

Designing on metamodels of air traffic management architecture modeling based on multi-frame modeling language

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Abstract

Purpose – This paper aims to propose a set of metamodels applicable to the architecture modeling of air traffic management systems|air traffic management system (ATMS) under the UAF methodology. The designing of metamodels also needs to meet modeling requirements for the introduction of new supersonic airliners into the ATMS.

Design/methodology/approach – In order to complete the designing of metamodels and the architecture modeling work in the case study, the GOPPRR method and the M0–M3 modeling framework are used in this paper. The design and modeling work carried out in this paper was done in the multi-architecture modeling tool Airdraw.

Findings – In this paper, the set of metamodels applicable to the architecture modeling of ATMS under the UAF methodology was proposed, which has a quantity of 102 object metamodels, eight point metamodels, 98 property metamodels, 41 relationship metamodels, 36 role metamodels and 65 graph metamodels.

Originality/value – The metamodel design proposed in this thesis allows for architectural modeling of the ATMS. Comparing with the traditional method of system engineering, which uses files to define, the model-based ATMS architecture can be updated for different ATMS and different aircraft types by modifying the parameters of the corresponding views or adding relevant supplementary model views in the architecture model library, which greatly improves the compatibility and modifiability of the system definition.

Keywords Air traffic management system, Model-based systems engineering, Metamodel, GOPPRR method

Paper type Case study

1. Introduction

As an important part of the aviation system, the air traffic management systems|air traffic management system (ATMS) ensures the safety and efficiency of air traffic. For different environments and aircraft types, ATMS need to be designed differently. Now that the Concorde has been out of service for more than 20 years (Candel, 2004), there is a lack of supersonic airliners in the civil aviation market that can be officially put into commercial

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operation. In this regard, the “Qi Fei” team designed a new supersonic airliner, which is shown in [Figure 1](#).

However, for the ATMS, since the supersonic passenger aircraft is a new type of aircraft involved in air traffic management services ([Sun and Smith, 2017](#)), the relevant indexes and properties of the existing air traffic control system need to be optimized and modified for the supersonic passenger aircraft.

In order to better integrate the system definitions and descriptions of the ATM system with the supersonic airliner and to provide the design requirements under the ATM system, the model-based systems engineering approach ([Wymore, 2018](#)) is introduced. Compared with the traditional document-based systems engineering approach, this approach realizes the modeling representation of the ATM system by establishing a system modeling of the ATMS to form a model library. The ATMS architecture model library obtained by this method can be updated for different ATC systems and different aircraft types by modifying the parameters of the corresponding views or adding relevant supplementary model views in the architecture model library, which greatly improves the compatibility and modifiability of the system definition.

In this paper, the main purpose of the research is to focus on the construction of the architecture model of the ATMS under the model-based system engineering method under the platform of multi-architecture modeling tool, which used the multi-architecture modeling language KARMA as its basic language.

2. Description of method

2.1 GOPPRR method

This paper uses the GOPPRR method ([Wang et al., 2019](#)) to build a meta-model library based on six meta-meta models (graph, object, point, property, relationship and role), that is, a domain-specific language to support domain model design and thereby assist system development. Among them, the meanings of the six meta-meta models are as follows:

Graph: The graph element contains several other elements, analyzes a certain viewpoint of the system and describes the system in a block diagram.

Object: The main element in the model, used to represent an entity, which can exist alone or be linked to other objects.

Point: Usually attached to an object, used to represent the port connecting the object and the character.

Property: Cannot exist alone and is attached to other meta-models to represent its characteristics.

Role: At both ends of the relationship, it indicates the identity in which the object is connected.

Relationship: Connection between roles and objects, indicating the connection between objects.



Source(s): Authors' own work

Figure 1. “Qi Fei II” supersonic aircraft

GOPPRR concepts are the basic compositions of meta-meta models, including non-property concepts and property. In the GOPPRR method, each non-property concept, such as an object, is allowed to decompose into one graph or to explore into one or more graphs. These are two ways to represent the mappings from each object (Lu *et al.*, 2020), relationship, role and point to the new graphs. When building models, new models can be linked to these non-property concepts to represent the interrelationships of decomposition and explosion among them as follows:

- (1) Decomposition, referring to a breakdown mapping from a non-property concept to one new graph. When developing a new graph model, it represents a breakdown system structure of the related non property concept.
- (2) Exploration, referring to mappings from one non property concept to one or more graphs. When developing a new graph model, it represents additional architectural views of the related non-property concepts.

Thus, we can define the interrelationships among the GOPPRRE concepts as shown in Table 1.

After defining the meta-meta models and their interrelationships, the metamodels can also be defined with the GOPPRR method.

3. Designing of the metamodels on ATMS

With the definition of GOPPRR concepts, it is able to define the metamodels under different modeling methodologies. Considering the case environment of the ATMS, we finally choose the UAF methodology and give the definition of the metamodels as shown below.

First is the metamodel of a graph, which can be defined as:

$$Graph_i = \left\{ \sum Object_i, \sum Relationship_i, \sum Ob - Ro Bonding_i \right\} \quad (1)$$

where $\sum Object_i$ and $\sum Relationship_i$ refer to the summary of object metamodels and relationship metamodels that are included in this graph, and $\sum Ob - Ro Bonding_i$ refers to the summary of the bonding that object metamodels and role metamodels made in this exact graph.

To explain the definition of graph metamodels more deeply, below shows each of the three components included in the graph. As object metamodels can be defined like below:

Table 1. Interrelationship among GOPPRRE meta-meta models

GOPPRR concept	Graph	Object	Point	Relationship	Role
Graph	–	Decomposed or Explored	Decomposed or Explored	Decomposed or Explored	Explored
Object	Include	–	Included	–	Connected in graph
Point	–	Include	–	–	Connected in graph
Property	Have	Have	Have	Have	Have
Relationship	Include	–	–	–	Starting and Ending
Role	–	Connect in graph	Connect in graph	Start and End	–

Source(s): Authors' own work

$$Object_i = \left\{ \sum Property_i^{Ob}, \sum Point_i \right\} \quad (2)$$

where $\sum Property_i^{Ob}$ refers to the summary of all the properties that are included in this object, and $\sum Point_i$ refers to the summary of all the points that are included in this object.

Below explains the definition of the point metamodels, which can be seen in the defining method of the object metamodels:

$$Point_i = \left\{ \sum Property_i^{Po} \right\} \quad (3)$$

where $\sum Property_i^{Po}$ refers to the summary of all the properties that are included in this point.

Come back to the further explanation of the graph metamodels; below it defines the relationship metamodels and the bonding of object metamodels and role metamodels:

$$Relationship_i = \left\{ \sum Property_i^{Re}, \sum Role_i \right\} \quad (4)$$

$$Ob - Ro Bonding_i = f_{Re_i} \left(\sum Role_i, \left(\sum Object_i, \sum Point_i \right) \right) \quad (5)$$

where $\sum Property_i^{Re}$ refers to the summary of all the properties that are included in this relationship, and $\sum Role_i$ refers to the summary of all the roles that are included in this relationship.

The definition of the bonding can be seen as a function $f_{Re_i}(Role_i, (Object_i, Point_i))$, which uses roles and suitable objects or points as input; after combining with the rules defined by the exact relationship metamodel, the bonding is defined as the output.

Below explains the definition of the role metamodels, which can be seen in the defining method of the bonding part:

$$Role_i = \left\{ \sum Property_i^{Ro} \right\} \quad (6)$$

where $\sum Property_i^{Ro}$ refers to the summary of all the properties that included in this role.

Using these definitions and the basic logic of UAF methodology, we can define the metamodels on the work of the ATMS. This defining process can be finished on a multi-architecture modeling tool, taking the definition of the object metamodel actual consisting mission as an example, which is shown in [Figure 2](#).

The metamodel defining process ends up with 102 object metamodels, eight point metamodels, 98 property metamodels, 41 relationship metamodels, 36 role metamodels and 65 graph metamodels. The basic information and settings about these metamodels are shown in [Table 2](#).

4. Case study

4.1 Introduction and analysis of the case

Based on the relevant documents provided by International Civil Aviation Organization (ICAO), the specifications and functionalities of the ATMS were extracted, and the architectural modeling was completed with the following specific objectives:

- (1) The ATMS is described through different viewpoints to create a methodological model view.

basic information
This section defines the general settings of the meta object, such as name and other information.

local label: Actual Consisting Mission

description:

object Settings
This section defines the fixed syntax and icon path for the object metamodel.

display format: containerMode

direction: Vertical

fixed grammar: rectangle

image:

icon: Actual Consisting Mission.png

property setting
This section defines the attribute settings of the meta object, and provides attribute operations such as adding, modifying, and deleting.

property reference name	meta property id	data type	uniqueness	LocalLabel	Value	
Object_ActualEnduringTask...	Property_name	String	false	Name	null	add
Object_ActualEnduringTask...	Property_CapabilityForTask	String	false	Mission Ability	null	edit
Object_ActualEnduringTask...	Property_type	String	false	Category	null	delete

point settings
This section defines the point attribute settings of the meta object, and provides attribute operations such as adding, modifying, and deleting.

point reference id	meta point id	meta point name	direction	
				add
				edit
				delete

Source(s): Authors' own work

Figure 2. Definition of object metamodel in Airdraw

Table 2. Interrelationship among GOPPRRE meta-meta models

Metamodel category	Quantity	Included property types	Typical classification	Typical metamodel	Average number of metamodel/ Graph
Graph metamodel	65	—	Classified by different domains	Defined by UAF methodology	1
Object metamodel	102	Name, Provider, Usage, etc.	Entity, Concept, etc.	System, Requirement, Ability, etc.	1.57
Point metamodel	8	Name, Status, etc.	Input port Output port	Operation port input, Operation port output, etc.	0.12
Property metamodel	98	—	String property, Mathematical property, etc.	Name, Provider, Latitude, Altitude, etc.	1.51
Relationship metamodel	41	Name	Logical relationship, Connector, etc.	Make up, Coupling connector, etc.	0.48
Role metamodel	36	—	Relationship provider and receiver, Neutral role, etc.	From ability demander, From ability provider, etc.	0.8

Source(s): Authors' own work

- (2) The nature of the ATMS, as defined in the relevant ICAO documents, is completed to be universal, i.e. it conforms to the standard ATMS architecture model regardless of whether or not the ATMS supports the operation of supersonic airliners.

- (3) A model of the architecture of part of the ATMS specially designed for supersonic passenger aircraft was completed in conjunction with the new supersonic passenger aircraft designed by the “Qi Fei” team.

4.2 Modeling of the UAF methodology

To finish the modeling work, we finally choose to adopt the methodology model framework based on UAF (Hause *et al.*, 2017). In the multi-architecture modeling tool, the methodology tool module of the tool is used to complete the modeling of the methodology document, and the final methodology model structure is shown in Figure 4.

4.3 Settings of the metamodels

In part 3 of this paper, we designed 102 object metamodels, eight point metamodels, 98 property metamodels, 41 relationship metamodels, 36 role metamodels and 65 graph metamodels for the architecture modeling work of the ATMS.

4.4 Inspection of metamodels: construction of model library

According to the guidance document of UAF methodology, a recommended process is given (Forman, 2000) in the document when building a system engineering. Using this process, combined with the supersonic aircraft designed by the “Qi Fei” team, 24 basic models of the ATMS can be built (Li and Deng, 2022).

The model covers eight domains of UAF methodology. The actuals resources (Figure 3(a)) analysis evaluates different options and assumptions and weighs actual resource allocations to illustrate desired or realized actual resource allocations and relationships between actual resources. In this case, the supplementary model of the actual resource domain mainly describes the situation of the actual resources related to the ATMS. For example, the real resource structure view (Figure 4(a)) shows that ATMS is mainly divided into two practical organizations in the actual operation of air traffic management organization and air service operation organization.

The resource domain (Figure 3(b)) defines the architecture of the resources required for the solution to implement the operational requirements of the system, including the organization, software, artifacts, capability configuration, natural resources and so on. In this case, the supplementary model of the project domain mainly illustrates the architecture design of the ATMS related to various resources. The resource structure view (Figure 4(b)) describes the target information resources needed to ensure the flight plan execution of the aircraft in the system, including aircraft state parameters, external environmental factors, flight plans and other resources, which are related to the emergency and communication system.

In the strategic domain (Figure 3(c)), the architect can model the definition and logic of the system at the strategic level and the model in the strategic domain describes the top-level strategic design of the system. In this case, the supplementary model of the strategic domain mainly illustrates the architecture design of the ATMS and the top-level strategic decision. The strategic structure view (Figure 4(c)) defines that ensuring aircraft complete the flight plan is one of the most important capabilities in the ATMS, which is composed of five capabilities, including reviewing flight plans, avoiding collisions and making air plans.

The project domain (Figure 3(d)) shows the relationships and structure between different projects. It describes the dependencies between organizations and projects that contribute to the project. In this case, the supplementary model of the project domain mainly illustrates the architecture design of the specific operational project in the ATMS. The project connection view (Figure 4(d)), for example, shows the project of ensuring aircraft to complete the flight plan in the ATMS consists of three sub-projects: flight plan approval, communication and condition parameter monitoring.

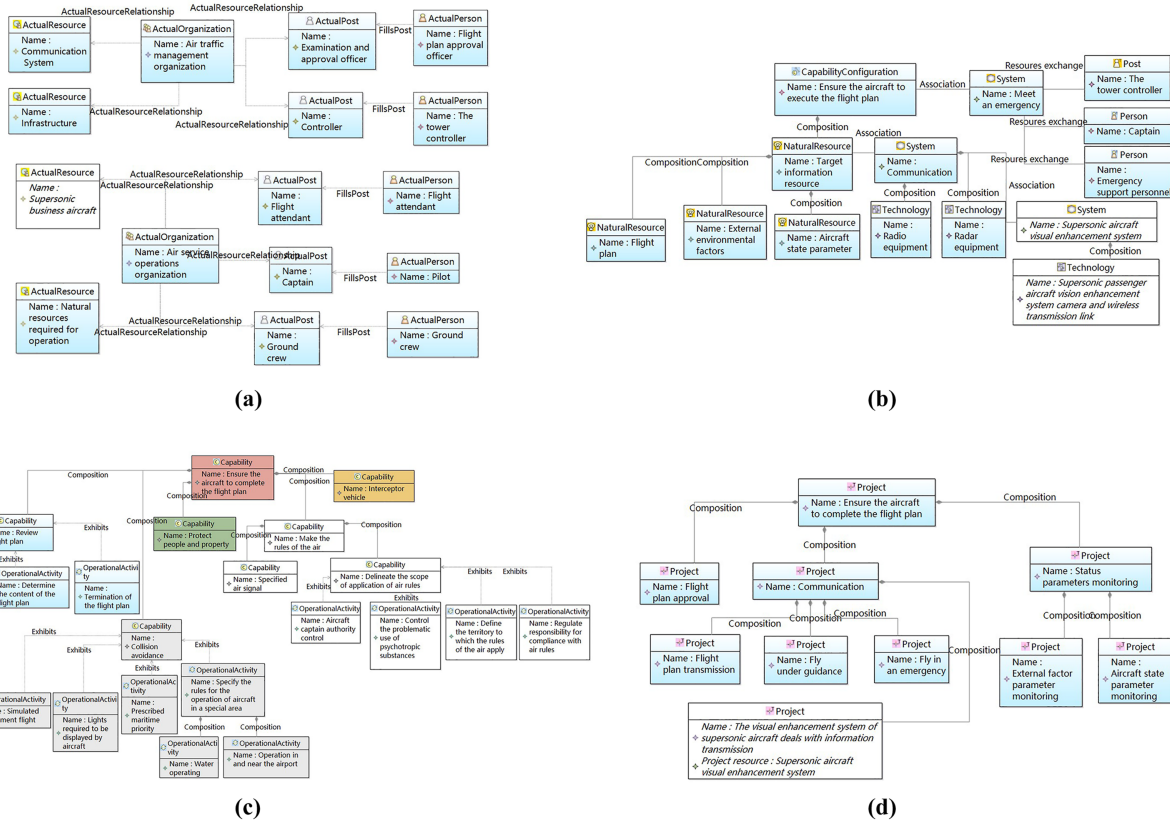
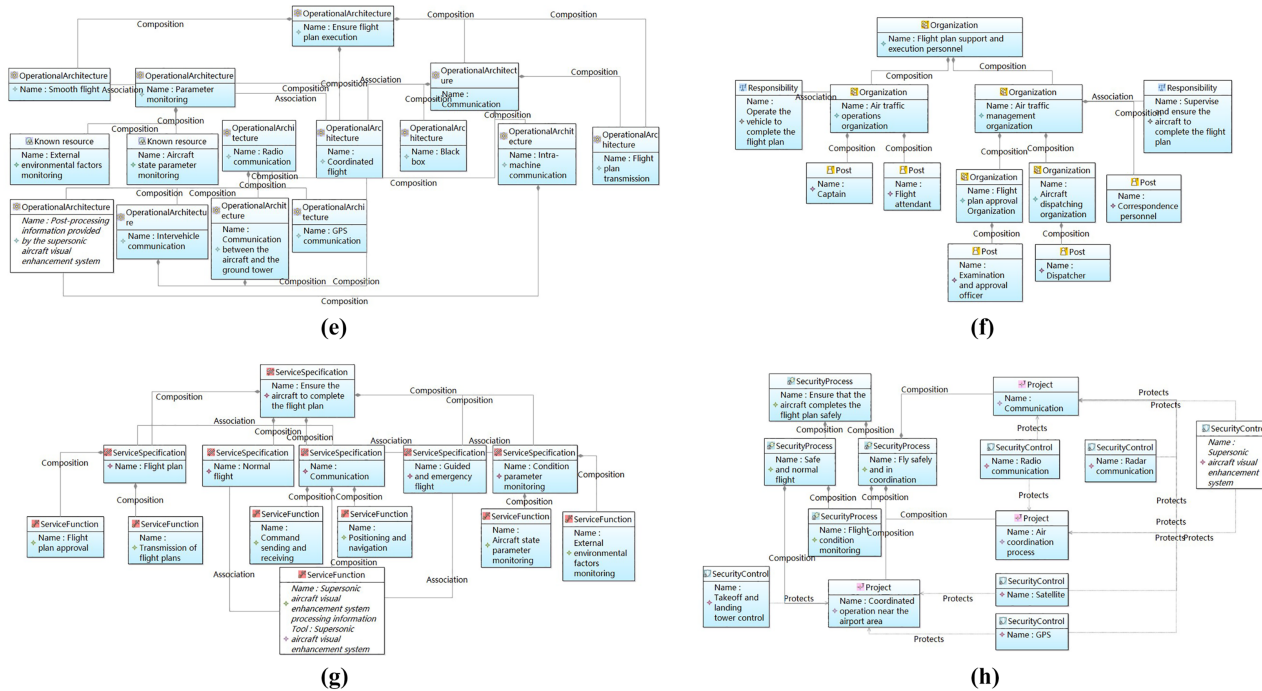
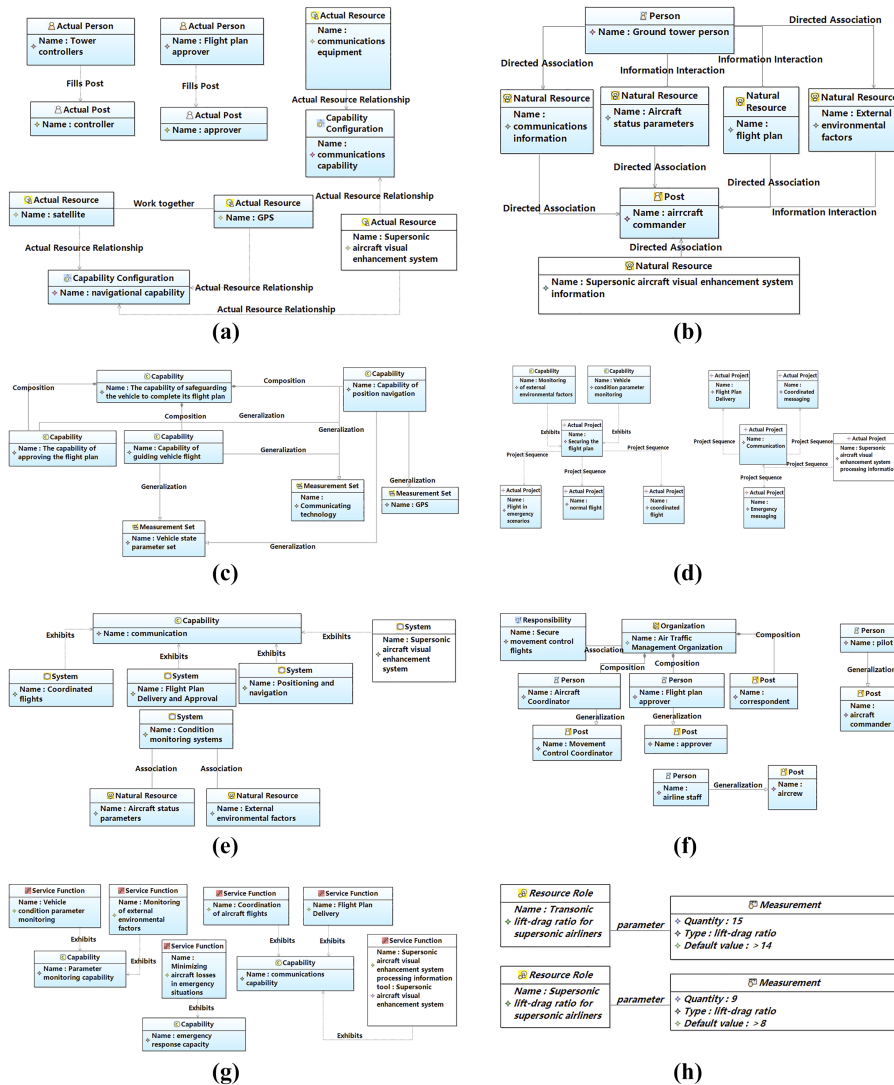


Figure 3. Domain architecture model based on UAF methodology



Source(s): Authors' own work

Figure 3. (continued)



Source(s): Authors' own work

Figure 4. Supersonic aircraft ATM system models of domains

The operational domain (Figure 3(e)) describes the logical architecture. It describes the requirements, operational behavior and structure required to support the functionality. The operational domain independently defines all the operational elements in the solution. In this case, the supplementary model of the operational domain mainly illustrates the relevant situation of the ATMS in actual operation. For example, the operational structure view (Figure 4(e)) determines the composition relationship between different operational architectures and the resources required for each level of operational structures.

The personnel domain (Figure 3(f)) describes human factors and aims to clarify the role of human factors in the creation of an architecture to facilitate human factor integration and

systems engineering. In this case, the supplementary model of the personnel view mainly illustrates the architecture design of the ATMS related to people. For example, the people structure view (Figure 4(f)) illustrates the analysis of staffing, describes which specific positions are made up of each level of organization and gives a partial description of the responsibilities of these organizations.

The service domain (Figure 3(g)) shows the services that can be provided in the system and the types of services that can be provided or carried out by each business activity. In this case, the supplementary model of the service domain mainly describes the architectural design of the ATMS related to the services provided by the system. The service structure view (Figure 4(g)) shows the structural relationship between the different services provided by the system. This view can intuitively show the hierarchy and parallel relationship between the services provided by the system.

The security domain (Figure 3(h)) shows all the contents related to security and risk of the system, and the model in the security domain will explain the security control process and risk impact of the system. In this case, the complementary model of the safety domain mainly illustrates the architectural design of the ATMS related to safety and risk in operations. The security structure (Figure 4(h)) shows the radio communication security in the air traffic relations system can protect the communication security and the air coordination process, and the air coordination process is an integral part of the safety process of flight under the safety coordination. Different from the traditional aircraft, the introduction of the new supersonic passenger aircraft in the ATMS adds the protection means of the supersonic passenger aircraft visual enhancement system to the safety control of the communication system in the model view.

5. Conclusion

In this paper, through the study of the ATMS under the ICAO regulations, combined with the new supersonic airliner designed by the “Qi Fei” team, the introduction of the GOPRR method and the M0–M3 modeling framework, we have proposed a set of metamodels applicable to the architecture modeling of the ATMS under the UAF methodology. The architectural model library of the ATMS was constructed in Airdraw, a multi-architecture modeling tool, using the UAF methodology. The set of metamodels has a quantity of 102 object metamodels, eight point metamodels, 98 property metamodels, 41 relationship metamodels, 36 role metamodels and 65 graph metamodels.

After the actual modeling, it is found that the metamodel design proposed in the paper meets the actual requirements, but whether the metamodel design can be iterated by designing a methodology different from that of the UAF in order to achieve higher modeling efficiency and model completeness needs to be followed up with related research.

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