applied sciences

MDPI

Article

Reconfigurable Modeling Method of Task-Oriented Architecture for Space Information Networks Based on DaaC

Shaobo Yu and Lingda Wu *

Science and Technology on Complex Electronic System Simulation Laboratory, Space Engineering University, Beijing 101416, China; 13204808788@163.com

* Correspondence: wld@nudt.edu.cn; Tel.: +86-10-6636-4329

Received: 26 December 2018; Accepted: 8 January 2019; Published: 13 January 2019

Abstract: As an important national strategy infrastructure, the Space Information Network (SIN) is a powerful platform for future information support. The architecture model of the SIN is of great significance to the construction and development of the SIN. For the problems related to the poor versatility, portability, and recombination of the existing architecture modeling methods of the SIN, in this paper, based on the Data as a Center (DaaC) modeling idea, we propose a reconfigurable model of the task-oriented architecture of the SIN. Combining with the typical characteristics of the SIN, and drawing on the advantages of activity-based flexibility, service-oriented integrity, and object-oriented reusability, we propose a DaaC modeling idea with space data. The DaaC modeling idea can solve the problems related to the poor versatility and portability of the SIN architecture. Based on the DaaC idea, we analyze the requirements of the task-oriented architecture, and define the basic concepts of SIN reorganization, including the reconfigurable target, reconfigurable scheme, and reconfigurable SIN. We establish the reconfigurable principles of loose coupling, compatibility, isolation, and deconstruction. Meanwhile, we analyze the realization mechanism and methods of the task-oriented reconfigurable model of the SIN based on DaaC. Finally, we take a typical SIN as an example, and make a case study on land-based anti-missile combat activities as the task background based on the DoDAF2.0 (Department of Defense Architectural Framework 2.0) framework and the STK (Satellite Tool Kit) simulation platform. The case results are consistent with the theoretical expectation, and it verifies the feasibility and effectiveness of our proposed method.

Keywords: space information networks; architecture; data as a center; reconfigurable model; task-oriented; resource reorganization

1. Introduction

In recent years, with the rapid development of manufacture level of satellites, launch technology of rockets, and interstellar communication technology, the role of the Space Information Network (SIN) is more important to national defense and people's livelihoods [1–3]. There are many countries of the world that are fully aware of the important role of SIN in international competition and national economic development. They are actively carrying out research in relevant areas, especially in countries such as the United States, Russia, and Japan [4]. The SIN is developing from the space-based integrated information network, space-based information system, and space information system [5]. As a complex information system, the SIN is the main platform for information support, and it is the important infrastructure for situational awareness. Since 2013, the National Natural Science Foundation of China has carried out a major research project on the "Basic Theory and Key

Technologies of Space Information Networks" [6]. For the scientific issues of network architecture, dynamic information transmission theory, space information characterization, and space-time fusion in SIN, the research teams from Wuhan University, Tsinghua University, Hong Kong Polytechnic University, Nanjing University, and the Chinese Academy of Sciences, and so on, have done a lot of in-depth research, and they also have achieved considerable results [5,7–12].

Relating these results to the current research situation, although the scholars have studied the above-mentioned scientific problems from different angles, the development of the SIN is still in the primary stage. Meanwhile, there are still some scientific issues to be studied further, including: (1) the architecture models of SIN being poor in standardization, versatility, and portability; (2) the lack of research results regarding the topology evolution model of the SIN; (3) the lack of a visualization system to assist users to build, develop, maintain, and manage SIN. For these problems, we have carried out the research on the topology evolution model, and the interactive visualization system of the SIN in our previous work [13,14]. However, for the architecture models of SIN, we have proposed a Data as a Center (DaaC) modeling idea, and the DaaC modeling idea can solve the problem of the poor versatility and portability of the SIN architecture [15]. In this paper, for the problem of recombining the existing architecture modeling methods of the SIN, we propose a reconfigurable modeling method of task-oriented architecture of SIN based on the DaaC idea.

Architecture is originating from the meaning of design and construction in architecture, and later it is introduced into computer technology, system engineering, and other fields [16–18]. The definition and understanding of architecture is also constantly deepening and perfecting. Up until now, the academic circles have thought that architecture refers to the structure of the network or system and its mutual relations, and the principles and guidelines to guide the design and development of the network or system [19]. For example, in the construction of the C^4ISR (Command, Control, Communication, Computer, Intelligence, Surveillance, and Reconnaissance) system, the United States (U.S.) military requires that the architecture of the system be designed first. Moreover, the corresponding investment and development plan ought to be determined according to the system architecture, in order to guide the development and construction of the C^4ISR system [20,21]. Through analogy with the SIN, the architecture is the blueprint of its construction and development throughout its life cycle. Meanwhile, it is also an indispensable link for the construction and development of the SIN.

Through the joint efforts of scholars in recent years, for the modeling issue of SIN architecture, there are some basic methods. Those methods are summarized as an integrated two-tier architecture modeling method based on a service layer and a network layer [22], the networking and modeling method of the SIN based on the hierarchical autonomous domain [5], the modeling method of the SIN architecture based on the distributed star-group [23], etc. The advantages of the above methods, including the complexity of structure of SIN, are fully considered. Therefore, the design of its architecture is carried out through stratification and chunking. However, those methods are poor regarding their versatility and portability. As a national infrastructure, the SIN provides information support and information guarantee for military and people's livelihoods. In fact, the size of the tasks and the focus of task requirements are different, and the differences in the provision of services by SIN are greater. For a specific task, if the whole SIN is involved in this task, it can lead to the following phenomena. One is that the delay of information transmission will be increased due to the large structure. The other is a huge waste of space resources due to the introduction of some non-essential components. Thus, it is necessary to consider the recombination of the SIN architecture.

As a result, in the processes of modeling and designing the SIN architecture, we not only need to consider the versatility and portability of its architecture, but also the recombination of its architecture. Considering the versatility and portability of SIN architecture is for the overall situation. However, the reconfigurable SIN architecture is based on the whole situation, and is for specific tasks, that is, it is task-oriented. For the task-oriented requirements, the SIN architecture is rapidly reorganized for the specific task with the task as the traction. After the task is finished, it can realize the real-time release of the recombinant resources. Ultimately, the reconfigurable SIN provides the required functionality with minimal resources and smaller cost.

As mentioned earlier, we have proposed a DaaC modeling idea that solves the problem of the poor versatility and portability of the SIN architecture. To overcome the problem of recombining the SIN architecture, and meeting the needs of the dynamic reorganization of the architecture according to specific task, we present a reconfigurable modeling method of task-oriented architecture for SIN based on DaaC in this paper.

The remainder of the paper is organized as follows. Section 2 discusses the related work, including the concepts and features of SIN and the DaaC modeling ides. In Section 3, we build the reconfigurable model of the task-oriented architecture of SIN based on DaaC. Section 4 presents the verification of the instances, and we use a typical SIN as an example for the implementation. Section 5 discusses the verification results. Section 6 concludes the paper.

2. Related Work

The purpose of this section is to introduce the concepts and features of the SIN, and analyze the modeling idea of DaaC.

2.1. SIN Concept and Its Features

Researchers have presented various interpretations for SIN [7–12]. Combined with the main research plan of the National Nature and Science Fund of China, "Space information networks-based theory and key technology [6]", we define the concept of SIN as follows.

Definition 1 (SIN). *SIN is an integrated information network system and network infrastructure that is carried by space platforms. It is composed of a GEO (Geostationary Earth Orbit) satellite system, a MEO (Medium Earth Orbit)/LEO (Low Earth Orbit) satellite system, other information systems (such as HABs (Hot Air Balloons) or UAVs (Unmanned Aerial Vehicles) in near-space), and ground terminals (which are mainly responsible for control). It can support real-time data acquisition, transmission, and the processing of mass data, and achieve systematic information service application through integrated network interconnecting. It provides integrated investigation, navigation, communications, and other services, and realizes battlefield situational awareness (such as communication broadcasting; investigation and surveillance; intelligence detection; navigation and positioning; missile warning; and weather, hydrology, and terrain).*

Combining the concept and functional requirements, we design the composition and architecture of SIN as shown in Figure 1.

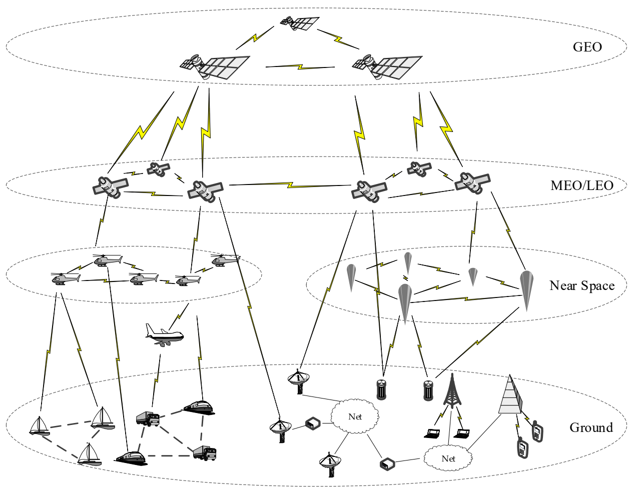


Figure 1. Composition and architecture of the Space Information Network (SIN) (adopted from S.Y. et al. [13]).

As shown in Figure 1 above, we designed the four-layer structure of the SIN. By analyzing the structure of its backbone network and other supporting facilities, we determined the specific components of the SIN. According to its function and Definition 1, the SIN should be mainly composed of four layers: the GEO layer satellite system, the MEO/LEO layer satellite system, the near-space layer information system, and the ground layer terminals. Meanwhile, the basic design ideas are building space-based backbone networks—including GEO and MEO/LEO layer satellite systems to solve global coverage issues—building a near-space backbone network, including the near-space layer information system to solve regional strengthening issues, and building ground layer terminals to achieve command and control.

Compared with other network systems, the SIN has both similar basic features and some typical features, and those typical features are the key focus and critical links of the research on the SIN. As shown in Table 1, we divide and categorize some typical features of the SIN.

Table 1. Typical Feature Classification of SIN (Space Information Network).

	Basis of Division	Feature Categories
1	Scale Structure	Complex Feature
2	Networking Structure	Heterogeneous Feature
3	Scope of Business	Heterogeneous Feature
4	Resource Distribution	Restricted Feature
5	Space Distribution	Hierarchical Feature
6	Space-Time Behavior	Dynamic Feature

As shown in Table 1, the emergence of the above characteristics has led to many difficulties in the study of the SIN, such as the difficulty in system design, information acquisition, dealing with the satellite, routing on the satellite and network management, etc.

2.2. DaaC Modeling Idea

Space data is accompanied throughout the cycle of SIN, and it includes entity data and network data. No matter how the composition structure of the SIN changes, one of its components is invariance, and the space data resources will not be reduced. Meanwhile, with the collection, storage, and management of space data, the amount of space data resources will also gradually increase. In the current period, with the vigorous development of the theories and technologies of big data, data resources have gradually become a valuable asset in various fields. This is no exception for SIN. Therefore, this leads us to explore whether we can build the SIN architecture by making full use of those space data resources.

At the beginning of the architecture framework design, scholars proposed a concept of "product" to meet the basic needs of system architecture design and modeling. Its essence and core is to make the reusable and interoperable data into a "product". The most common products include graphics, documents, etc. [24]. Since the proposal of the concept of the product, it has been considered the best choice for the description and modeling method of system architecture. In addition, earlier versions of the DoDAF (U.S. Department of Defense Architecture Framework)—version 1.0 and version 1.5—relied on "products" to run through the entire process of architecture description and modeling [25]. With the continuous use of "products", its shortcomings are increasingly prominent. The method has artificial subjectivity, and its portability and versatility is relatively poor.

As a new concept, the SIN is gradually evolving from the concepts of the space information system (SIS), space equipment system (SES), etc. Therefore, this inspires us to consider whether we can refer to the architecture modeling method formed by its predecessor as the object and realize the architecture modeling of the SIN. For the predecessors of the SIN, some typical architecture modeling methods have been formed, and can be summed up into three categories: the modeling method based on the unified modeling language (UML), the activity-based architecture modeling method, and the service-oriented architecture modeling method [17,26–28]. Through comparative analysis, it can be seen that the UML-based method is an object-oriented analysis method, which is highly reusable and easy to upgrade and maintain. The activity-based approach takes the activity as the starting point; it is based on the core entity object of the architecture, and it has the advantages of flexibility and cross-product association. The service-oriented approach itself involves distributed software architecture that can describe the system architecture as a whole, thus improving the flexibility and adaptability of the architecture design. However, there are some shortcomings in the above methods, such as the poor interoperability and dependence on experience in the design process.

Combined with the concept and features of the SIN, it can be seen that its nodes and links are dynamic and diverse. Correspondingly, the increase of network scale and the enhancement of network operation dynamics will increase the complexity of updating and planning the SIN architecture. Therefore, graphics, documents, and other "products" cannot be copied to accurately achieve effective the architecture description and modeling of the SIN. In addition, for a network with more complex structures, there is an urgent need to explore a new idea in order to realize the description and modeling of its architecture. The product is generated by data, and the generation of products is a kind of processing and operation of data. Therefore, we can use the idea of the reduction method to better consider the role of data.

Based on the above thinking, we explore the modeling idea for the architecture of the network and system that moves the concept of "product" as the center to "data" as the center; thus, we produce the concept of DaaC. DaaC is the abbreviation for Data as a Center, where "data" refers to "architectural data" that is acquired in order to achieve architectural description and modeling. It includes both space data resources and new data that is generated by preprocessing the corresponding space data. The concept of the DaaC architecture modeling idea is given below.

Definition 2 (DaaC Architecture Modeling Idea). *DaaC architecture modeling refers to a kind of data description of the architecture of a complex network system, and it is a method to guide the top-layer design of the network system architecture. The method is based on the architecture data of the network, and runs through the pre-life cycle of the architecture design of a complex network system. The architecture modeling method based on DaaC has the characteristics of high data reusability and high development efficiency. It can guarantee the consistency between the network architecture, and it can help realize the purpose of analyzing the network system by generating the data report of the network architecture.*

In the description and modeling of SIN architecture based on DaaC, the objects contained in the SIN architecture can be divided into three categories: space entities, connections, and attributes. The attribute relationships between the SIN architecture objects are shown in Figure 2 below.

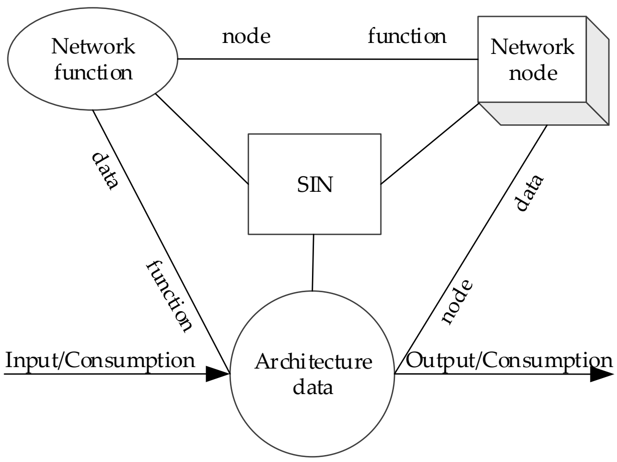


Figure 2. SIN architecture object diagram.

As shown in Figure 2 above, for SIN, the architecture data runs through the design process of the entire architecture. SIN nodes determine their network functions, and the function of the SIN is also the embodiment of its node function.

Combined with the definition of the DaaC architecture modeling idea and the SIN architecture objects, the development process of DaaC architecture design is given according to the guiding principles of applicability, simplicity, relevance, and organization [25,29]. The architecture development process is mainly divided into six steps, as shown in Figure 3 below.

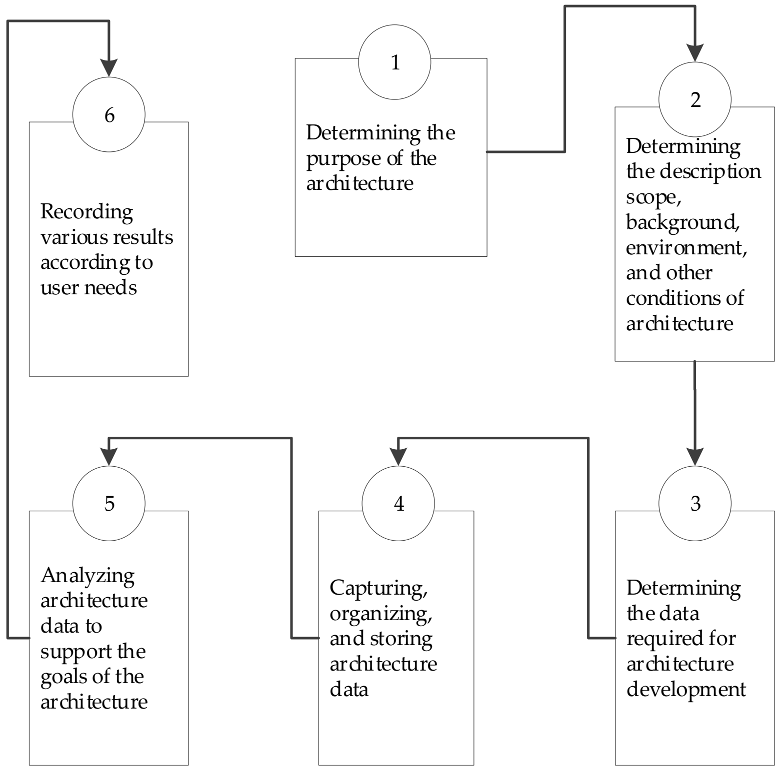


Figure 3. Data as a Center (DaaC) Architecture development process.

The specific process is given below.

Step_1: Determining the purpose of the architecture. First, we should clarify the purpose and the intention of the SIN architecture. We determine the type of data needed, and determine the way to carry out the concrete implementation.

Step_2: Determining the description scope of the architecture, etc. Scope determines the depth and breadth of the SIN architecture model. Therefore, it is necessary to collect the problem of SIN architecture modeling, and then refine the level of detail that is required for SIN architecture. The different scope of the architecture development effect is different, so there are differences in the purpose that is achieved.

Step_3: Determining the data needed to support the development of the SIN architecture. The core idea of architecture modeling idea is that the architecture data runs through the entire process of architecture development. Therefore, it is necessary to analyze the data that it needs based on determining the purpose and scope of the architecture, in order to determine the details of the required data entities and attributes. Thus, it can provide guidance for the collection of architecture data. Meanwhile, it is necessary to determine the perspective of the development architecture based on satisfying the use and scope of the architecture.

Step_4: Capturing, organizing, and storing architecture data. Based on the architecture purpose, scope, and required data of SIN in the first three steps, we can collect the required data through effective organization and storage, thus providing data support for the development of the architecture.

Step_5: Analyzing architecture data to support the goals of the architecture. The analysis of the architecture data is an important link in order to ensure that the preparation at this stage deviates from the original purpose. In this step, we can also identify additional process steps, or we can refine another work, and so on.

Step_6: Recording various results according to user needs. In the final part of the architecture design, it is necessary to create the corresponding architectural view based on the existing architecture data, and then present it to different users. Due to the difference of the views needed by different users of the SIN, a variety of results need to be recorded for comparative analysis.

In addition, because the SIN architecture needs to be updated and changed in real time according to task traction, it is also needs to be able to adapt to dynamic change at all times. Therefore, the development of the SIN architecture is a process of repeated iterations, that is, it repeats the development process and steps that have been shown above. Meanwhile, considering the generality and portability of the DaaC architecture model, the architecture model based on DaaC is also suitable for the modeling of multi-task multi-objective requirements. That is, for different time sensitivities, different task types of architecture are also applicable. For network systems with significant dynamics, the architecture models at different times can be described by constructing "instantaneous snapshots". An ordered time series can fully reflect the process of its dynamic change. Meanwhile, it can also realize the improvement of the architecture description and constantly update.

3. R-SIN Architecture Model Based on DaaC

The DaaC architecture modeling method can realize the overall design of the SIN architecture and overcome the lack of versatility and portability of existing methods. The idea of reconfigurable modeling has been studied in the fields of computer software, robot, and compression systems [30–32]. Based on the DaaC architecture model idea, in order to realize the recombination of the task-oriented SIN architecture, we study the reconfigurable SIN (R-SIN) architecture model based on DaaC.

Taking military application as an example, future war patterns will gradually evolve into a local war under the condition of informationization. If the whole SIN is involved in the information support and situational awareness of a combat task, it will inevitably increase the time of OODA (observation, confirmation, decision, and action). Correspondingly, it will also add some non-essential costs, as well as generate a huge waste of resources. On the contrary, if the scope of a particular operation is determined, the physical equipment of the SIN that meets the requirements of the mission will be rapidly reorganized to provide the required information support services. When the combat activity is over, it can be deconstructed to release these resources and bring them back to a natural state of operation. Based on this method, it can not only shorten the delay of OODA, improve the efficiency of combat, and ensure the effective information support, it can also reduce the cost of use and improve the efficiency of the SIN.

Of course, the SIN defined usually is a whole, and the reorganization SIN (R-SIN) is a subnet of it. An R-SIN is a state in which structural reorganization and functional reproduction are achieved within a local area to achieve specific functions and provide specific services. Thus, based on the DaaC architecture model, taking the space entities as the minimum physical resources and the space data as the center, we propose a task-oriented architecture model of the SIN in order to provide some new ideas and methods in order to meet the top-level design of SIN architecture to realize multi-tasks.

In this section, firstly, we define some concepts as the basis for the model presentation. Then, we build the reconfigurable principles. Finally, we analyze the realization mechanism and methods of the reconfigurable model of task-oriented architecture for the SIN based on DaaC. The details are as follows.

3.1. Definitions and Principles

3.1.1. Basis Definitions

Definition 3 (SIN Reorganization and R-SIN). *SIN reorganization refers to a process of regrouping the entities of the SIN according to the specific requirements of the task, function, and service. After the reorganization, the corresponding network is called the reorganization SIN, which is abbreviated as the* ***R-SIN****. The SIN that is discussed is usually an integrated and information-supported national infrastructure. However, R-SIN is a sub-SIN that is built with task- oriented requirements as traction.*

Definition 4 (Reorganization Goal, RG). *According to the needs of the task, the RG is a blueprint that is used to guide a new state that is achieved and entered by the SIN through reorganization. Among them, mainly includes that what rather functions the reconfigurable network should have, how to reorganize the various functional entities, and what extent the functional entities should serve, etc.*

Definition 5 (Reorganization Scheme, RS). *RS is the guidance for specific networking of R-SIN according to RG. In conjunction with the specific circumstances of space entities, it is also the specific plans for achieving specific tasks, providing specific services, and working with each other between entities.*

Definition 6 (R-SINs Management Center, RMC). *RMC is primarily responsible for managing the processes and ways of building R-SIN. It determines the size and composition of the R-SIN tasks based on the task-oriented requirements and superior commands. Meanwhile, RMC is responsible for the delivery of related instructions throughout the build process. It includes sending incentives of building networks, accepting responses to data centers and entity resource pools, and so on.*

Definition 7 (R-SINs Resource Center, RRC). *RRC is primarily used to provide the entities and data resources of R-SIN. It includes an entity resource pool (****ERP****) and data center (****DC****). The ERP contains the entire contents of all the components of the SIN. When building an R-SIN, we only need to select the required entities resources from the pool, and connect them so that it can function as needed.*

3.1.2. Main Principles

The nature of a reconfigurable SIN refers to the situation of SIN architecture in which it can be transformed from one form to another for a task. The architectures of the SIN before and after conversion are not only different in composition, but also have different functions in implementation. Meanwhile, the architectures before and after conversion are not a simple arrangement combination, but rather embody the overall ability. Combining the reconfigurable characteristics and the development trend of the SIN in the future, we think that we should ensure the advantages of flexibility, scalability, and applicability. Meanwhile, for realizing the establishment of its architecture model, we should also observe these principles as follows.

Principle 1: Loose-coupling principle

The recombinant network in an R-SIN is a reorganization that is based on a specific function and task. It is based on the business needs of specific users to provide the corresponding network services. Therefore, its service and demand are one by one corresponding, and the kind of network is a loosely coupled model.

Principle 2: Compatibility principle

The components of an R-SIN consist of a variety of heterogeneous heterogeneity entities, and it also spans across different levels. Therefore, to carry out real-time information support, it is necessary to realize real-time data information sharing. In addition, achieving good compatibility and integration is the prerequisite and foundation for ensuring its overall functionality.

Principle 3: Isolation principle

For an R-SIN, the networks that are built according to different needs of their clients are also different. In order to ensure that the network that is built can provide services efficiently, it is necessary to isolate the network that is built from other networks, and avoid interference and influence by other networks. That is, decoupling is to be done from the implementation.

Principle 4: Deconstruction principle

An R-SIN provides a specific service, and it is implemented over a specific period and within a specific local-area. When the demand for a task is over, the built network has no value in existence. Therefore, in order to avoid the waste of resources, it needs to be deconstructed; that is, the physical resources contained in the R-SIN need to be released. After deconstruction, these entity resources are restored to their natural state, and are always ready to prepare for the reorganization of the next specific task.

3.2. Realization Mechanism

3.2.1. Recombination Mechanism

In order to analyze the process of reconstructing the R-SIN architecture model, through combining the content above, we can implement an R-SIN architecture from two angles: the management layer, and the resource layer. The management layer is the management center of the R-SIN, named the R-SIN management center (**RMC**), and the resource layer is the R-SIN resource center (**RRC**). The two complement each other, and jointly complete and realize the task-oriented reorganization of the SIN. The R-SIN framework is as follows; there are three parts, including the RMC, data center (DC), and entity resource pool (ERP), as shown in Figure 4.

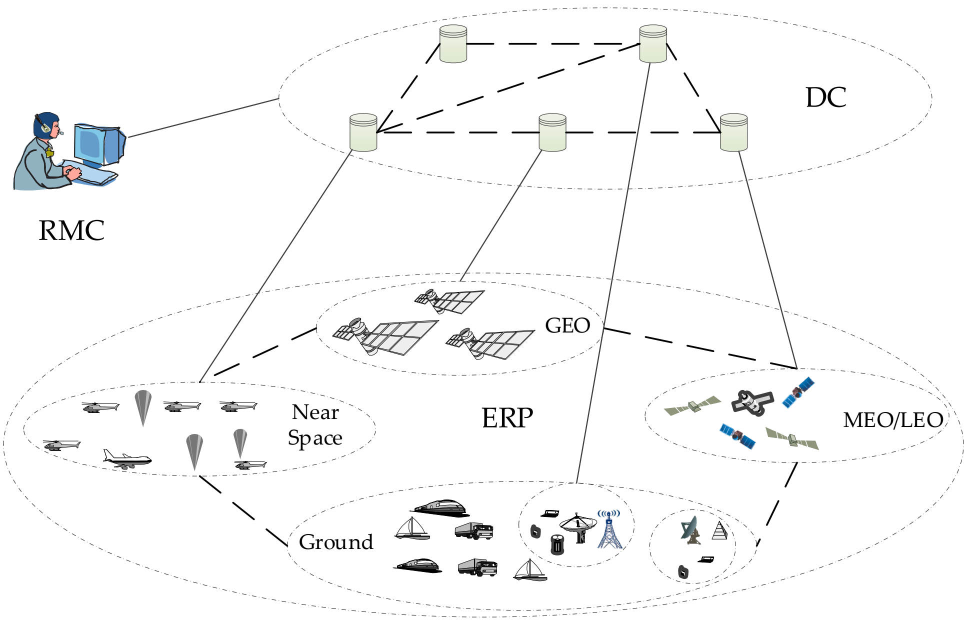


Figure 4. Reorganization SIN (R-SIN) framework.

RMC and RRC play decisive roles in the construction of the R-SIN, so we present its operating mechanism graphically, as shown in Figure 5.

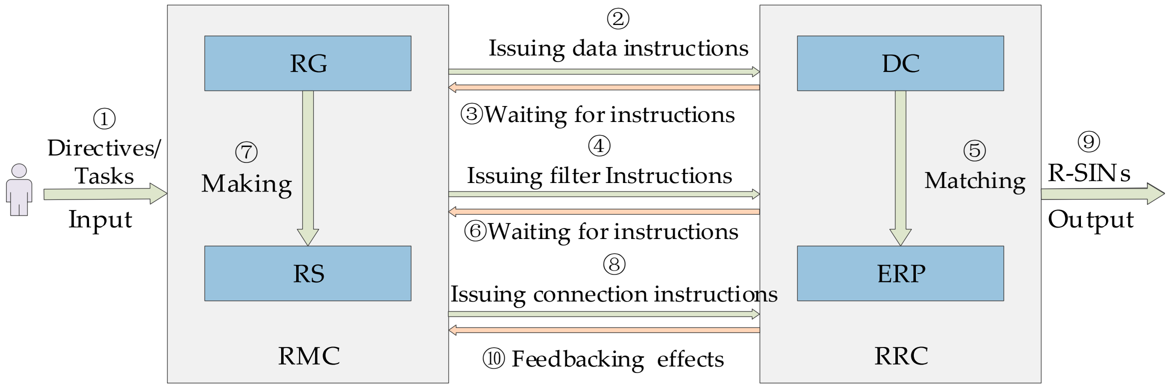


Figure 5. The operation mechanism of each module of the R-SIN.

As shown in Figure 5, we give the operation mechanism of the R-SIN, which is mainly implemented between RMC and RRC. The following is a detailed discussion of the RMC operation mechanism and RRC operation mechanism, respectively.

(a) RMC operation mechanism

The RMC acts as the core of the management and control, acting as the brain, which is also the interface for accepting tasks/instructions. After receiving the orders/instructions, it sets the RG according to the demand and the service that is to be provided. Meanwhile, it sends instructions to the RRC, and analyzes the data information that can meet the needs of the target. After the RRC completes the score data, it can send a second instruction to the RRC, and receive reply information. Through combining this information with the identified physical resources, we can make the reorganization scheme (RS) based on the reorganization goal (RG) and send instructions to establish a connection. While receiving feedback instructions for the establishment of an R-SIN, a comparative analysis of the functions and directives/tasks provided by the network is required in order to further optimize and adjust the RS. If there is room for improvement, repeat steps ⑧–⑩.

(b) RRC operation mechanism

The RRC mainly provides data resources and equipment entity resources, and plays the role of the resource base. It has an interface that accepts RMC instructions, and an interface that outputs a reconfigurable network. The DC is formed by bringing together the data of the entities that are contained in the entity resources, and organizing them in an orderly manner. Moreover, it has numbered and detailed data descriptions for all of the entity resources, including attribute information and data for all of the entity resources. In addition, it is the central link between the RMC and the ERP, which acts as a bridge and link.

The R-SIN mainly involves the collaboration of the RMC and RRC to achieve service-oriented reorganization. According to the RG, combined with the RS, by analyzing the data resources of the DC, some related resource entities are dispatched from the ERP to eventually generate a SIN that can achieve specific functions and provide the required services. Therefore, we use five tuples to define the reconfigurable model.

Definition 8 (R-SINs Architecture Model, RAM). *RAM formalization is expressed as:*

$$M_{RA} = \langle RG, RTS, RD, RE, RS \rangle \tag{1}$$

where RG represents a formal description of what styles and services are built on an R-SIN, which are driven by task requirements. RTS is an abbreviation for the R-SIN topology structure, and RTS represents a formal description of the structure, components, and connections of an R-SIN in order to achieve the RG. The reconfigurable functional resource collection contains a reconfigurable entity (RE) and reconfigurable data

(RD), and it represents the process of analyzing eligible data resources and determining the entity resources that meet the requirements to achieve the RG. The RS describes how to construct and reorganize the entire process. In addition, the RS also includes the process of adjusting, optimizing, and perfecting the R-SIN.

3.2.2. Description Mechanism

In order to put forward the reconfigurable modeling method of task-oriented architecture for the SIN based on DaaC (R-SIN) into practice, it is necessary to rely on the specific guidance framework in order to carry out the concrete realization. The DoDAF framework is a normalized method that describes the architecture, and it is a guide to the design and development of the architecture [25]. The activity-based and service-oriented architecture modeling approaches mentioned in Section 2.2 are implemented based on the DoDAF. In the military field, the DoDAF is an effective means for the architecture description and modeling of objects such as SES and SIS. Of course, in our early work, the specific practice of the SIN architecture based on DaaC is completed based on DoDAF2.0. Therefore, the reconfigurable modeling method of task-oriented architecture for the SIN based on DaaC is also based on the DoDAF2.0 to implement.

The DoDAF2.0 is an upgrade and perfection based on the DoDAF1.0 and DoDAF1.5. In comparison, in the DoDAF2.0, more attention is paid to the importance of data throughout the life cycle of a network system. In the DoDAF 2.0, the idea of the product is weakened, and has gradually highlighted the importance of "data". It coincides with the DaaC modeling idea of this article. What is most important is that the relevant scholars have successfully applied the DoDAF2.0 to other objects, including space-based information systems and space information systems. All of this provides the possibility and feasibility for this paper to realize the description and modeling of the reconfigurable modeling method of task-oriented architecture for the SIN based on DaaC with the DoDAF2.0. Moreover, up until now, the U.S. military has developed the fifth version of the DoDAF architecture framework, and formed a set of more scientific and standardized architecture design methods. In particular, in 2009, the official release of the DoDAF2.0 edition also became the most widely used architecture design guide in the current period. To sum up, the DoDAF2.0 is an effective choice to realize the reconfigurable modeling method of task-oriented architecture for the SIN based on DaaC in this paper.

Admittedly, although the DoDAF2.0 is consistent with the idea of DaaC modeling, the feasibility needs to be refined if they are to be directly applied to the reconfigurable modeling method of task-oriented architecture for the SIN based on DaaC. The DoDAF2.0 is primarily a view-based representation of the architecture, and it is organized around data, models, and views [33]. Therefore, there are eight types view models, which are defined in the DoDAF2.0 as follows.

As shown in Figure 6, the above views need to be selected in conjunction with specific task requirements in the design of specific architectures. Not all of them need to be covered, and different views can be specifically divided into multiple sub-perspectives, thus achieving a comprehensive description of the architecture.

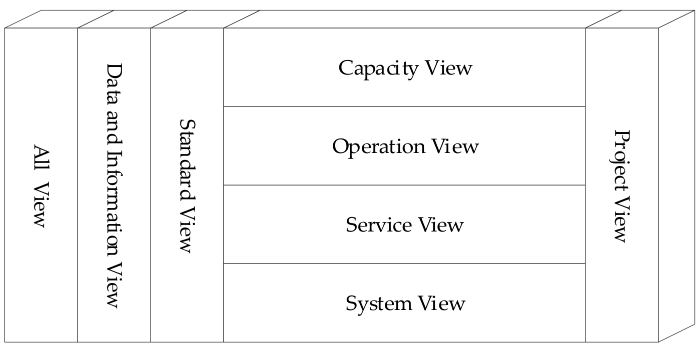


Figure 6. Architecture views in the Department of Defense Architectural Framework 2.0 (DoDAF2.0).

In fact, the DoDAF2.0 is a description process in the early stage of architecture modeling. In the later period, in order to display the concrete embodiment structure of the R-SIN in a formal way, it is necessary to simulate based on a simulation platform, such as the Satellite Tool Kit (STK).

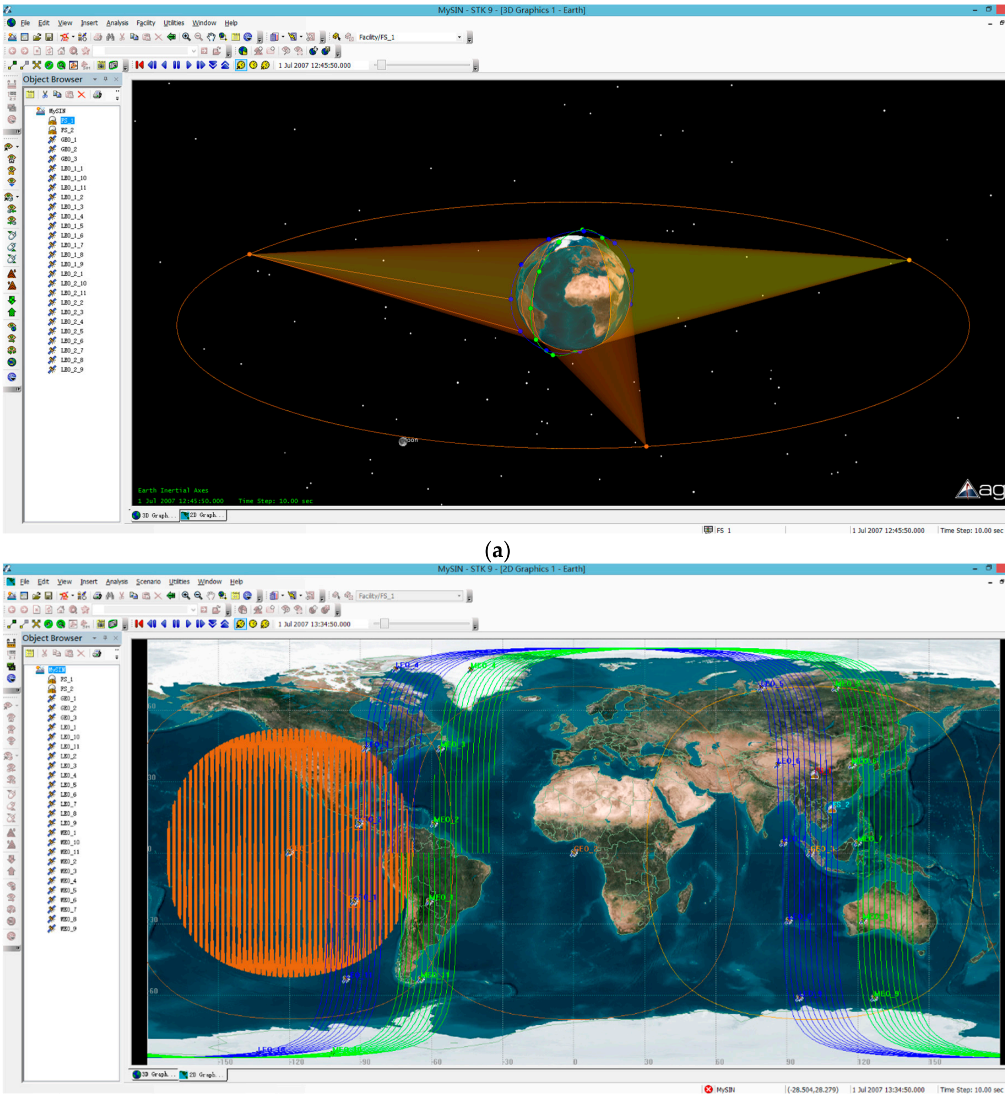
3.2.3. Simulation Mechanism

Combining with the concept and architecture of the SIN, in order to give a formal understanding of the SIN, we draw a typical demonstration model of the SIN based on the STK simulation platform.

Assumption: the SIN contains the following space entities, with a detailed list as follows:

- Three GEO Satellites (No.: GEO_1~GEO_3);
- 11 MEO Satellites (No.: MEO_1~MEO_11);
- 11 LEO Satellites (No.: LEO_1~LEO_11);
- Two Earth Stations (No.: F_1~F_2).

Based on the space entities mentioned above, the backbone network of the SIN is formed. As shown in Figure 7 below, we display the three-dimensional (3D) and two-dimensional (2D) diagrams of the SIN based on the STK.



(**a**)

(**b**)

Figure 7. The SIN demo model achieved by the Satellite Tool Kit (STK): (**a**) the three-dimensional (3D) demo model; and (**b**) the two-dimensional (2D) demo model.

As shown in Figure 7, it is an intuitive representation of the SIN from a 3D and 2D perspective. The STK-based approach helps to provide users with an intuitive understanding of the visualization of the SIN. This method complements the description model based on the DODAF2.0 perspective, and supports the top-level design of the SIN architecture, since the near-space layer complements the complex terrain that the satellite system cannot cover. Considering the limitations of the view interface range in the STK that contains the backbone network, the backbone network cannot be displayed clearly in the demo model of Figure 7. Therefore, the near-space layer information system is not placed in the demo model to display together.

The R-SIN architecture model simulation is a kind of re-operation of the SIN architecture simulation based on the DaaC model for a specific task. Combining the task requirements with the mission background, the R-SIN architecture modeling is the process of reproducing the reorganization and function of the space entities contained in the SIN. Therefore, the realization of R-SIN architecture modeling is an operation process that makes a task a traction, describing with the DoDAF2.0, and simulating based on the STK.

3.3. Realization Methods

According to the guiding principles of applicability, simplicity, relevance, organization, and reusability of architecture design [25], we make the reconfigurable architecture design and implementation algorithm, and process it as follows.

As shown in Algorithm 1, the variables that are used in the algorithm include *RD*, *RE*, *RG*, *RS*, *RE*, and *RN*, and their meaning is consistent with definitions 3–8 in the previous text. We are not to explain this process further in this part. Based on the pseudo-code shown in Algorithm 1, we further analyze the implementation process of the algorithm as follows:

1. For the superior instructions received, we can analyze its specific content, and determine information indicators to provide information support including position, orientation, period, and other indicators. Then, we can collate and sort out the reorganization need, and further formulate and prepare the *RG*.
2. Combined with the characteristics of the *RG*, and according to the indicators above, we can find the *RD* that meets the needs in the DC. Then, we can match the *RE* in the ERP with the selected *RD*.
3. Combining the *RG* and the characteristics of entity resources that have been identified, we can make the *RS*. Under the guidance of the *RS*, we can establish the connection between the selected *RE*, and ensure that the normal transmission of data information can be carried out.
4. Once all three parts of the work have been completed, the first version of the *RN* can be output. By testing the function and performance of the first version of the *RN*, we can judge its shortcomings and provide the feedback on the reorganization effect. It can provide the basis for optimization.
5. According to the feedback effect, we can optimize the *RN*, and determine whether the output network meets the requirements. If it is not satisfied, we can adjust the *RS*, and repeat the above steps. Meanwhile, we can realize the further optimization of the *RN*. When the requirements are met, the algorithm ends.

It is important to note that since this paper is the description and analysis of a task-oriented, reconfigurable architecture, therefore, every time we build it into practice, it results in a momentary state. Therefore, it is not possible to achieve the reconfigurable goals through one iteration. That is, according to the reorganization and feedback, we need to repeat the steps listed above many times. Finally, we can achieve the R-SIN.

Algorithm 1 The Algorithm Pseudo-Code of the R-SIN Architecture Design, SIN Architecture Reconfigurable Design

Input:	*RD*, *RE*, Instructions
Output:	R-SINs
1.	for enter a new instruction
2.	analyze instructions and determine *RG*;
3.	analyze *RG* and map *RD*;
4.	analyze *RD* and match *RE*;
5.	analyze *RG* and *RE*, and make *RS*;
6.	according to *RS* connection *RE*;
7.	Output *RN*;
8.	end for
9.	while *RN* is not meet R-SINs
10.	repeat step 5 and step 6
11.	end while

In addition, to highlight the iterative nature of the process in the above algorithm, we use *RN* to represent the reconfigurable network in the initial moment. When *RN* is the same as the R-SIN, the algorithm ends.

4. Results

The purpose of this section is to analyze the validity and feasibility of the proposed model from a case perspective. The reconfigurable modeling method of the task-oriented architecture for the SIN based on DaaC is a kind of architecture design according to the specific task. Therefore, in the case analysis of this section, we have to implement a combat assumption at first. That is, we should design a task scenario, and then according to the algorithm proposed in Section 3.3, carry out the concrete implementation.

4.1. Combat Assumption

Hypothesis: the enemy wants to attack one of our military heavy (coordinates: **N, **E) through a ballistic missile. We carry out land-based anti-missile combat activities, and in the whole process, we need the SIN to provide information support. The higher authority has issued the instructions to RMC.

According to the R-SIN architecture development process, we can learn that the SIN provides information support throughout the cycle in the anti-missile activity (***RG***). In combination with the possible direction and location of the enemy missiles, it can be determined that the SIN will be involved in the following tasks, including ① pre-war detection; ② early warning; ③ guided and search; ④ tracking, etc. Therefore, through analysis and screening to meet the requirements of ***RD***, it was determined that the following ***RE*** would be involved in the task, including the: Reconnaissance Satellite (A), Mapping Satellite (B), Early Warning Satellite (C), Relay Satellite (J), Radar Tracking Aircraft (D), Radar Early Warning Machine (F), Space-Based Information Processing Centre (Nc), and Ground Allegation Centre (Lc).

Therefore, in order to be able to implement all of the completed tasks, we believe that these entities should establish the following link relationship that is shown in Table 2. The content of the table is also the ***RS*** of the R-SIN.

Table 2. R-SIN Architecture Data List.

Name of *RE*	Level Information	Number of Edges
Reconnaissance Satellite (A)	MEO	1
Mapping Satellite (B)	LEO	1
Early Warning Satellite (C)	GEO	1
Relay Satellite (J)	GEO	4
Radar Tracking Aircraft (D)	Near Space	1
Radar Early Warning Machine (F)	Near Space	1
Space-Based Information Processing Centre (Nc)	Near Space	3
Ground Allegation Centre (Lc)	Land (*N, *E)	1

Based on the above architecture data list in Table 2, the concept demonstration of the connection scheme is further given as shown in Figure 8.

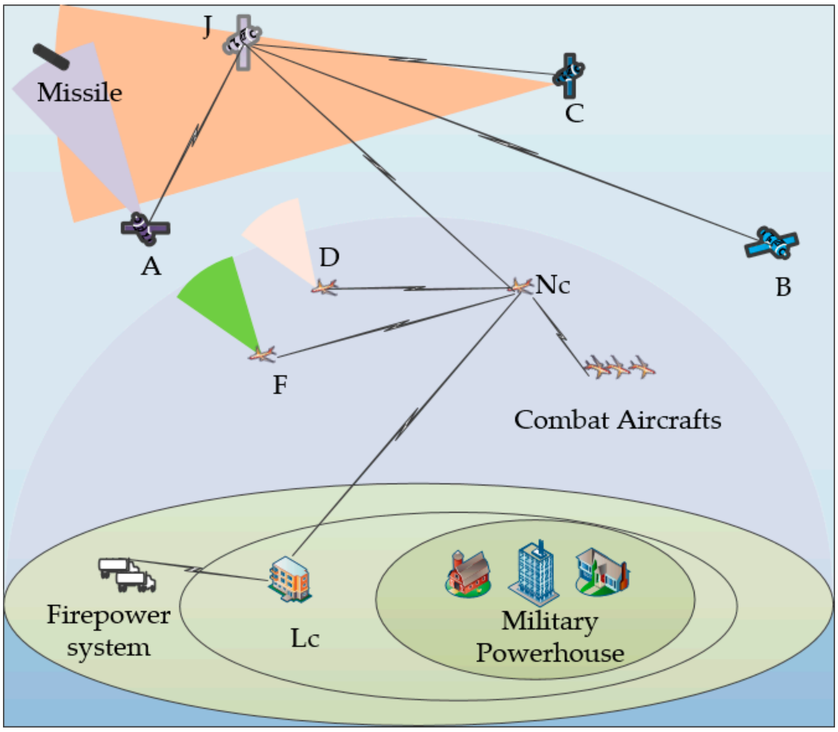
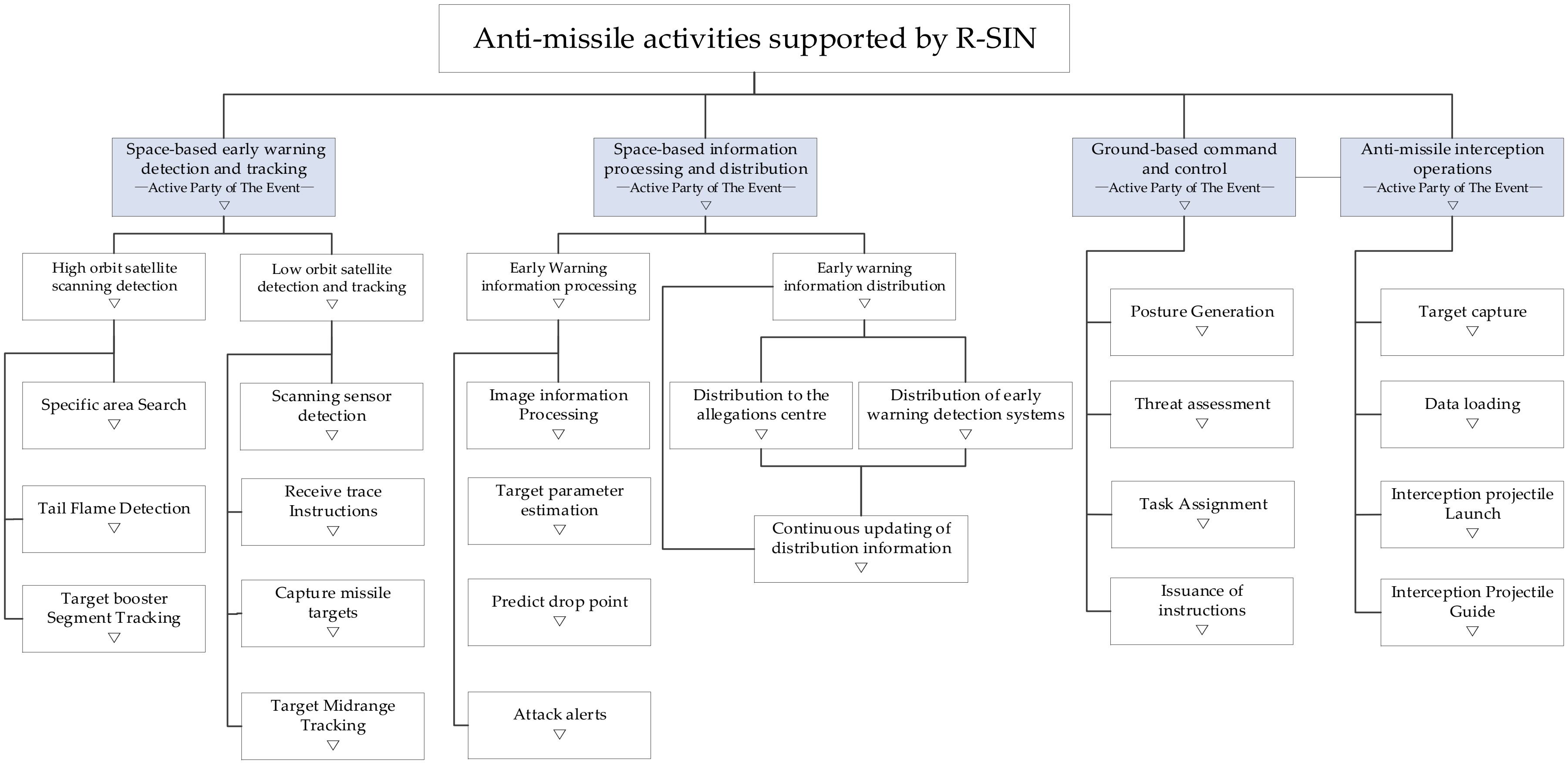


Figure 8. R-SIN advanced operational model supporting anti-missile tasks.

As shown in Figure 8, the RN is the rudiment of the R-SIN. In order to bring the design of the ***RN*** closer to the real needs of the R-SIN. Next, we will combine the DoDAF 2.0 framework and the STK platform for a more detailed design.

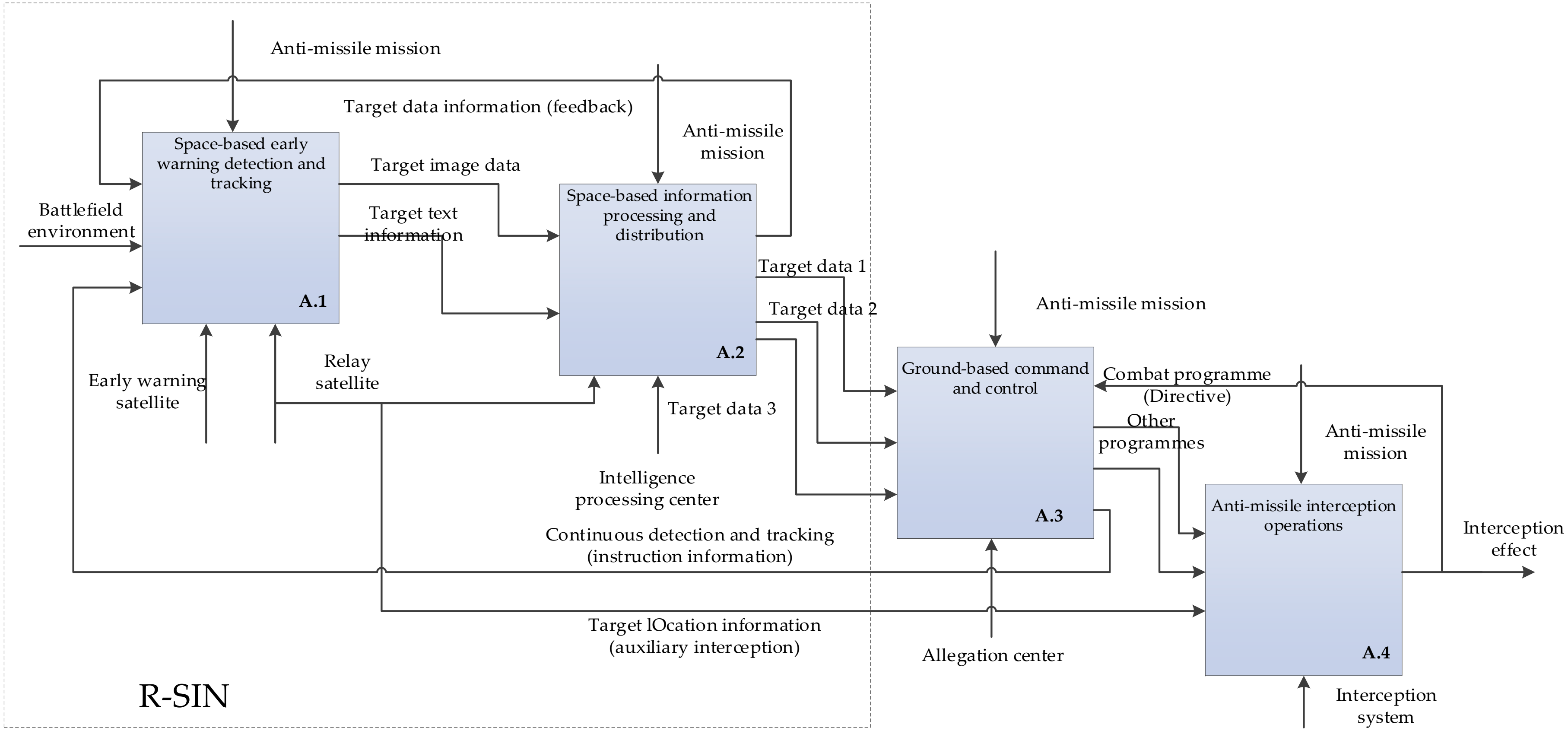
4.2. Data Display of R-SIN Architecture

Combining the needs, tasks, and mission of this anti-missile activity, there is a need to establish a decomposition hierarchy. The hierarchy includes a part of the space-based early warning detection and tracking, a part of the space-based information processing and distribution, a part of the ground-based command and control, and a part of the anti-missile interception operations. Based on the first-level decomposition model, the two-level combat activity decomposition model is obtained. The decomposition model can be carried out in more detail, in order to show its specific details by analogy. The combat activity decomposition model for anti-missile missions is shown in Figure 9 below.



(**a**)

Figure 9. *Cont.*



(**b**)

Figure 9. R-SIN combat activity decomposition model supporting anti-missile tasks: (**a**) the first-level combat activity decomposition model; (**b**) the two-level combat activity decomposition model.

As shown in Figure 9, the ∇ between activities and activities indicates the implementation conditions, data information (input), execution platforms, and implementation results (output), and so on. In order to describe the deployment of the combat nodes, the deployment of nodes, and the demand lines for information exchange between nodes, we determine the logical network of information flow and further construct the connection description model of the combat activity node, as shown in Figure 8.

As shown in Figure 10, we analyzed the combat nodes of the anti-missile activities supported by the R-SIN. Figures 8–10 come from the operation view (OV) in Figure 6, which all belong to the DoDAF 2.0. This corresponds to the theory that we described in Section 3.2.3.

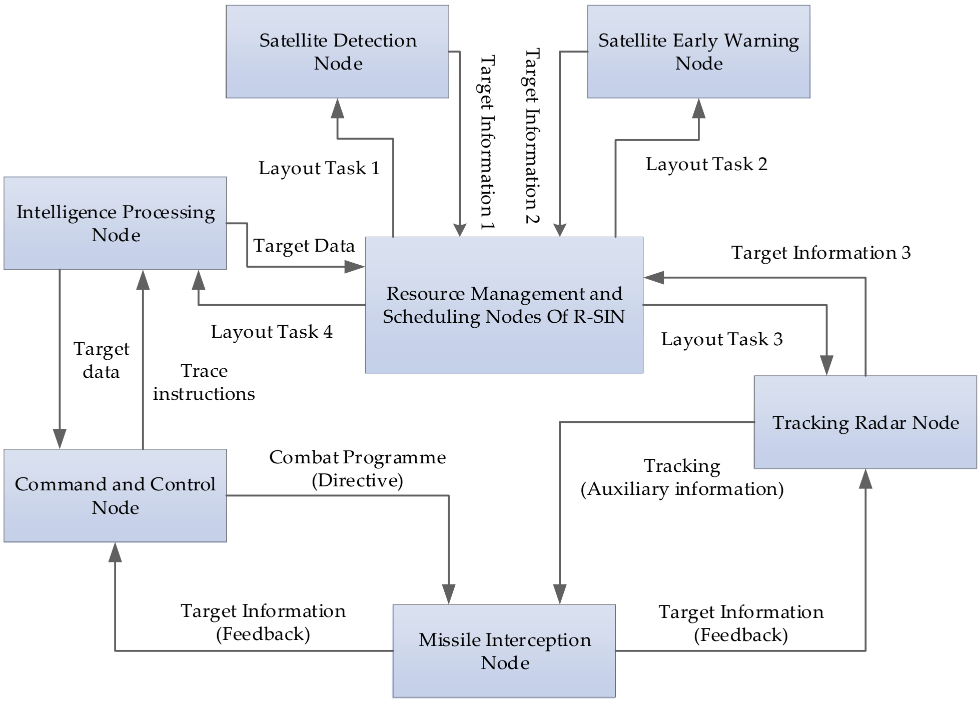
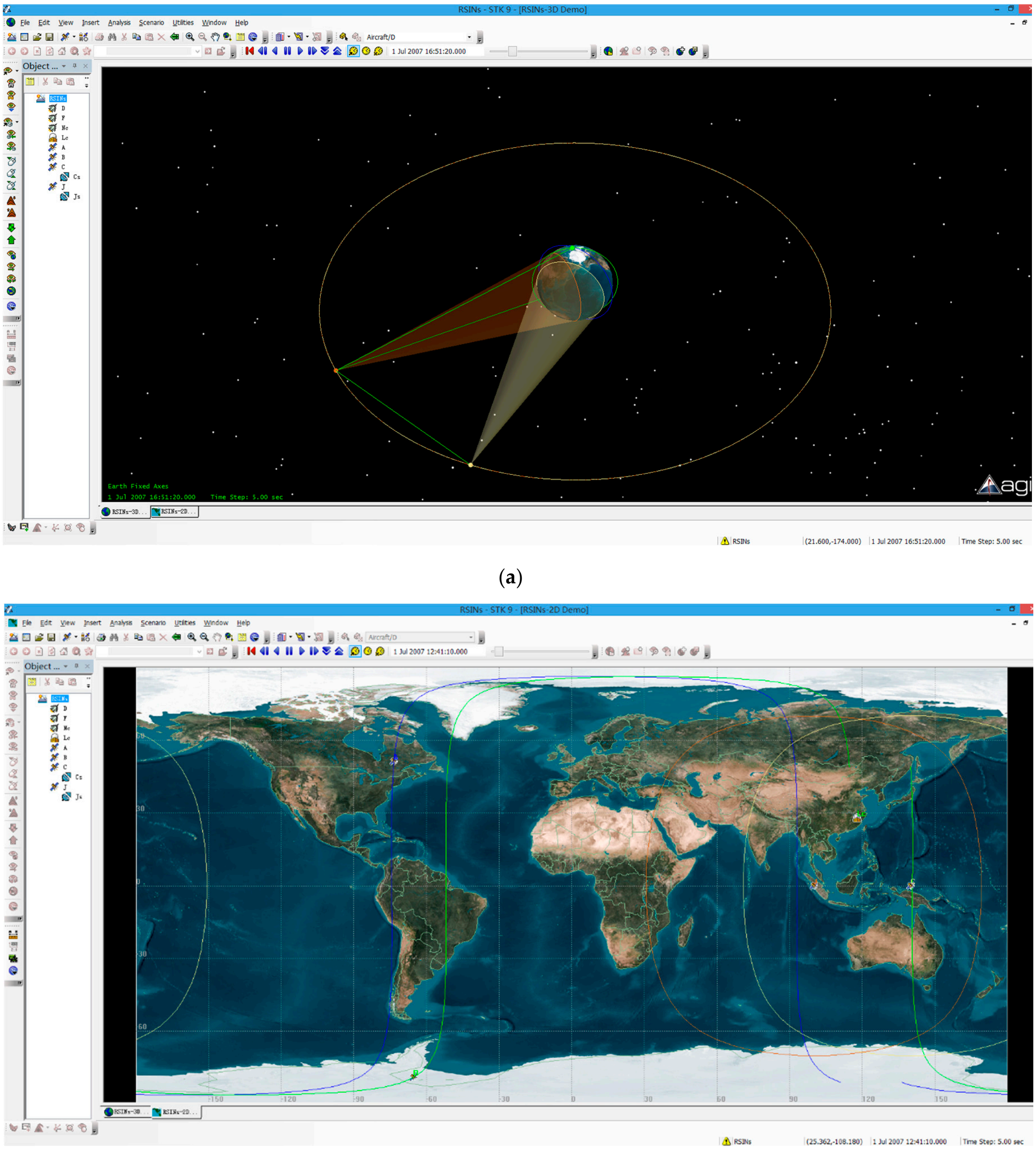


Figure 10. The R-SIN combat node connection, and the description model supporting the anti-missile tasks.

The above content is designed according to the needs of the R-SIN architecture design to achieve the specific implementation. Next, we carry out the simulation implementation based on the STK platform, and give the architecture of the R-SIN supporting the anti-missile task. Based on the STK platform, the 3D and 2D of the R-SIN demonstration model are implemented respectively, as shown in Figure 11.



(**a**)

(**b**)

Figure 11. The R-SIN demo model supporting anti-missile tasks: (**a**) the three-dimensional (3D) demo model; (**b**) the two-dimensional (2D) demo model.

As shown above, the A, B, C, and J are shown in different highlights, and the slightly, smaller green highlight in the illustration represent the Lc. Since the illustrated screenshot interface is limited, the Nc, D, and F are not clearly displayed in the diagram. Meanwhile, combining the data information and transmission relationships with Table 2 and Figure 8, the connection relationship between the entities are established, which are represented with the green solid lines in the diagram.

5. Discussion

For the problem of SIN architecture modeling, this paper presents a reconfigurable modeling method of task-oriented architecture of the SIN based on DaaC. The aim is to realize the design of SIN architecture with good portability, good versatility, flexibility, and recombination. The results of the case analysis also verify the validity and feasibility of the method proposed in this paper. However, there are some problems and inadequacies with this modeling method. Therefore, only by comparing this method with other similar methods can the shortcomings be better explored. Such comparisons can also lay a foundation for the next research. Therefore, we summarize and collate some typical architecture modeling methods, and compare and analyze the advantages and disadvantages of those methods. The details are shown in Table 3 below.

Table 3. Definiteness Analysis of SIN Architecture Modeling Methods.

Name	Reference	Typical Methods	Advantages	Disadvantages
Method 1	[22]	An integrated two-tier architecture modeling method based on the service layer and the network layer.	For the complexity of SIN, the modeling effect can be achieved to a certain extent through stratification and chunking.	The versatility and portability is poor.
Method 2	[5]	The networking and modeling method of SIN based on a hierarchical autonomous domain.		
Method 3	[23]	The modeling method of the SIN architecture based on the distributed star-group.		
Method 4	[26]	The architecture description and modeling method based on the unified modeling language (UML).	High reusability, easy to upgrade and maintain, suitable for the development of large and complex networks.	Interoperability is poor and lack of experience in the design process.
Method 5	[27]	The architecture description and modeling method based on activity.	Flexibility to meet a wide range of design needs, flexibility, and cross-product correlation.	
Method 6	[17,28]	Service-oriented architecture description and modeling method.	Strong integrity, flexible design, and strong adaptability, reorganization, and so on.	
Method 7	Original	A reconfigurable modeling method of task-oriented architecture based on DaaC.	Wholeness, portability, recombination, and formalization.	

As shown in Table 3 above, we compare and analyze some typical architecture modeling methods. Method 1~method 3 are proposed for the SIN, and its advantages and disadvantages are common, so there is no separate discussion. Considering that method 7 (that is, the modeling method proposed in this paper) is a fusion and improvement based on method 4~method 6. However, method 7 solves the problem of the integrity and portability of the existing architecture modeling method, and realizes the demand for the reconfigurable architecture under the large space-time scale. However, similar to method 4~method 6, method 7 has poor interoperability and relies on the experience of decision makers, architecture designers, and other related personnel in the design.

6. Conclusions

As a national infrastructure, the SIN has important significance for the military and people's livelihoods. It also has become a hot research field in recent years. For the requirement of the SIN architecture modeling, we propose a reconfigurable architecture modeling method based on DaaC for the shortcomings of the existing methods. By analyzing the concept and architecture of the SIN, the users have an intuitive understanding of the SIN. Combining with the space data of SIN in the whole life cycle, we put forward a DaaC modeling idea. Combined with the task-oriented requirements, based on the basis definitions, main principles, realization mechanism, and methods, we propose a reconfigurable model of SIN based on DaaC. From the combat assumption and the display of data of the two aspects of the R-SIN architecture, we take a typical SIN as an example, and verify the feasibility and effectiveness of the method. Finally, we analyze and compare some typical modeling methods.

Of course, there are some another works that need to be carried out, such as the improvement of design principles, the realization of process and algorithm optimization, etc. Meanwhile, there is a lack of quantitative analysis in the feasibility and validity verification of the model, and it is also the main content that needs to be studied in the future.

Author Contributions: S.Y. and L.W. completed the overviews and methods; S.Y. structured the evolution model; S.Y. accomplished the theory and simulation verification; L.W. helped in the verification; S.Y. wrote the paper.

Funding: This work was supported by the Equipment Pre-Research Foundation under Grant No. 6142010010301.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Li, D.R.; Shen, X.; Gong, J.Y.; Zhang, J.; Lu, J. On construction of China's space information network. *Geomat. Inf. Sci. Wuhan Univ.* **2015**, *40*, 711–715.
2. Wang, Y.; Sheng, M.; Zhuang, W.H.; Zhang, N.; Liu, R.Z.; Li, J.D. Multi-resource coordinate scheduling for earth observation in space information networks. *IEEE J. Sel. Areas Commun.* **2018**, *36*, 268–279. [CrossRef]
3. Min, S.Q. An idea of China's space-ground integrated information network (1). *Digit. Commun. World* **2016**, *6*, 28–29.
4. Yu, Q.Y.; Meng, W.X.; Yang, M.C.; Zheng, L.M.; Zhang, Z.Z. Virtual multi-beamforming for distributed satellite clusters in space information networks. *IEEE Wirel. Commun.* **2016**, *23*, 95–101. [CrossRef]
5. Wang, J.C.; Yu, Q. System architecture and key technology of space information network based on distributed satellite clusters. *ZTE Tech. J.* **2016**, *22*, 9–13.
6. National Natural Science Fund Committee. Research Plan of the Basic Theory and Key Technology of Space Information Network 2017 Annual Project Guide. Available online: http://www.nsfc.gov.cn/publish/portal0/zdyjjh/info68778.htm (accessed on 13 June 2017).
7. Jiang, C.; Wang, X.; Wang, J.; Chen, H.; Ren, Y. Security in space information networks. *IEEE Commun. Mag.* **2015**, *53*, 82–88. [CrossRef]
8. Dong, F.H. *Optimization Design and Research of Spatial Information Network Structure*; PLA University of Science and Technology: Nanjing, China, 2016; pp. 1–10.
9. Wei, Z.; Geng, Z.; Zhi, X. A hierarchical autonomous system based space information network architecture and topology control. *J. Commun. Inf. Net.* **2016**, *1*, 77–89.
10. Yu, Q.; Wang, J.C.; Liu, B. Architecture and critical technologies of space information networks. *J. Commun. Inf. Net.* **2016**, *1*, 1–9. [CrossRef]
11. Huo, C.L.; Zhou, Z.X.; Ding, K.; Pan, C.H. Online target recognition for time-sensitive space information networks. *IEEE Trans. Comput. Imaging* **2017**, *3*, 256–263. [CrossRef]
12. Zhang, X.; Wang, J.J.; Jiang, C.X.; Li, H.W.; Guo, Q.; Wang, X.; Ren, Y. Hardware-in-the-loop simulation system for space information networks. *J. Commun. Inf. Net.* **2017**, *2*, 131–141. [CrossRef]
13. Yu, S.; Wu, L.; Mu, X.; Xiong, W. Research on the weighted dynamic evolution model for space information networks based on local-world. *Information* **2018**, *9*, 158. [CrossRef]
14. Yu, S.; Wu, L.; Zhang, X.; Meng, X.; Cen, P. SINDVis: User-centered dynamic interactive visualization system for space information networks. *Electronics* **2018**, *7*, 316. [CrossRef]
15. Yu, S.; Wu, L.; Zhang, X. Data as a center: An architecture modeling of space information network. *J. Commun.* **2017**, *38*, 165–170.
16. Mach, P.; Becvar, Z. Mobile edge computing: A survey on architecture and computation offloading. *IEEE Commun. Surv. Tutor.* **2017**, *19*, 1628–1656. [CrossRef]
17. Razaque, A.; Rizui, S.S.; Khan, M.J.; Hani, Q.B.; Dichter, J.P.; Parizi, R.M. Secure and quality-of-service-supported service-oriented architecture for mobile cloud handoff process. *Comput. Secur.* **2017**, *66*, 169–184. [CrossRef]
18. Behroozpour, B.; Sandborn, P.A.M.; Wu, M.C.; Boser, B.E. Lidar system architectures and circuits. *IEEE Commun. Mag.* **2017**, *55*, 135–142. [CrossRef]

19. Michael, L.; John, M.; Ronald, S. Model-based architecture and programmatic optimization for satellite system-of-systems architectures. *Syst. Eng.* **2018**, *21*, 372–387.
20. Levis, H.; Lee, W. C4ISR architectures: I. developing a process for C4ISR architecture design. *Syst. Eng.* **2000**, *3*, 225–247. [CrossRef]
21. Yang, L.J.; Fu, J.; Rui, P.L. Architecture integration method for C4ISR system. *Command Inf. Syst. Technol.* **2016**, *7*, 1–6.
22. Fei, D.; Jing, W.; Jie, Y. Distributed satellite cluster network: A survey. *J. Donghua Univ. Eng. Ed.* **2015**, *32*, 332–336.
23. Zhang, W.; Zhang, G.X.; Bian, D.M.; Gou, L.; Xie, Z.D. Network model and topology control algorithm based on hierarchical autonomous system in space information network. *J. Commun.* **2016**, *37*, 94–405.
24. Amissah, M.; Handley, H. A process for DoDAF based systems architecting. In Proceedings of the 10th Annual IEEE International Systems Conference (SysCon), Orlando, FL, USA, 18–21 April 2016; pp. 1–7.
25. General Staff 61st Institute (Translation). *U.S. Department of Defense Architecture Framework Version 2.0*; Defense Industry Press: Beijing, China, 2009; pp. 1–50.
26. Lallchandani, J.T.; Mall, R. A dynamicslicing technique for UML architectural models. *IEEE Trans. Softw. Eng.* **2011**, *37*, 737–771. [CrossRef]
27. Jian, P.; Xiong, W. Research on activity based methodology of modeling C4ISR system architecture. *J. Acad. Equip. Command Technol.* **2009**, *20*, 50–55.
28. Jian, P.; Zou, P.; Xiong, W.; Chen, Z.K. Research on serveice-oriented of modeling architecture. *J. Acad. Equip. Command Technol.* **2011**, *22*, 91–96.
29. Xiong, W.; Liu, D.S.; Jian, P. *Modeling Simulation and Evaluation Technology of Space Information System*; Defense Industry Press: Beijing, China, 2016; pp. 2–18.
30. Liu, Q.; Wang, B.Q.; Xu, K. Construction and reconstruction method of hierarchical reconfigurable network based on construction. *J. Comput.* **2010**, *33*, 1557–1568.
31. Wang, X.F.; Zhang, M.L.; Ge, W.M.; Liu, J. Dynamic modeling and configuration adaptive control for modular reconfigurable robot. *Adv. Mech. Eng.* **2017**, *9*, 1–13. [CrossRef]
32. Burns, D.J.; Danielson, C.; Zhou, J.; Di Cairano, S. Reconfigurable model predictive control for multievaporator vapor compression systems. *IEEE Trans. Control Syst. Technol.* **2018**, *26*, 984–1000. [CrossRef]
33. Qiao, X.; Li, Y.B.; Ge, X.K. Architecture design of multi-aircraft cooperative detection system based on DoDAF V2.0. *J. Air Force Eng. Univ. Nat. Sci. Ed.* **2017**, *18*, 20–26.

© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).