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The Research on Driving Meta-model of Large Rotary-type Cylindrical Antenna

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Abstract. As a complex system with highly integrated multi-discipline, the large rotary-type cylindrical antenna is favored by more and more researchers in IPS detection and large-area survey observation. Due to its complex structure, huge volume and large motion inertia, high requirements on the drive system are indispensable, and there exist some certain limitations in the traditional system design method. This article proposes a large rotary-type cylindrical antenna driving system modeling method based on the meta-model. The domain-specific modeling language of the antenna driving system is defined by extending SysML, and the domain meta-model of the antenna driving system is constructed on this basis. The functional modeling of the antenna driving system is based on the meta-model to support the analysis of the antenna driving process, improve the modeling efficiency and model reusability, and provide a research foundation for the subsequent system modeling design of large antenna.

1. INTRODUCTION

The large rotary-type cylindrical antenna is an important equipment for deep space exploration in astronomy, which indirectly completes the detection of solar wind and dark matter dark energy through Interplanetary Scintillation (IPS) detection and sky survey observation. As the antenna design shows the trend of larger aperture, higher driving accuracy and more complex structures are proved to be needed, the traditional antenna driving design is based on natural language and 3D modeling description, lacking demand analysis and forward derivation, which is difficult to describe and analyze the driving process in detail. To address the above problems, the system model is used to visualize the antenna drive system. On the one hand, it is easy for engineers in different fields to understand and discuss the drive system through the model description and reduce the threshold of use; on the other hand, the model can describe the drive process and the composition of the drive system in detail and improve the design efficiency. Therefore, the concept of domain meta-model is introduced to address the design complexity of antenna drive system, it forms the antenna drive domain modeling language. And carry out the design research of system model to solve the problems of model expression irregularities and reuse difficulties in traditional design.

Wang Peng [1] addressed the problem of insufficient standardization of satellite simulation model design, based on the concept of meta-model, clarified the design process and composition elements of satellite simulation meta-model, realized the standardized design of satellite simulation meta-model and effectively guided the design development process. Yuan Wenqiang [2] took the high voltage system of the rolling stock as the research object, defined the functional meta-model and component meta-model according to the system domain knowledge, and constructed the model library of functions and components. And realized the automatic generation of its architecture scheme by defining the inference rules of the high voltage system of rolling stock, which improved the design modeling efficiency. By analyzing and extracting the domain knowledge of avionics system, Zhang Xiaoli [3] adopted the analysis method based on oriented domain meta-modeling, constructed the meta-model of integrated avionics partition-level communication and generated the domain-oriented meta-modeling language, with good comprehensibility and ease of use, which can significantly improve the development efficiency of avionics systems.

The current modeling of large complex systems is based on domain-specific modeling, mainly because the standard System Modeling Language (SysML) is a domain-independent modeling language, which needs to be extended based on domain semantics to form Domain-specific Modeling Language (DSML) in practical applications [4].In order to improve the efficiency of large antenna system design, reduce the threshold of use and standardize the design process, this paper combines practical experience to propose a modeling method for large rotary-type cylindrical antenna drive meta-model, model and analyze the drive process in detail based on the drive meta-model, and provide a research basis for the subsequent design of large rotary-type cylindrical antenna system.

2. META-MODEL MODELING METHODS

In order to define the DSML of the large rotary-type cylindrical antenna driving system, it is necessary to create the driving system meta-model. The meta-model is the model of a model, through which the concepts, attributes and relationships of the model can be defined, and it is the specification that guides data storage and exchange. The meta-model not only standardizes the acquired metadata and defined concepts and determines the basic elements of the constructed system model, but also solves the problem of data consistency and information sharing in the system and improves the reusability of the model [5]. The creation of meta-models requires compliance with certain modeling languages and specifications, and the current common meta-modeling specification is the Meta Object Facility (MOF), which is one of the standards included in the Model Driven Architecture (MDA) proposed by the Object Management Group (OMG) [6]. As shown in Figure 1 it contains the following four-tier:

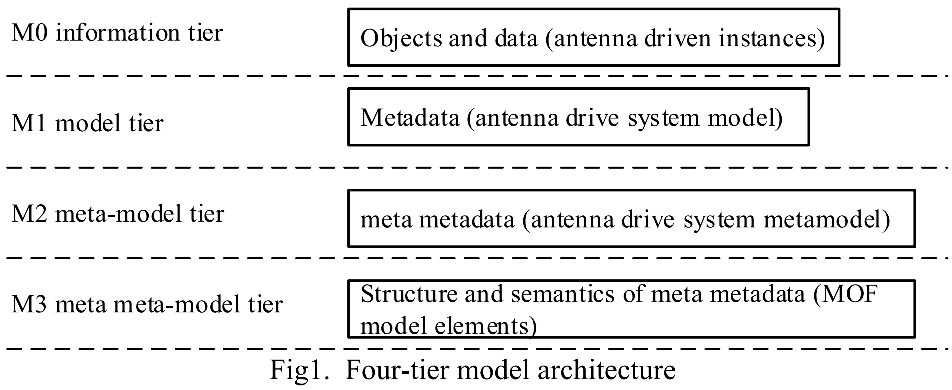

Fig1. Four-tier model architecture

(1) Information tier M0, which consists of object-specific data to describe the details of the object.

(2) Model tier M1, consisting of metadata, is an "abstract language" without concrete syntax or symbols defined to describe the information tier. The data in the information tier is an instance of the model tier.

(3) Meta-model tier M2, which consists of metadata, defines the structure and semantics of metadata, and is an "abstract language" defined to describe the model tier. The model tier is richer and more detailed than the meta-model tier, and the abstraction of the model tier can lead to the meta-model tier. The model is an instance of a meta-model.

(4) Meta meta-model tier M3, which defines the structure and semantics of meta metadata, is an "abstract language" defined to describe the meta meta-model. The definition of meta meta-model is more abstract and concise than meta-model, and a meta meta-model can define multiple meta-models, and each meta-model can be associated with multiple meta meta-models. A meta-model is an instance of a meta meta-model.

In this paper, the DSML of the antenna drive system is constructed based on the meta-model tier of the four-tier modeling architecture, using the class diagram of the Unified Modeling Language (UML) to create the domain meta-model of the antenna drive system and to standardize the model elements and the relationships between them. The extension of SysML is to carry the specifics of the domain meta-model by creating the stereotype, on which the antenna drive system model is created using the stereotype. So the functional modeling of the antenna drive system based on the meta-model is carried out in the three steps in Figure 2.

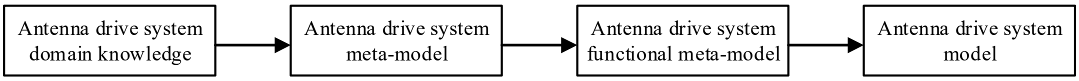

Fig2. Drive system modeling method based on meta-model

(1) Extraction of system domain knowledge: Identify the concepts, relationships and interfaces involved in the antenna drive system based on the domain knowledge involved.

(2) Define the abstract syntax: Based on the knowledge of MOF syntax, define the abstract language of the above domain knowledge using UML class diagrams, and construct the domain meta-model of the antenna drive system.

(3) Definition of concrete syntax: SysML is extended by creating the stereotype, which defines the corresponding representation and notation for each model element as its concrete syntax based on the abstract syntax, thus generating a functional metamodel of the antenna drive system.

(4) Establish system model: Based on the functional meta-model of antenna drive system, establish the functional model of antenna drive system.

3. ANTENNA DRIVE SYSTEM DOMAIN META-MODEL

The antenna drive system domain meta-model is built based on the domain knowledge of the drive system. This section first extracts the domain knowledge of the antenna drive system and creates the antenna drive system domain meta-model to provide a model basis for the subsequent specific modeling process.

3.1. Extraction the drive system domain knowledge

The large rotary-type cylindrical antenna is an important equipment used for IPS detection and large area patrol observation, and the antenna needs to be tilted and rotated during the observation process to expand the area of patrol observation to receive more electromagnetic wave signals.

The aperture of the antenna is 40m×44m, the angle of pitch rotation is ±45º, the pitch rotation speed is 0.15º/s, the rotation form is intermittent rotation, and the main driving method is cable traction drive.

Define the functional meta-model based on the domain knowledge involved in the antenna driving process. Describe the elements of the functional model of the antenna drive system and the relationships between them. As shown in Figure 3, functions are represented by the Function elements, which can be divided into basic functions, auxiliary functions and extended functions according to their different natures.

Further refinement of function types can become more semantically specific function types, such as basic functions can be divided into rotation, braking, sensing, support, detection and tensioning, and extended functions can be divided into locking, unloading, positioning, lubrication and sealing, etc.

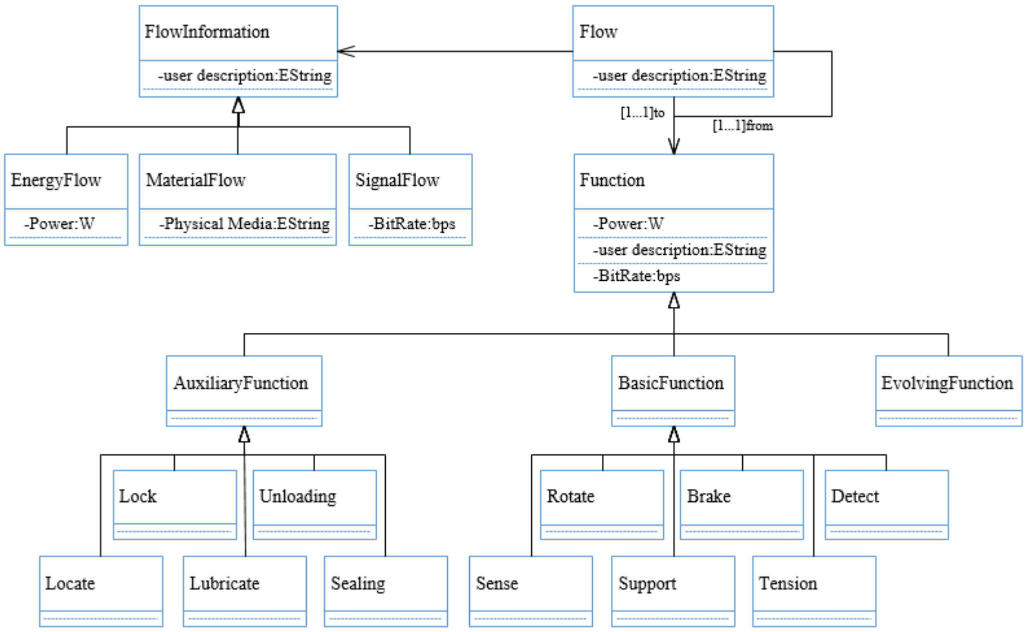

Fig3. Functional meta-model

The types of functions in the antenna drive system and their meanings are shown in Table 1.

Tab.1 Function types and meanings

MOF elements	Information Type	Meaning
Basic Function	Basic	Antenna drive systems have basic types of functions, such as rotation, braking, sensing, support and tensioning.
Auxiliary Function	Assist	The type of function that the antenna drive system has a secondary role in satisfying the the needs of basic function, such as locking, positioning, sealing, etc.
Evolving Function	Extension	Types of features that are not currently available in the antenna drive system, and new types of features that may be introduced in the future.

Information is transferred between functions through Flow, and the information type is expressed through Flow Information, which is divided into energy flow, material flow and signal flow according to different information types, and the various types of flow information types and their meanings are shown in Table 2.

Tab.2 Flow information types and meanings

MOF elements	Information Type	Meaning
Energy Flow	Energy	The energy transferred between functions, such as heat, electricity, etc.; the attribute Power indicates the power of energy.
Material Flow	Matter	The material transferred between functions, and the attribute Physical Media denotes the physical medium through which the material is transferred.
Signal Flow	Signal	The electronic signal passed between functions, and the attribute Bit Rate indicates the bit rate of the signal transmission.

3.2. Extending the drive system modeling language based on SysML
Based on the domain meta-model of the antenna drive system, the model elements which provided by SysML are extended by creating the stereotype to create model elements containing domain related semantics. According to the semantics, function represents a certain expected goal that the drive system should achieve; according to the syntax, function can be decomposed or instantiated to form other functions. The functional meta-model consists of three main parts: (1) functions and their subclasses, which represent various types of functions. (2) flows between functions, which represent the information transfer relationship between functions. (3) flow information and its subclasses, which represent the information passed between functional flows. Therefore, from the syntactic and semantic point of view, the closest SysML model element to the function is Activity, and the stereotype of the function and its subclasses are extended from Activity. The properties of the function are defined by the tag inside the stereotype, and the information transfer between Activities is represented by Object Flow, and the Flow is extended. As shown in Figure 4, there is a corresponding relationship between stereotype and function meta-model which shown in Figure 3, including basic functions, auxiliary functions and extended functions, and then more detailed types of functions are refined from them.

Function instance is a specific execution of function, the function is represented as Activity, and the specific execution is represented as Action, because the semantics of this class action is the most flexible, and its specific execution can be described by natural language, so Opaque Action is chosen as the base type of function instance. As shown in Figure 4, the stereotype of the functional instance is extended from Opaque Action, the property is added as functional mode, and the two states of the functional mode are enumerated as stationary and rotating according to the two different states of the driving process.

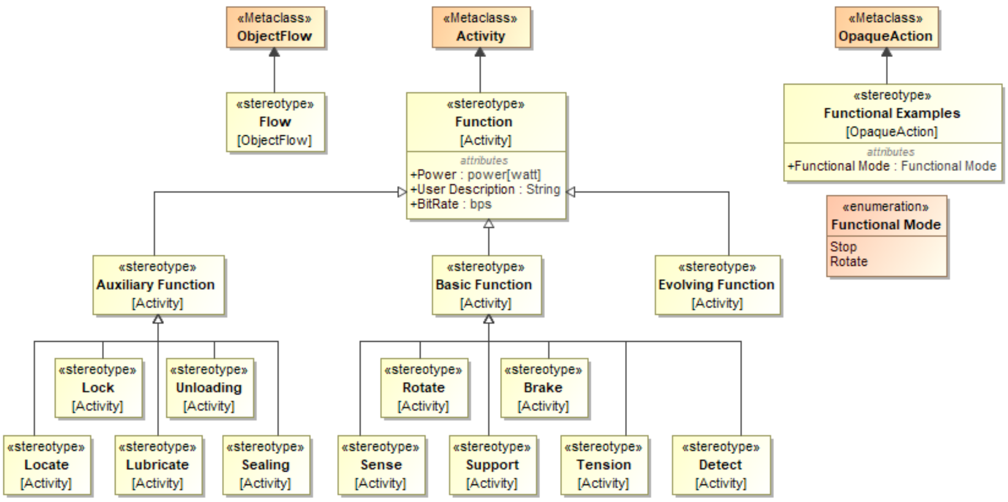

Fig4. Functionally related stereotypes

The functional parameters, conditions and interfaces in the functional meta-model are not define the stereotype, for the reason that they are subordinate to the functions as well as functional instances. The functional parameters are represented by the Activity's Parameter and Constraint, and the functional interfaces are represented by the Action's Pin, and their stereotype can be inferred from the functions and functional instances. The logical relationships between functional instances in the meta-model are represented by Control flow between Actions, where complex logical relationships are represented by control nodes such as Decision and Fork. In SysML, the information conveyed by Object Flow is represented by the attribute Conveyed Information, which describes the types of information conveyed by setting the defined Block. As shown in Figure 5, the stereotype of Flow Information is inherited from the Block, and different types of flow information, such as energy flow, material flow and signal flow, are distinguished through sub-stereotype.

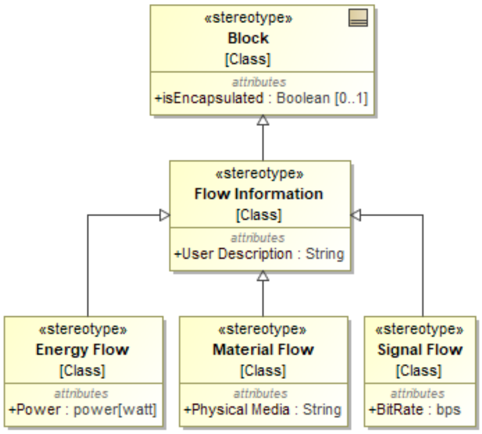

Fig5. Stream information related stereotypes

3.3. Drive system meta-functional modeling process

Meta-functions as basic units are able to compose various complex functional processes, thus improving the reliability and efficiency of functional modeling. Based on the domain meta-model in the previous chapter, the meta-function of the antenna drive system is established, and some of the meta-functions are shown in Figure 6. The modeling of each meta-function is divided into four steps as follows:

(1) Creating the SysML Activity, naming it the name of the meta-function to be created.

(2) Setting the sub-stereotype of the meta-function for the Activity, such as drive, brake, etc.

(3) Describing the attributes of the meta-function by the Tag of the stereotype, such as power, rate, etc.

(4) Defining functional parameters for the Activity, such as pull, displacement, etc., and also specify the type for the functional parameters.

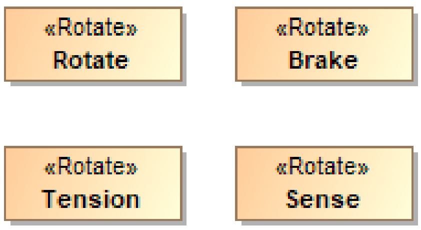

Fig6. Meta function example

Functional modeling is divided into two steps: functional decomposition and process analysis:

(1) Functional decomposition. The complex function can be decomposed into several sub-functions, which can describe the antenna drive process in more detail, and the inclusion relationship between the upper and lower level functions is represented by Composite, and the different decomposition layer relationships are represented by block definition diagrams. The derivation relationship between the functions is represented by the Allocate. An example of function decomposition and derivation relationship is shown in Figure 7. The cable traction drive function is the upper function, which can be decomposed into two lower functions, drive and brake, and these two functions can deduce the guide rail rotation and obtain the position information.

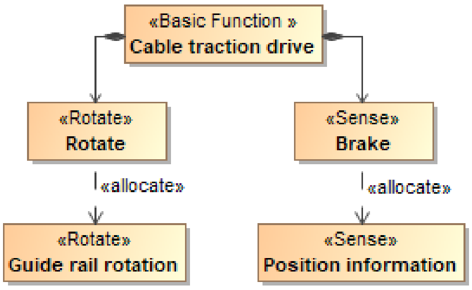

Fig7. Example of functional decomposition

(2) Process analysis. For complex functions, by analyzing the input-output relationships between sub-functions, the specific execution process of the function can be clarified and described specifically with activity diagrams. For the identified sub-functions, if they are still complex functions, the above two steps of functional decomposition and process analysis are carried out iteratively for these functions, so that all underlying functions can be identified. Process analysis example is shown in Figure 8, in the activity diagram shows the relationship between the two activities of rotation and braking and their input-output relationship. During the rotation of the antenna, the input starts as tension, the rotation function starts, the output is the displacement of rotation, and after reaching a certain position, the braking function starts, and the output is the friction force, resulting in a complete functional flow.

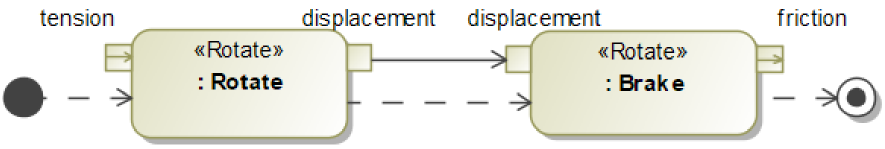

Fig8. Process analysis example

4. VERIFICATION OF FUNCTIONAL MODELING FOR DRIVE SYSTEM BASED ON META-MODEL

Based on the functional meta-model and functional modeling process, the driving process of large rotary-type cylindrical antenna can be modeled and analyzed. The antenna is driven mainly by cable traction, and the back frame of the antenna is rotated by the winch at the bottom to drive the cable and pull the rolling guide rail, so as to realize the change of different observation angles. The functional modeling of the antenna drive system starts to from the drive scenario, and firstly analyzes the antenna drive scenario, showing the composition of various elements in the drive system and different activity scenarios through use case diagrams, and analyzes the use case scenarios involved in the process of the cable traction drive. As shown in Figure 9, the designer, maintainer and operator are the stakeholders in the process of cable traction drive, and the cable traction drive is the main use case, from which four sub-use cases of cable drive, infrared sensing, ball bearing and rail braking can be subdivided. The top-level functional activities of the cable traction drive can be developed from the use cases, and the activities of the cable traction drive are configured as basic functions, corresponding to the classification of functions in the functional element model.

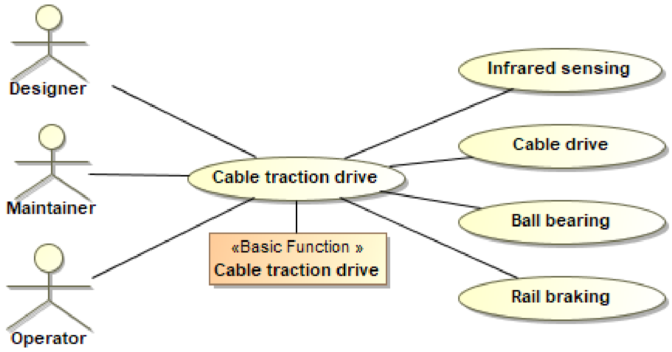

Fig9. Drive use case

Analysis of the cable traction drive, the antenna will follow the following driving process for each rotation, firstly, the drive system is energized, the cable drive mechanism drives the upper rail of the rolling guide to rotate, thus driving the ball between the upper and lower rails to roll, after rotating a certain angle to a fixed position, the infrared sensor touches the positioning contact on the lower rail after the cable stops pulling, the antenna stops rotating and observation, repeat the above process to complete the observation task. The function of the observation process is organized into a functional activity flow, including functional activities such as rail rotation, ball rolling, reaching fixed position, sensing position and rail stop, etc. The corresponding functional activities such as rotation, positioning, sensing and braking stereotype are set respectively, and the functional activities are connected in order through the control flow to form a complete activity flow, as is shown in Figure 10.

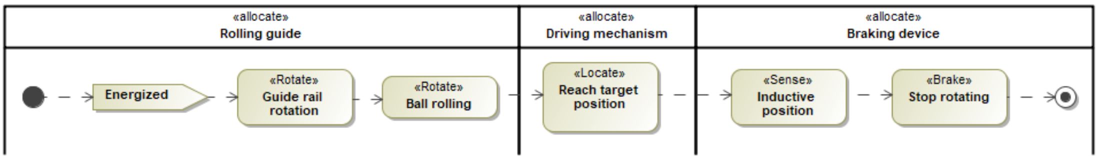

Fig10. Cable traction drive process

Decomposition of the functional activity of the rail rotation, as is shown in Figure 11, when the antenna rotates in the first direction, the first duplex reel winch is turning positively involved in the cable, pulling the upper rail to the first direction; the second duplex reel winch unlocks itself, the cable on the second duplex reel winch is rolled out under the pull of the upper rail, the second duplex reel winch makes the cable being pulled out to maintain a taut state. In this process it is necessary to detect the tension on the cable and control the tension value within the set threshold to ensure the safety of the transmission process. Organize the above process into functional activities, and set the corresponding stereotype for them, and connect them through the control flow to become a complete functional activity process. In addition, consider the failure problem in the process of cable pulling the upper rail movement, there are mainly two main faults in the rotation process, motor failure and cable breakage, and need to reflect this functional process in the activity diagram, so two taps are divided with decision control nodes behind the motor positive rotation activity diagram and the tension induction activity diagram, one is the process of normal rotation and the other is the process of fault.

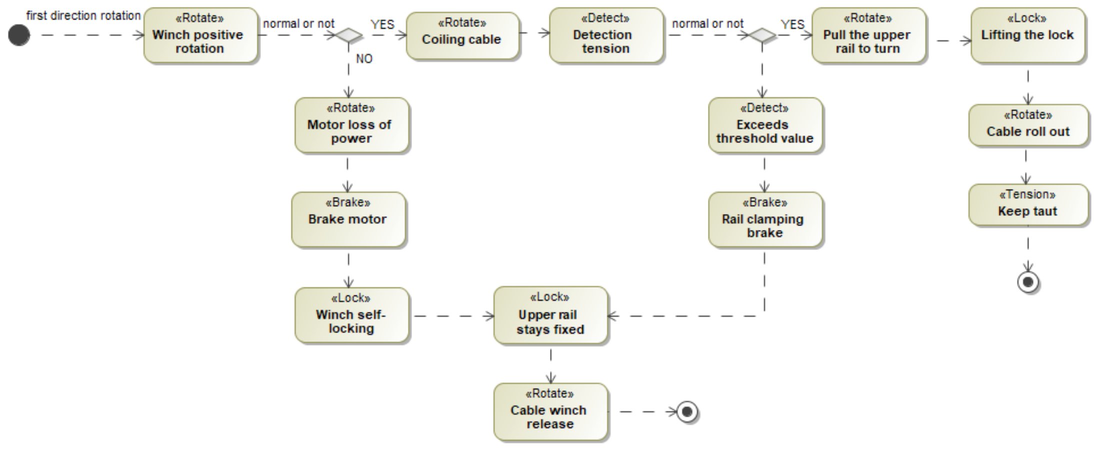

Fig11. Function decomposition of cable traction drive

After completing the functional decomposition, the functions are assigned to logical components to generate the composition structure of the antenna drive system. As is shown in Figure 12, each functional activity is mapped to the corresponding logical component according to the cable traction drive process, for example, the functional activities of the winch are mapped to the winch, the functional activities of the brake are mapped to the brake, the functional activities of the guide are mapped to the rolling guide, and the functional activities of the cable and tension are mapped to the cable set.

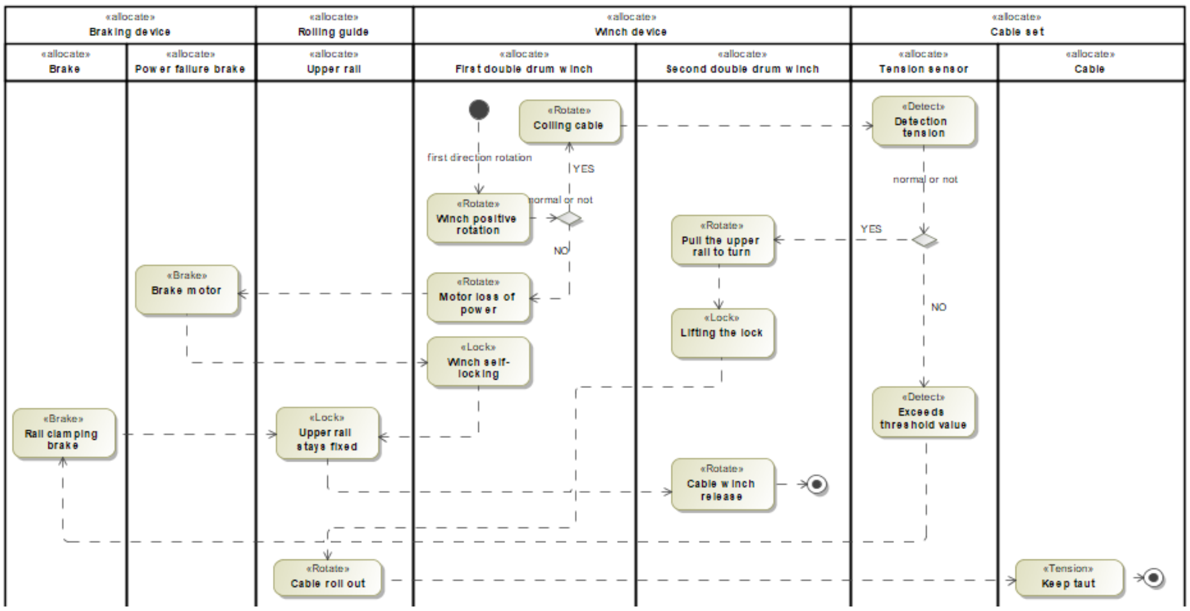

Fig12. Cable traction drive function allocation

A more complete logical component of the drive system is obtained through the functional decomposition and function allocation of the cable traction drive, as is shown in Figure 12, the drive system mainly includes three parts, such as rolling guide, drive mechanism and brake device. The upper component can be further subdivided to obtain more detailed components, such as rolling guide including upper and lower guide, drive mechanisms including winches, cable sets and pulley sets, and braking devices including brake blocks, de-energized brakes and locking mechanisms.

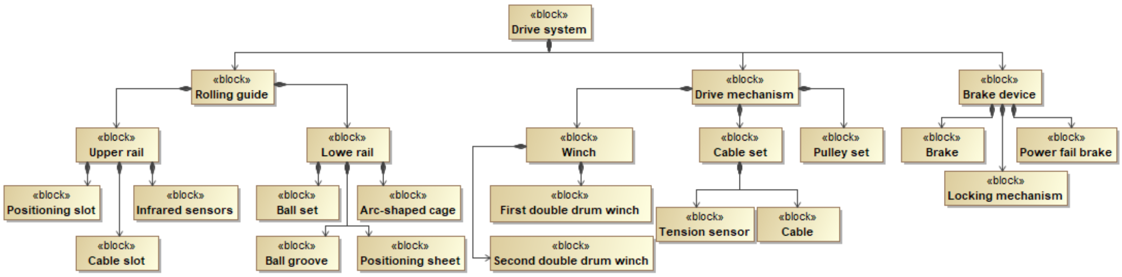

Fig13. Logical components of the drive system

5. Result & Discussion

By carrying out model based and meta-model based engineering pilot practice for large rotary-type cylindrical antenna drive systems, the advantages and disadvantages of the ordinary model-based design process and the meta-model based design process are compared and analyzed, and the results of the comparison of the two methods are shown in Table 3.

Table 3 Comparison of ordinary model design process and meta-model design process

Sequence	Compare	Ordinary model design process	Meta-model design process
1	Modeling languages	Based on UML, SysML.	Based on DSML.
2	Design basis	Based on the ordinary design process.	Based on large antenna domain design process.
3	Usage threshold	Proficiency in UML, SysML, ordinary modeling methods and antenna domain knowledge.	Proficiency modeling methods and domain knowledge in large antenna.
4	Reusability	Model elements need to be redefined for each design.	Data can be extracted from different tiers after each design to form a database with good reusability.
5	Guidance role	Easy to access and highly instructive.	The design can be iterated quickly in the database, which is practical and efficient.
6	Modelling efficiency	The modeling of the antenna drive system took about 70 hours.	The modeling of the antenna drive system took about 24 hours.

From the comparison in Table 3, it can be seen that the ordinary model design process is based on UML and SysML, and the design through the ordinary design process needs to be familiar with the above methods and combine with antenna domain knowledge, which is high demand on modelers and poor model reuse. The meta-model design process based on antenna domain modeling language only requires the mastery of antenna domain modeling methods and domain knowledge, which can be extracted into a database after the design is completed, with low threshold of use, good reusability and high practicality. By designing the same antenna drive system with both methods, its meta-model modeling time is reduced by about 34%.

6. Conclusion

This paper constructs the domain meta-model of the antenna drive system by extending SysML by creating stereotypes, establishes the functional meta-model of the drive system, and finally validates the analysis by antenna drive examples. The results show that the functional decomposition and process analysis of the complex functions of the cable traction drive by this method improves the reusability of the model and modeling efficiency, and makes the functional analysis process more standardized. Future work will further explore the large antenna system meta-model based on the existing work, and provide some research basis for the system modeling analysis based on large rotary-type cylindrical antennas.

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