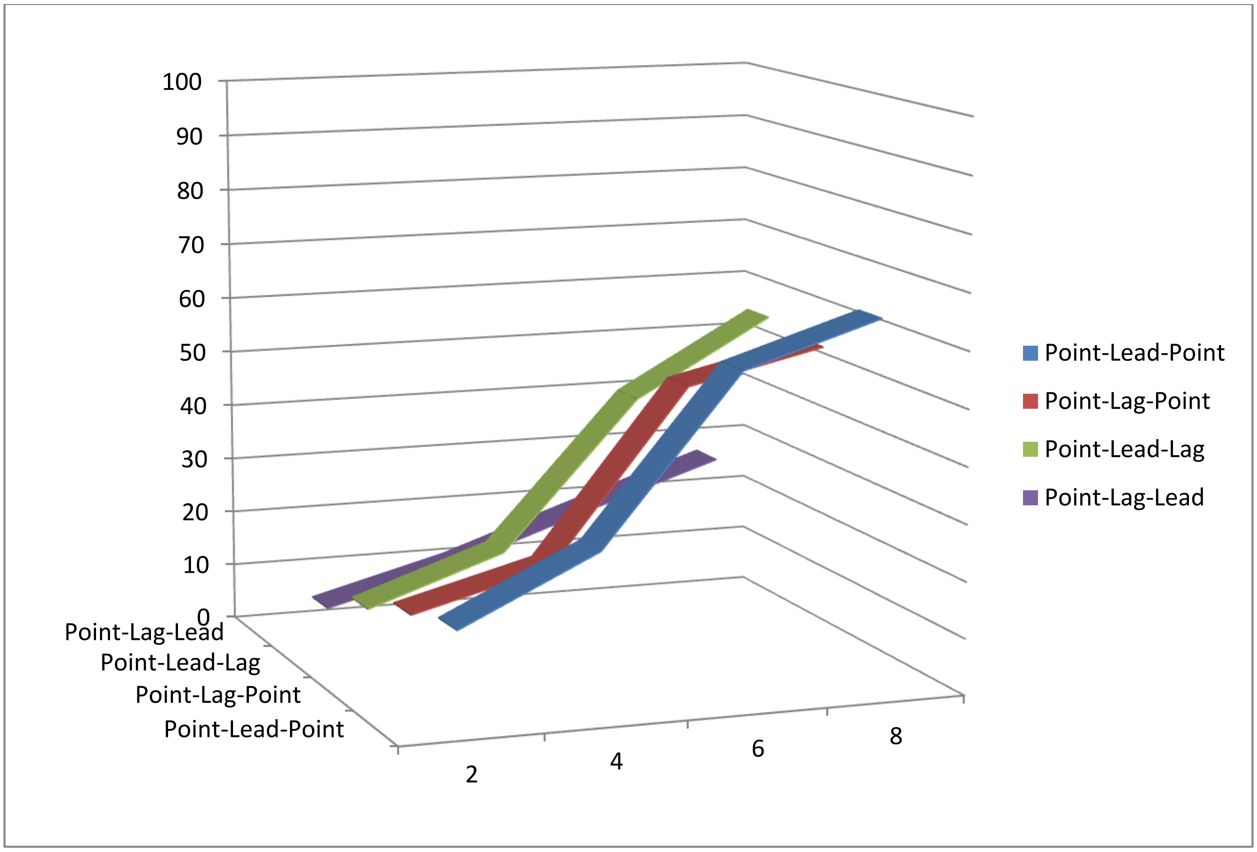

Figure 8 a result of probability of successful attack vesus ownship speed and tactics

Moreover, the officer can decide speed of the submarine for best successful attack from this result. In Figure 8, the probability of a successful attack at 8 knots of the submarine looks higher than the one at 6 knots. But nobody can`t say that the case of 8 knots has better result for effectiveness of successful attack than the case of 6 knots because each confidence interval, which represents minimum and maximum probability of successful attack, for them are overlapped. Therefore, it is a reasonable decision to set the speed of the submarine as low value (in this case, 6 knots) if there is no significant difference in stochastic analysis. Besides, High speed of the submarine just causes the noise level and the fuel consumption increase.

CONCLUSION

Even though there are many factors that affect the probability of successful attack such weapon characteristics, sensor, and reaction of the target. under condition that the submarine keeps undetected, the probability of successful attack depends on not only the result of TMA but also geographic position of the submarine after TMA calculation. And those values are affected by a tactic like maneuver sequences during TMA processing. According to result, Tactics which is not including lag-type leg among alternatives is more preferred. In fact, lag-type leg makes it grow distance between the submarine and target. So even if the result of TMA is obtained correctly, the submarine tends to be located geographical position over maximum attack range of its torpedo. Eventually, torpedo cannot be launched and the attack is failed.

This paper introduces interoperation of heterogeneous levels of models as one of the reasonable methodologies for high fidelity simulation. Engagement-level model representing decisions of human is supported by engineering-level models representing the detailed functionality of its composites such as detection, maneuver. Additionally, result of this research can be extended to operator training simulator. For example, a steering training simulator of submarine can be easily configured using engineering-level model, that is maneuver model in the simulation, of this research. And the steering training simulator will be interoperated with the heterogeneous model based simulation developed in this research. This is considered as interoperation between Constructive and Virtual simulator. Therefore, trainees can experience mission-based steering training on diverse situation generated by various scenarios of the experiments and know how the result of steering controlling has an effect on TMA result.

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