Model-Based Systems Engineering Supporting Integrated Modeling and Optimization of Radar Cabin Layout

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Abstract. The equipment layout optimization of a UAV (Unmanned Aerial Vehicle) radar cabin can decrease cable length in order to promote the quality of radar and UAV system. Model-based Systems Engineering (MBSE) is widely used for UAV development, particularly for the layout design of UAV radar cabin. In this paper, a semantic modeling approach based on KARMA language is proposed to create the system model of the radar cabin layout based on an MBSE approach for formalizing Requirement, Function, Logical and Physical structure (RFLP). Moreover, the KARMA models for UAV radar cabin layout modeling are transformed to the Genetic Algorithm (GA) in MATLAB toolkit for radar cabin layout optimization by code generation. Based on the layout information generated from the KARMA models, the optimized layout solution is generated by the MATLAB toolkit. From the case study, we find the KARMA language enables to formalize the radar cabin design based on nine diagrams of SysML specification. And optimizations can be executed automatically after getting data generated from KARMA models. Thereby, the proposed semantic modeling approach improves design efficiency and quality during radar cabin design.

Keywords: MBSE · RFLP · KARMA · Radar cabin layout

1 Introduction

Model-Based System Engineering (MBSE) is an emerging technology that supports the development of complex systems and has been widely used in academia and industry. MBSE formalizes requirements, design, analysis, verification, validation, and other specific development activities involved in the entire lifecycle based on a formal modeling approach [1, 2]. Before the physical prototype of the UAV radar cabin is formally put into use, through MBSE formalisms, simulations, and optimizations, design risks can be captured as early as possible. MBSE is proposed to reduce the iterations during product development, to reduce costs, to shorten the development lifecycle [3], and to improve

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the efficiency of product design. Moreover [4], the use of optimization algorithm can improve the capability to find the optimal solution across optional product alternatives during product design [5].

UAV radar is a complex system, and the design of the UAV radar cabin is challenged because its design process is involved with many layout configuration parameters and constraints. At present, there are three main problems when designing the layout of the radar cabin: (1) The document-centric radar layout design increases the designer's difficulty in understanding the architecture of radar layout and gaps among radar engineers and UAV engineers; (2) The layout design of the radar cabin is based on an empirical approach which lacks capabilities for generating layout automatically and rapidly. (3) During the iterative design of UAV radar cabin among UAV engineers and radar engineers, consistency management between radar cabin design and radar layout simulation cannot be supported in an appropriate way.

In this paper, we adopt MBSE to support UAV radar cabin layout design and optimization. Some researchers proposed related works on this topic. Youguang et al. [6] studied the specific application of the MBSE method for radar systems to improve the entire radar development process based on MBSE. The authors suggest making use of MBSE to support radar design to improve development efficiency and eliminate the gaps across radar designers. When designing the radar layout, Yang et al. [7] identified equipment consistency, color consistency, and space utilization optimization are important to radar layout. Mcdonald et al. [8] analyzed the antenna layout of an improved super-dual-auroral radar network (SuperDARN) high-frequency radar.To handle the high technical risks and rapid new technology application needs in MBSE process, Yao et al. [9] proposed a parallel Verification approach for new technology application in complex radar system. In general, there are a few studies on radar system or radar layout design using MBSE approach, so we adapt a new way to design radar layout using semantics modeling and MBSE approach.

This paper mainly proposes an MBSE approach for the layout design of the radar cabin system: (1) KARMA [10] language-based semantic modeling, and RFLP approach for formalizing the radar designer's understanding of the radar layout. (2) GA analysis for optimizing the radar cabin layout through simulations. (3) Code generation is used to support consistency management across MBSE models and optimization models in order to realize a fast and efficient layout, and improve design efficiency. First, radar design information is expressed through a graphical system model which is based on the KARMA language. The system model captures the aspects of the radar cabin layout from requirement, function, logical, and physical structure [11]. Then the system models are transformed into a GA toolkit for optimizing the layout of the radar cabin through code generation. The GA toolkit enables the generation of the optimal solutions of the radar cabin layout.

The rest of this article is organized as follows. In Sect. 2, the existing problems of radar layout design are introduced. In Sect. 3, descriptions of the semantic modeling and optimization of radar cabin layout are presented. Finally, we discuss our proposed approach in Sect. 4, and the conclusion is given in Sect. 5.

2 Problem Statement

When designing a radar cabin for UAV, it is one of the main carriers of radar equipment and operators. Its interior can be simplified to a cube of $7992 \times 1100 \times 1400$ mm, which is divided into 12 cuboid spaces. The fuel tank has occupied the space in the middle four cuboid spaces, which leads to that the cables can be only allowed for being routed. The two sides of each frame of the fuselage are equipped with antenna arrays, each of which is 333×350 mm, and each frame has 2×4 collections on one side. There are 96 antenna arrays on one side of the fuselage (see Fig. 1a), the required layout of the device in the engine room, and the logical relationship of the device (see Fig. 1b). "A, B, C…" indicates the type of device. Each device has the characteristics of quantity, length, width, and height.

In the current radar cabin layout, the document-centric radar layout design increases the designer's difficulty in understanding the architecture of radar cabin layout and gaps among radar engineers and UAV engineers. In terms of simulation optimization, the radar cabin's layout design is based on empirical approach, which lacks capabilities for generating layout automatically and rapidly. During the iterative design of UAV radar cabin among UAV engineers and radar engineers, consistency management between radar cabin design and radar cabin layout simulation cannot be supported in an appropriate way.

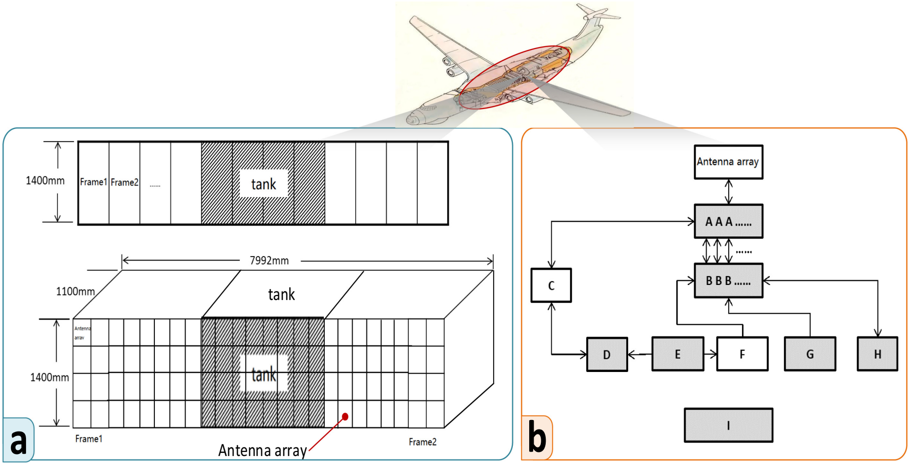

Fig. 1. Radar cabin (a) and the logical relationship diagram of the devices in the cabin (b)

In the design of radar nacelle layout in this paper, the cable length of all equipment A to the antenna array is r and the same length. And the length between device I and other devices are required to be as short as possible.

Through the above content, this paper makes uses of the MBSE approach and semantic modeling to support the radar cabin layout optimization and takes the model as the primary reference to manage consistency across design parameters of all devices. By integrating with the simulation optimization algorithm, an optimal layout can be generated. The optimization results can be configured to the MBSE models in order to manage consistency between design models and optimization models.

3 Semantic Modeling and Optimization of Radar Cabin Layout

3.1 Meta-modeling and Modeling of Radar Cabin Layout Using KARMA

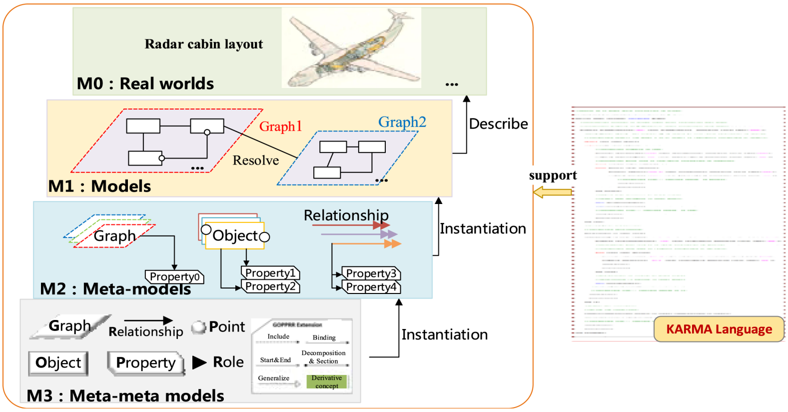

Fig. 2. M0-M3 Domain-specific modeling and GOPPRR

In order to support the MBSE process for radar cabin design, the framework of M0-M3 describes meta-meta models, meta-models, models, and the real world, as shown in Fig. 2. Meta-meta models refer to the six key elements, including Graph, Object, Port, Property, Relationship, and Role [12, 13], which are used to construct meta-models. In this paper, Meta-models are constructed based on the SysML specification. Meta-models are the model compositions for developing models. The models are used to describe the real world. Based on the GOPPRR meta-meta models and M0–M3 framework, the KARMA language is a semantic modeling language to describe meta-meta model, meta-mode, and models. In the KARMA language, it provides concrete syntax and abstract syntax to describe meta-models and models using a textual semi-formal approach.

Through KARMA language, meta-models are developed based on the SysML specification to support an RFLP (requirement function logical physical) MBSE approach. RFLP allows the definition of product elements and their relationships at different levels of abstraction [14]. Using the RFLP approach, requirements (R) refer to requirements associated with systems and subsystems. In order to support requirement formalism, we construct the meta-models, including the Requirement Diagram based on SysML specification as shown in Table 1. Function (F) is a function used to meet the defined requirements [15]. As shown in Table 1, we construct the meta-models, including the Use Case Diagram and the Activity Diagram based on SysML specification. Logic (L) is used to define logical components that can describe the radar cabin layout. Based

Table 1. Summary table of the radar system general layout modeling analysis

Meta Model: Graph	Model	Purpose
Requirement Definition		
Requirement Diagram	Radar system overall requirements diagram	Describe the functional & performance requirements of the radar system. (see Fig. 4a)
Function definition		
Use Case Diagram	Radar detection use case diagram	Describe the functional interaction of signal interception, tracking, and recognition during the detection process of the radar system. (see Fig. 4b)
Activity Diagram	Radar detection activity diagram	Describe the activity flow of the radar system to perform detection functions based on the environment. (see Fig. 4c)
Logical definition		
State Machine Diagram	Radar detection state machine diagram	Describe the state transition between radar detection signal, capture signal, and signal report. (see Fig. 4d)
Sequence Diagram	Radar detection sequence diagram	Describe the interaction of the radar system processor, sensors, and detectors overtime during the radar detection process. (see Fig. 4e)
Physical definition		
Block Definition diagram	Radar cabin layout block definition diagram	Describe the relationship between the components of the radar system and the constraint blocks between the components. (see Fig. 4f)
Internal block diagram	Radar cabin layout internal block diagram	Describe the internal components of the radar cabin and the topologies between the components. (see Fig. 4g)
Parameter Diagram	Radar cabin layout parameter diagram 1	Describe the parameters of devices (including length, width, height, quantity) (see Fig. 4h)
	Radar cabin layout parameter diagram 2	Describe device layout parameters (space coordinates of the devices) (see Fig. 4i)

on SysML specification, we construct the meta-models, including the State Machine Diagram and the Sequence Diagram, as shown in Table 1. Physical (P) is used to set up real physical components, focusing on design parameters about the radar cabin layout. Table 1 shows the Parameter Diagram, Internal block diagram, and the Block Definition Diagram based on SysML specification.

3.2 Optimized Algorithm Design

MATLAB optimization toolbox provides a commercial off-the-shelf library for optimization. The radar cabin layout optimization is implemented by MATLAB's built-in genetic algorithm toolkit. Users can freely adjust the values of parameters (individual, number of iterations, genetic mutation crossover operations, etc.) and intuitively observe the results of dynamic iterations.

According to the problem statement, this paper summarizes three optimization goals of the radar cabin layout: (1) the connection length between equipment A and the antenna array surface is the shortest. (2) the connection length difference between device A and the antenna array surface is the smallest. (3) the shortest connection length between device I and other devices. Through the optimization algorithm, the input information -- device characteristics (length, width, height, quantity) and the optimization targets can be output as the space coordinates of the devices.

3.3 Data Transmission Between KARMA Models and Optimization

As shown in Fig. 3a, code generation [16] is used to support the automatic generation of input files for the layout optimization model from the system model for describing radar cabin layout. In addition, after the layout optimization model is executed by the GA toolkit, the results are input to the MBSE models (the space coordinates of each device) to ensure the consistency of the system model information and the layout optimization model information.

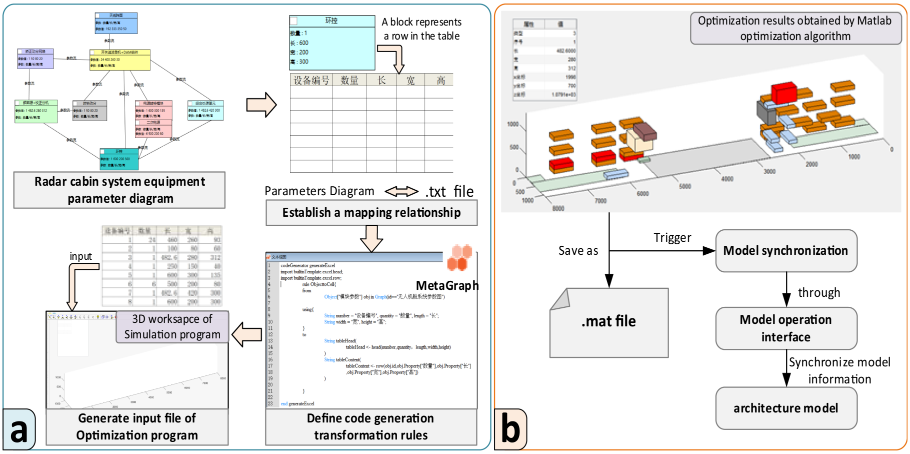

Fig. 3. Optimize process and parameter passing

As is shown in Fig. 3a, we adopt MetaGraph (MetaGraph is a multi-architecture modeling tool developed by Z.K. fc http://www.zkhoneycomb.com/) to construct KARMA language library for meta-models in Table 1. Moreover, in MetaGraph, the KARMA script for defining code-generation rules is developed, as shown in Fig. 3a. When defining the code generation script, mappings between model elements and the expected output table elements are created. Based on the above mappings, the KARMA script for code generation is compiled by the KARMA compiler and is executed by the code-generator. Then, the expected output tables are generated. Finally, the genetic algorithm toolkit in MATLAB is executed by loading the input table.

After obtaining the optimization results, referring to an optimal layout (including the space coordinate of each device), a mat file with such information is generated. Then a developed model synthesis tool kit load the information in the mat file and configure the parameters in the KARMA model through MetaGraph APIs. In the KARMA model, devices's property of the device space coordinate are null in the Radar cabin layout parameter diagram 2 (see Fig. 4i). After optimization, null values are changed to concrete spatial coordinates. Through the model synthesis toolkit, the property value in the KARMA model is synchronized from the optimization results (see Fig. 3b).

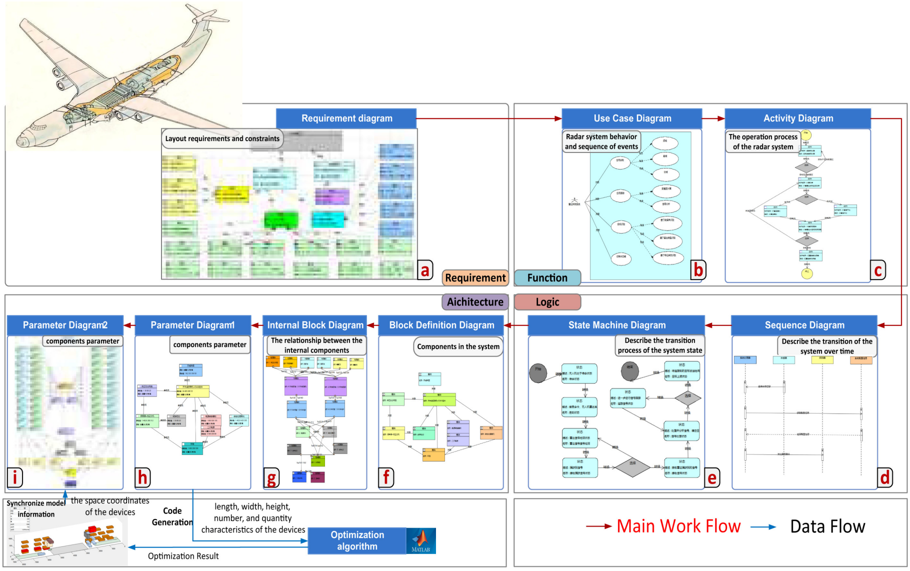

Fig. 4. RFLP modeling and data transfer process

4 Case Study and Discussion

In this paper, a UAV radar cabin case is proposed to evaluate our proposed semantic modeling approach. As shown in Fig. 4, the RFLP (Requirements-Functional-Logical-Physical) approach is used to build the KARMA models for the UAV radar cabin layout

MetaGraph. Requirement diagram model is created to describe the functional and performance requirements of radar cabin (Fig. 4 a). The use case diagram and activity diagram models are created to describe the use case and function flow of radar detection (Fig. 4b and c). State machine diagram and Sequence diagram models are created to describe data processing workflow for radar detection (Fig. 4 d and e). Then Block definition diagram and Internal block diagram models are developed to describe the physical structure of the radar compositions, particularly for radar cabin (Fig. 4 f and g). Moreover, one Parameter diagram 1 model is used to define each device's parameters (including length, width, height, quantity), referring to one object instance in the internal block diagram model (Fig. 4 h). Another parameter diagram model is used to define the space coordinate parameter of each device referring to one object instance in the internal block diagram model (Fig. 4 i).

After code generation from KARMA models, the table file is load into the MATLAB optimization toolkit, which implements the optimization and provides results, as shown in Table 2. Before the optimization, the coordinates of devices are null. Then through the model synchronization toolkit, the parameter diagram models are configured based on the optimization results.

Table 2. Summary table of the part of the optimization results

Divice	X coordinate	Y coordinate	Z coordinate
A	600	0	93
C	1998	400	798
D	333	800	798
F	2331	300	798
H	5328	200	393

For the case study, we create 8 Graph meta-models, using 649 lines of KARMA language, and 9 models using 6932 lines of KARMA language, presented in Table 3. We find through the KARMA semantics, and all the model information is described by semantics modeling. Moreover, through code-generation and model synchronization, the data between KARMA models and optimization models can be integrated. In summary, the contribution of this paper is to use the semantic modeling based on KARMA language and the RFLP approach to formalize the radar layout and to implement optimization for radar layout automatically through the code generation and model synchronization.

Table 3. Summary table of models information

Model type	Number	Lines of code in the Karma language
Graph meta-models	8	649
Models	9	6932

5 Conclusion

This article mainly makes use of MBSE to optimize the layout of the radar cabin and to support consistency management of design parameters across MBSE models and optimization models. We adopt KARAM language to support semantics modeling for the radar cabin layout from the perspectives of requirement, function, logical and physical structure. Then by using code-generation, KARMA models are transformed to optimization models, which are executed by MATLAB optimization toolkit. From the GA algorithm, the optimal layout is obtained and synchronized with the KARMA model. From the case study, we find the KARMA language enables to formalize the radar cabin design based on 9 diagrams of SysML specification. Moreover, optimizations can be executed automatically after getting data generated from KARMA models. Finally, the optimization results enable to synchronize with KARMA models. Thereby, the proposed semantic modeling approach improves design efficiency and quality during radar cabin design.

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