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Model-Driven Combat Effectiveness Simulation Systems Engineering

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ABSTRACT

Model-driven engineering has become popular in the combat effectiveness simulation systems engineering during these last years. It allows to systematically develop a simulation model in a composable way. However, implementing a conceptual model is really a complex and costly job if this is not guided under a well-established framework. Hence this study attempts to explore methodologies for engineering the development of simulation models. For this purpose, we define an ontological metamodelling framework. This framework starts with ontology-aware system conceptual descriptions, and then refines and transforms them toward system models until they reach final executable implementations. As a proof of concept, we identify a set of ontology-aware modelling frameworks in combat systems specification, then an underwater targets search scenario is presented as a motivating example for running simulations and results can be used as a reference for decision-making behaviors.

Keywords: Metamodelling; Semantics; Model-driven engineering; Effectiveness simulation

1. INTRODUCTION

Modern engineered simulation systems have reached a complexity that requires inevitably the joint use of ontologies and models to ensure correct domain descriptions and favourable model specifications[1]. Based on Model-Driven Engineering (MDE), employing ontologies to capture domain knowledge is considered as a key attempt to systematically develop a correct simulation model. Meanwhile, ontologies and models, usually represented in different forms due to different preferences of simulation modellers, are shared by a group of people in a certain domain. These differences make the model composability[2] particularly the semantic composability very difficult, leading to a low efficiency, productivity and quality of products.

Traditional commonly known specifications such as high level architecture (HLA)[3], simulation model portability (SMP)[4,] and discrete event system specification (DEVS)[5,6] try to tackle with the syntactical facet of model composability. The goal of these specifications is to build a commonly accepted standard. Such a standard can represent system knowledge in a unified form through a set of prescriptive meta-concepts, or integrate models in a fixed way by defining a collection of predefined interfaces. However, without any consideration on the semantic facet from a technological point of view, models are hard to be integrated meaningfully. For this reason, some of the domain specific simulation systems or platforms, like Extended air defense system (EADSIM)[7], System effectiveness analysis simulation (SEAS)[8], and Joint mission effectiveness analysis simulator for utility, research and evaluation (JointMEASURE)[9], concentrate on the abstraction of domain knowledge, and have acquired considerable successful applications.

All of these attempts lay a well foundation for realising the semantic composability of simulation models and also provide a lot of valuable experience for complex systems modelling and simulation. Yet, we identify that a set of composable modelling frameworks is the key to engineering the semantic composability of simulation models[10]. And, these frameworks are not trivial and must be built in a systems engineering way.

Recently, there have been many attempts to increase the probability of success in modelling and simulation (M&S) studies by proposing common modelling and simulation processes. Inspired from the detailed and comprehensive M&S lifecycle[11], a simulation models development and execution lifecycle as well as its supporting infrastructure, including various stages, related M&S objects, activities, and infrastructure, is presented as a good guidance[12]. Although the specific context of a given application may appear different, most simulation models development processes follow the traditional V cycle[13] and underline three important stages: conceptual modelling[14], model specification, and model implementation.

2. THE ONTOLOGICAL METAMODELLING FRAMEWORK

Employing ontologies into MDE permits simulation modellers to group simulation models around ontologies[15]. Generally, MDE has two important practices: Model-driven architecture (MDA) and Domain specific modelling (DSM). The former aims to divide the overall lifecycle of model development into three phase: conceptual, platform independent, and platform specific, each of which produces respective models that are described using United modelling

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language (UML). This can be viewed in a horizontal direction to generate a final product from initial concepts step by step. Instead, from a vertical direction, the goal of the latter one is to design a domain specific language based on Meta-object facility (MOF). Inspired from the MDD4MS framework[16], Fig. 1 illustrates such an ontological metamodelling framework based on MDE. This framework integrates the ontological metamodelling methodologies along with MOF and MDA, with the objective of engineering semantic composability between kinds of simulation models. At the left side contains information about a given system from the perspective of system users. This side belongs to the problem domain, in which an analysed method is often adopted and models are usually represented in the form of descriptive models, e.g. ontology. Whereas, at the right side concerns details of a system's specification from the perspective of system developers. This side belongs to the methodology domain, in which a designed method is applied and simulation models are prescriptive models.

3. CASE STUDY

This section describes a motivating example of combat effectiveness simulation systems (CESS) engineering process to illustrate the semantic composability of simulation models based on the proposed framework.

3.1 Domain Knowledge Decomposition

Different researchers classify knowledge in different ways. In an organisation, knowledge is classified into three types, explicit knowledge, tacit knowledge and cultural knowledge, features in different levels of accessibility. These types of knowledge are interrelated and form a knowledge base. Other classifications include heuristic knowledge, procedural knowledge, and declarative knowledge[17]. In CESS, knowledge is classified from two perspectives: knowledge decomposition and knowledge abstraction, as shown in Fig. 2.

The decomposition perspective is to decrease the level of system complexity by decomposing the knowledge base into

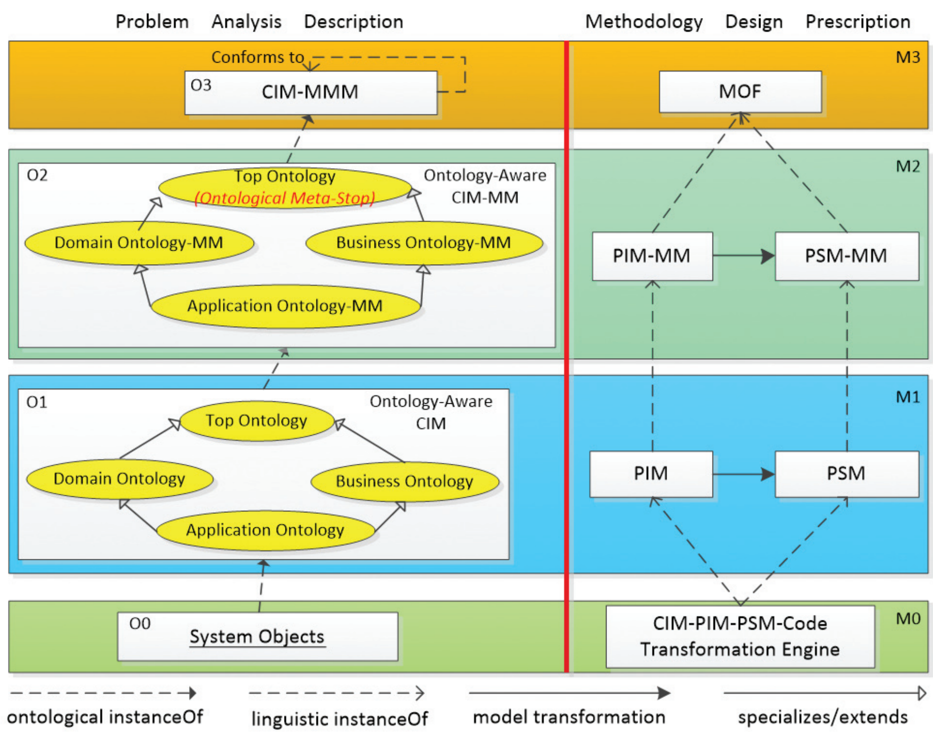

Figure 1. The ontological metamodelling framework based on MDE.

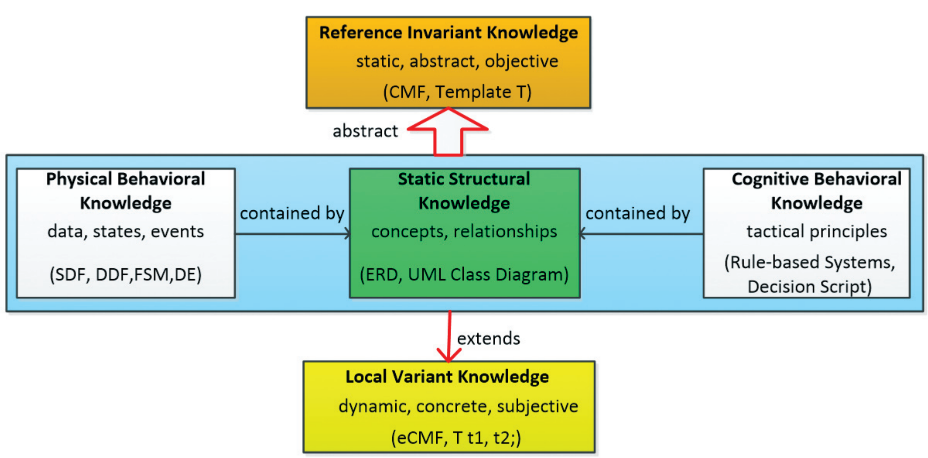

Figure 2. The three-decomposition plus two-layer CESS knowledge architecture.

static structural, physical behaviour, and cognitive behaviour knowledge. By this way, different domain knowledge has different levels of flexibility, thus ensuring the more stable parts unchanged when the knowledge with higher level of flexibility updates.

Static structural knowledge indwells in the system nature and is the most stable part that can be seen, communicated with others and is easy to manage. It can be communicated because it contains a number of inherent concepts and their relationships that can be represented in a formal way using a set of symbols. For example, entity-relationship diagrams (ERD) and UML class diagrams are usually used to capture the system concepts, properties, relationships as well as domain specific constraints. Ontologies are also used to capture system structural concepts.

Physical behaviour knowledge belongs to the physical or information domain and is relatively stable but in a somewhat more flexible form because the inherent dynamics of physical behaviour. Most physical behaviour knowledge is expressed in the form of diagrams that contain symbols of segments such as dataflow, states, and events. Static and dynamic dataflow (SDF and DDF), finite state machine (FSM), and discrete event models (DE) are employed to represent system physical behaviours.

Cognitive behaviour knowledge belongs to the cognitive or social domain where human wills play key roles and can be defined as a matter of personal interpretation, ability and skill. It is embedded in people's mind and is not easy to extract and share with others. Nevertheless, it is possible to document it into tactical principles or rules and articulate its implicit information through an inference engine.

The abstraction perspective identifies two types of knowledge, domain-level invariant knowledge and application-level variant knowledge, in order to maximally reuse the common knowledge across various applications. Hence, rather than representing knowledge with all parts and details of a specific system, only the knowledge framework needs to be defined, which can be able to reach simpler knowledge representation.

Domain-level invariant knowledge represents the common parts of a given system at a higher level of abstraction, i.e., the fundamental concepts and properties of a given system in its execution environment embodied by a number of model components, relationships, and build or evolution principles. Experience shows that a set of composable modelling frameworks (CMFs) is the key to capture domain-level invariant knowledge. Application-level variant knowledge extends or customises domain-level invariant knowledge at a lower level of abstraction, namely extensible CMF (eCMF), together with a variety of data for driving simulations. Its representation is usually achieved through general purpose programming languages, such as C++ and Python.

3.2 CESS ontoCMFs

Figure 3 shows a typical CESS ontoCMF built by UML extension with tags. In this ontoCMF, tmPlatform is tagged by two kinds of tactics: AirDefense and AntiSub. In fact, there are more tactics that could be tagged on this level. For brevity, here we only present relative tactics according to the concrete scenario. These details will be discussed in later subsection. It derives a concrete scenario of engagement between two sides, where the red side is an anti-submarine group that consists of a warship and a helicopter, while the blue side contains only an enemy submarine.

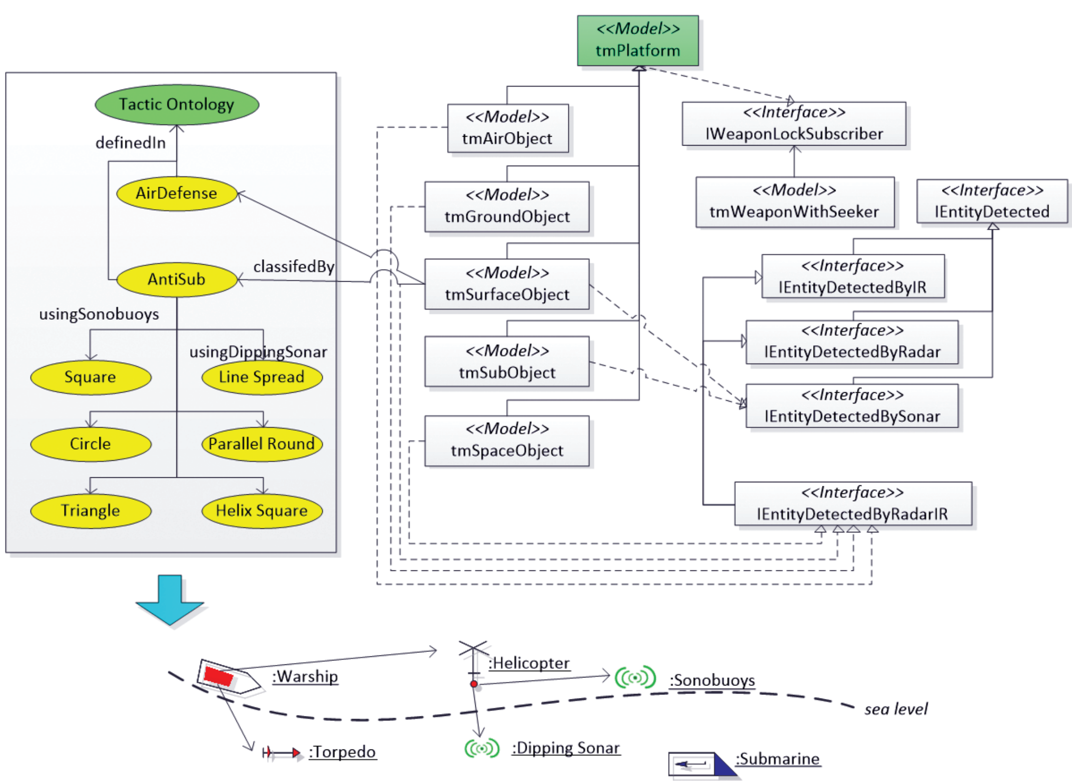

Figure 3. A typical CESS ontoCMF.

3.3 Underwater Targets Search

Sonar is generally used to exploit underwater acoustic sound propagation for navigating, communicating, or as a means of locating objects. In general, an individual sonar system has limited detection capability in a large search area hence the route of a helicopter must be arranged properly. This subsection introduces three typical tactics to search an enemy submarine using sonobuoys.

Square: Consider the search pattern Square, as shown in Fig. 4(a), in which sonobuoys are launched orderly and can work in a square formation. By this pattern a better effect can be obtained if the side length L of Square guarantees the distance d between two adjacent waypoints suffices $r \le d \le 2r$. In addition, suppose such an ideal ocean environment of which the salinity, temperature and even geographic location etc. are all located at a moderate layer, and every sonobuoy is working properly without any errors, so an adversary submarine cannot escape from the seamless search pattern of Square if the total number N of sonobuoys is multiple of 4. In contrast, if not, we take N up to a multiple of 4. Consequently, it will have gaps in the fourth quadrant.

We can easily know $N = 8$, $d = 2r$ and $L = 4\sqrt{2}r$, where N is the total number of waypoints, d is the distance of every two adjacent waypoints, r is the maximum detecting range of sonar, and L is the side length of the square. We can conclude that when N is a multiple of 4, i.e., $n = 4k(0 \le k < \infty, k \in Z^+)$, then the pattern *Square* is seamless. Otherwise, it has gaps, thus to satisfy exact division by 4, we defined $N' = N + (4 - N \bmod 4)$ instead of N. As a result, the coordinate $w_i(x, y)$ can be calculated by:

Firstly, for the first quadrant that i subjected to $0 \le i \le N/4$,

$$\left.\begin{aligned} x_i &= L/2 \times (1 - 4i/N) \\ y_i &= L/2 \times 4i/N \end{aligned}\right\} \tag{1}$$

Secondly, according to the symmetric relation of square, for the second quadrant that i subjected to $N/4 < i \le N/2$,

$$\left.\begin{aligned} x_i &= -x_{(i-N/4)} \\ y_i &= y_{(i-N/4)} \end{aligned}\right\} \tag{2}$$

Thirdly, the third and fourth quadrant that i subjected to $N/2 < i \le N$

$$\left.\begin{aligned} x_i &= -x_{(i-N/2)} \\ y_i &= -y_{(i-N/2)} \end{aligned}\right\} \tag{3}$$

Circle: As another search pattern using sonobuoys, consider the *Circle* as shown in Fig. 4 (b), in which the sonobuoys, like the *Square*, are launched orderly, but in a circular formation. If the radius D of *Circle* is initialised to guarantee that the distance d between every two adjacent waypoints is subjected to $r \le d \le 2r$, then a better search effect is more likely to occur. As the example as shown in Fig. 4(b), we can also determine $D = \sqrt{4+2\sqrt{2}}r$, where $d = 2r$ and $N = 8$.

In such a search pattern, a regular octagon centered at the origin o is obtained through the connectivity of each two adjacent waypoints, and the coordinate of every waypoint for *Circle* can be known by the following formulations:

$$\left.\begin{aligned} x_i &= D \times \cos\left(\frac{360 \times i}{N}\right) \\ y_i &= D \times \sin\left(\frac{360 \times i}{N}\right) \end{aligned}\right\} \text{ where } 0 \le i \le \infty \text{ and } i \in Z^+ \tag{4}$$

Triangle: The search pattern of Fig. 4 (c) is a Triangle that $D = 2\sqrt{3}r$, $d = 2r$ and $N = 9$, where D is the distance of segment ow_0, d, r and N are all similarly defined like *Square* or *Circle*. In general, *Triangle* is seamless if N is a multiple of 3 and an adversary submarine cannot escape from the vision of this search pattern, otherwise the third edge of this triangle is leaked.

We can conclude firstly when N is a multiple of 3, e.g., $n = 3k(0 \le k < \infty, k \in Z^+)$, *Triangle* is a seamless search pattern, while secondly if not, we defined $N' = N + (3 - N \bmod 3)$ instead of N to ensure N' is a multiple of 3. Thus the coordinate of each waypoint in this search pattern can be figured out from three parts:

Firstly, for edge L1 that i subjected to $0 \le i \le N/3$,

$$\left.\begin{aligned} x_i &= D - \frac{(D - (-D/2))}{N/3} \\ y_i &= \frac{3\sqrt{3} \times D \times i}{2 \times N} \end{aligned}\right\} \tag{5}$$

Secondly, for edge L2 that i subjected to $2N/3 < i \le N$,

$$\left.\begin{aligned} x_i &= -D/2 \\ y_i &= \sqrt{3}D/2 - \frac{(\sqrt{3}D/2 - (-\sqrt{3}D/2)) \times (i - N/3)}{N/3} \end{aligned}\right\} \tag{6}$$

Finally, for the last edge that i subjected to $N/3 < i \le 2N/3$,

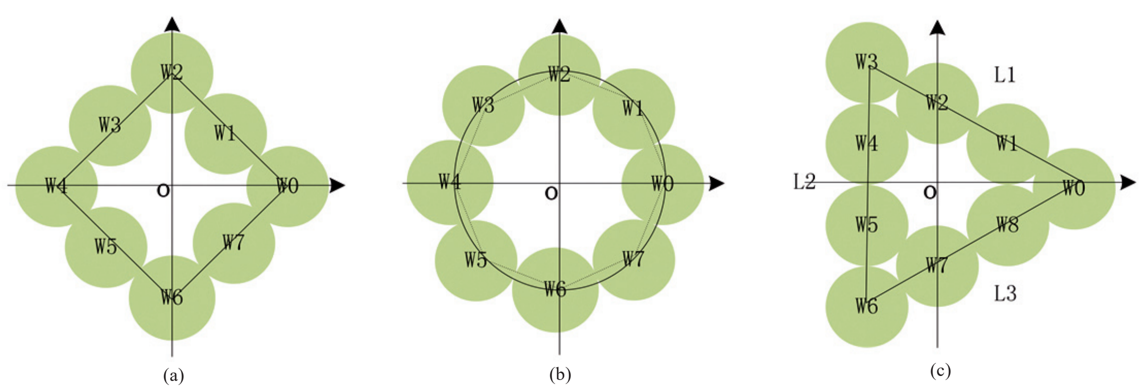

Figure 4. Search patterns with sonobuoys: (a) Square, (b) Circle, and (c) Triangle.

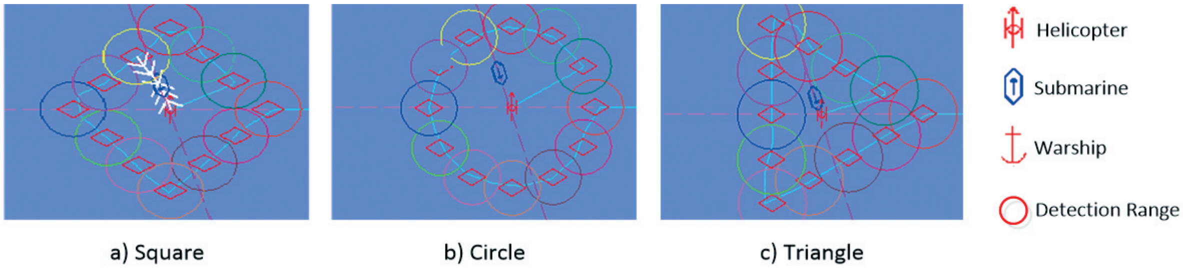

Figure 5. The 2D simulation display of each tactic.

Table 1. The simulation data of each tactic.

Number	Tactic	Found ratio	(s)	LastLostTime (s)	EnemyEvasionRatio
a)	Square	0.93	43.33	811.15	0.10
b)	Circle	0.91	42.59	811.15	0.11
c)	Triangle	0.96	42.30	811.15	0.08

$$\left.\begin{aligned} x_i &= -D/2 + \frac{(D-(-D/2))}{N/3} \times (i - 2 \times N/3) \\ y_i &= -2\sqrt{3}D/2 - \frac{\sqrt{3}D/2 \times (i - 2 \times N/3)}{N/3} \end{aligned}\right\} \quad (7)$$

4. RESULTS

Weapon effectiveness simulation systems (WESS) is a modelling and simulation platform for CESS domain[18]. In general, WESS has two workflows from different perspectives: domain model development (DMD) for modellers and simulation application development (SAD) for users. In the SAD workflow, a set of tools are developed to support data preparation and scenario editing, experiment design, and simulation display and results analysis. When all of the data are configured completely and simulation models are prepared, the next work is to run simulations then analyse the results to get meaningful information. We set the total logical running time for each simulation to 1000 s and performed 500 rounds of Monte Carlo simulations. Figure 5 shows the 2D simulation display of for each tactic.

Table 1 shows the simulation data of each tactic in terms of the found ratio, first found time, last lost time, and enemy evasion ratio. Obviously, the *Triangle* tactic enjoys a better value for each parameter compared to the other two tactics. For example, it has a higher found ratio, as well as an earlier first found time, and a considerable low ratio of enemy evasion. In addition, those three tactics of using sonobuoys share a similar last lost time, because the adversary submarine has not escaped out of the detection range until the simulation terminates.

5. CONCLUSIONS

This paper presents a model-driven ontological metamodelling framework based on MDE. This framework emphasises the role of ontologies at the phase of conceptual modelling with the objective to define a set of ontology-aware CMFs. As a proof of concept, this paper proposes a three-decomposition plus two-layer knowledge architecture to reduce the complexity of CESS system specification, then designs a set of ontoCMFs of CESS. Finally, an illustrative simulation example of underwater targets search is discussed. The simulation results can be used for operational decisions or equipment acquisitions. However, as a drawback more simulations about different scenarios are necessarily required as further illustrations.

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CONTRIBUTORS

Prof. Zhi Zhu is an Assistant Professor at National University of Defense Technology. He was also a visiting PhD student at Arizona State University. His research interests are language-driven development and system engineering.
In the current study, he designed the proposed ontological metamodelling framework by incorporating the model-driven engineering techniques. He has also conducted the illustrative simulation experiment and analysed the final results.

Prof. Yonglin Lei is a Professor at National University of Defense Technology. He was also a visiting scholar at Arizona State University. His research interests are complex system modelling and simulation, model-driven engineering, and simulation composability.
In the current study, he has provided the overall technical guidance for the feasibility of the proposed framework proposed in this research and has also the simulation platform to support the experiment.

Prof. Yifan Zhu is a Professor at National University of Defense Technology. He was also a visiting scholar at Virginia Polytechnic Institute and State University. His research interests are equipment system evaluation and demonstration, and agent-based modelling and simulation.
In the current study, he has extended the literature review on related topics to make this research more comprehensive, rigorous and profound.