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Extend UML Based Timeliness Modeling Approach for Complex System

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***Abstract*—With the increasing task demand for complex system, the timeliness of the system is becoming a prominent problem, especially in the inefficient system and may even lead to safety problems. This paper proposes a modeling method considering the issue of timeliness for complex system, in which the clock semantic information of MARTE (the modeling and analysis of real-time and embedded systems) is added into UML (United Modeling Language) model element through the extension mechanism of UML to describe the time constraint information. The UML model with MARTE annotation is recorded as a UML/MARTE model and the formal definition of the UML/MARTE model elements is given. Finally, the aircraft landing process is taken as an example to carry out modeling analysis to verify the validity of the model.**

Keywords—complex system; timeliness; MARTE; extend UML

I. INTRODUCTION

Complex systems such as rail transit systems, air transport systems, etc. not only pay attention to their performance, but also impose higher requirements on non-functional attributes such as timeliness. Timeliness refers to the ability and extent of the system's response within an effective time. As the task requirements increase continuously, the timeliness of the system becomes increasingly prominent.

At present, timeliness research focused mostly on medical assistance [1], information release [2], sample data [3], and combat allegations. Literature [4] studied the timeliness of C^3I system and pointed out the meaning and necessity of timeliness concept; literature [5] proposed the concept of information timeliness, and discussed its effectiveness in combat and decision-making; For the ground-to-air radar countermeasure system, the classification of system delay is proposed in literature [6]; literature [7] analyzed the factors affecting the timeliness of the C4ISR system structure through simulation experiments. In these studies, index weights and dynamic simulation methods were introduced to analyze the timeliness of information-based combat systems. There is no discussion of timeliness in general complex systems. In addition, the high integration of complex systems brings great difficulties to build the model. Most of the existing modeling methods are function-oriented models, not considering the timeliness problems in the system.

UML is a general-purpose, standardized modeling language that describes the structure and behavioral characteristics of a system from multiple perspectives. As an extension of UML, the MARTE specification has time modeling ability and make up for the shortcomings of UML in time properties modeling. For the timeliness problem in complex systems, this paper integrates the MARTE specification using the UML extension mechanism to establish a time model, and the concept of time delays is introduced to analyze the timeliness of the system and the weak links in the system is identified, which can provide ideas for system optimization.

II. THEORETICAL FOUNDATION

A. Timeliness of Complex Systems

Due to technical constraints and human factors, the system has various delays δ (δ is a non-negative real number) in the running process. These delays reflect the time characteristics in the system [6, 8], which have an important impact on whether the system can successfully complete the task. According to the functional structure of the complex system and the characteristics of the task process, the system delay can be divided into the following five categories:

Information acquiring delay(δ_a): refers to the time taken by the information acquisition device or department to obtain the original information.

Information handling delay(δ_h): refers to the time taken for handle intelligence information, allegation information, collaborative information and so on.

Information conveying delay(δ_c): refers to the time spent in the convey process by the original information and the processed various types of information.

System response delay(δ_r): refers to the react time after receiving the instruction for the instruction execution unit.

System operation delay(δ_o): refers to the time during which the instruction execution unit performs the operation.

All kinds of delays in the system will inevitably affect the task completion time. Only when the specified actions or functions are completed within the specified time, the operation is effective. The delay deviations in the system not only affect system tasks, but may even cause safety problems. Based on the specified task flow of a complex system, the timeliness is defined as follows:

Definition 1: Timeliness of complex systems is the probability that the system can complete the task within the specified time in the case of random system delays, when the system components do not fail and the personnel decisions and operations are correct.

B. UML Extension Mechanism

UML [9] is a graphical system modeling language developed by the Object Management Group (OMG). It can describe the static structure and dynamic behavior of system, and the system models are built from different perspectives to form different views of the system. In each type of view, one or more graphical modeling tools can be used to visualize the various concepts in the view.

UML provides three extension mechanisms to add new building blocks, create new features, and detail new semantics.

1) Stereotype: A new model element is constructed on the basis of a defined model element, that is represented by a literal string in double angle brackets.

2) Tagged value is used to extend the characteristics of UML building blocks and add new features. It can be used to store any information about an element, such as time information.

3) Constraints: Use an expression to represent semantic restrictions.

C. MARTE Clock Structure

Although UML has powerful description capabilities, it still cannot meet the needs of modeling in various fields. Therefore, UML provides a flexible extension mechanism that allows users to extend UML based on their needs. The MARTE [10] specification is an extension of UML released by OMG, which makes up for the shortcomings of UML in non-functional attribute modeling. MARTE adopts models of time that rely on partial ordering of instants. There are three main classes of time abstraction used to represent behavioral flows. The first is causal/temporal: in such models, one is only concerned about instruction precedence/dependency; the second is clocked/synchronous: this class of time abstraction adds a notion of simultaneity, and divides the time scale in a discrete succession of instants; the third is physical/real-time: this class of time abstraction demands the precise accurate modeling of real-time duration values, for scheduling issues in critical systems.

TABLE I. EXAMPLE OF STEREOTYPES AND TAGGED VALUES IN THE MARTE PROFILE

Characteristics	Stereotypes	Tagged values
Task/thread	<<swScheduable Resource>>	isPreemptable deadlineElements
Timing analysis	<<SaStep>>	deadline execTime
Hardware	<<Interrupt Resource>>	durationElements vectorElements

The MARTE provides pre-defined stereotypes and tagged values for non-functional properties modeling. TABLE I is an example of the stereotypes and tagged values defined in the MARTE package. This paper uses the stereotype <<SaStep>> and the tagged values deadline and execTime to describe the time constraint information of the system.

III. UML/MARTE TIME MODEL

A. Time Model of Complex Systems

For complex systems, this paper uses class diagram, sequence diagram and activity diagram to build the model (shown in TABLE II). The class diagram used to build the static structure model describes the classes used in the system and the relationship between them; the sequence diagram describes the messages exchange in chronological order between the objects in the system, focusing on messages convey process; the activity diagram describes the dynamic behavior of the system functions and the sequential relationship between the activities, which show the entire task flow of the system.

TABLE II. UML GRAPHICAL MODELING TOOL

Model	**Diagram**	**Purpose**
Structural Model	Class Diagram	class, attribute and relationship
Behavioral Model	Activity Diagram	business process
	Sequence Diagram	sequential interactions between objects

In this paper, based on the timeliness of complex systems, UML's extension mechanism is used to add system delays to UML model following MARTE specification to reflect the time properties; then, the timeliness of the system can be analyzed considering various delays.

B. UML/MARTE Time Model

The UML/MARTE time model consists of UML and MARTE annotations. The paper uses Class Diagram with MARTE annotations (CD/MARTE), Sequence Diagram with MARTE annotations (SD/MARTE) and Activity Diagram with MARTE annotations (AD/ MARTE) to describe time properties and constraints of the system.

1) CD/MARTE time model

a) The class Diagram with MARTE annotations

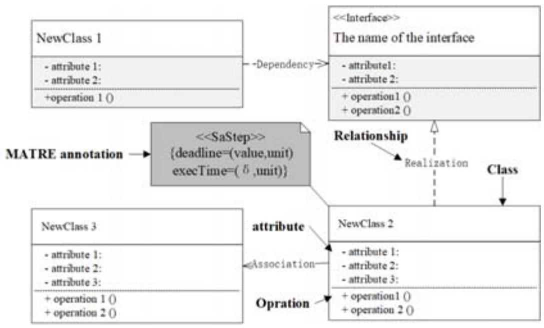


FIGURE I. A CLASS DIAGRAM WITH MARTE ANNOTATIONS

The class diagram is used to build a static structural model, describing the properties and operations of each object, and the relationships between the objects. The time constraints are described by adding MARTE annotations to the objects and the relationship between them in the class diagram.

FIGURE I is an example of a class diagram with MARTE annotations. There is stereotype <<SaStep>> and the tagged values deadline and execTime in the class diagram. Tagged value deadline represents the maximum time for the object to execute the activity, and execTime represents the execution time of the activity.

b) Formal definition of CD/MARTE

Definition 2 (CD/MARTE): A class diagram with MARTE annotations is a structure (N_{cd}, C_{cd}, R_{cd}, A_{cd}, O_{cd}, MA_{cd}) where:

- N_{cd} is the name of the class diagram.
- C_{cd} is a set of new classes in the complex system.
- R_{cd} is a set of relationships between new classes, which include association, generalization, dependency and realization.
- A_{cd} is an attribute of the class that describes a set of properties of the object.
- O_{cd} is an operation of the class, which is an action that a class can perform, or you (or another class) can perform on a class.
- MA_{cd} is a set of MARTE annotations. A MARTE annotation consists of a set of stereotypes and a set of tagged values.

2) *SD/MARTE time model*

a) The sequence diagram with MARTE annotations

The sequence diagram is a visual representation of messages conveying chronologically between objects in the system. It is used to describe message interaction process. The time constraints are described by adding MARTE annotations to the objects and the message between them in the sequence diagram.

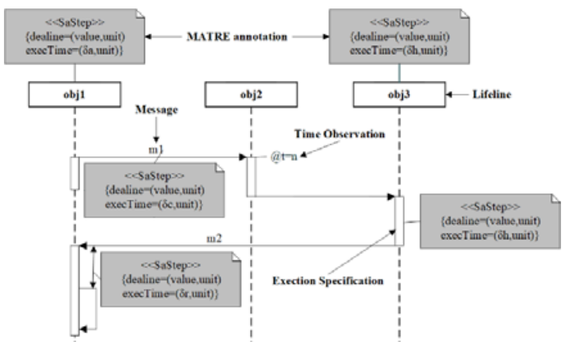


FIGURE II. A SEQUENCE DIAGRAM WITH MARTE ANNOTATIONS

FIGURE II is an example of a sequence diagram with MARTE annotations. Stereotype <<SaStep>> and tagged values deadline and execTime are added into each element of the sequence diagram to describe the time constraints that should be met during the messaging process in the system. The tagged value deadline represents the maximum time for messages transfer between objects, and execTime represents the time taken for messaging between objects.

b) Formal definition of SD/MARTE [11]

Definition 3 (SD/MARTE): A sequence diagram with MARTE annotations is a structure (N_{sd}, L_{sd}, O_{sd}, E_{sd}, M_{sd}, T_{sd}, MA_{sd}, $<_{sd} \subseteq O_{sd} \times O_{sd}$, $LOC_{sd}: O_{sd} \rightarrow L_{sd}$) where:

- N_{sd} is the name of the sequence diagram.
- L_{sd} is a set of lifelines.
- O_{sd} is a set of occurrence specifications. An occurrence specification represents a syntactic point at the starts or ends of messages or at the beginning or end of an execution specification (OMG 2011b).
- E_{sd} is a set of execution specifications. An execution specification consists of a start occurrence specification and a finish occurrence specification.
- M_{sd} is a set of messages. A message is composed of a sending occurrence specification, a receiving occurrence specification, a message name, and a message type.
- T_{sd} is a set of time observations. A time observation is composed of a time value and an occurrence specification.
- MA_{sd} is a set of MARTE annotations. A MARTE annotation consists of a set of stereotypes, a set of tagged values.
- $<_{sd} \subseteq O_{sd} \times O_{sd}$ is a set of total ordering functions. The orders describe an order relationship between two adjacent occurrence specifications.
- $LOC_{sd}: O_{sd} \rightarrow L_{sd}$ is a function which the location of an occurrence specification is defined.

3) *AD/MARTE time model*

a) The activity diagram with MARTE annotations

The activity diagram describes the dynamic functions, the sequence of activities, and the concurrent behavior of the system. Add MARTE annotations to the active nodes and transition arrows in the activity diagram to indicate the execution time of each node activity and the transition time between nodes.

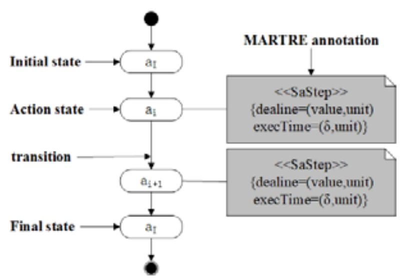


FIGURE III. AN ACTIVITY DIAGRAM WITH MARTE ANNOTATIONS

FIGURE III is an example of an activity diagram with MARTE annotations. Stereotype <<SaStep>>, tagged values deadline and execTime added to the active nodes and transitions indicate the execution time of the active node ai, a_{i+1} and the transition time from a_i to a_{i+1} respectively and they must be completed before the deadline.

b) Formal definition of AD/MARTE

Definition 4 (AD/MARTE): A activity diagram with MARTE annotations is a structure (N_{ad}, A_{ad}, T_{ad}, F, MA_{ad}, a_I, a_F) where:

- N_{ad} is the name of the activity diagram.
- $A_{ad}=\{a_1,a_2,\ldots,a_m\}$ is a set of action states.
- $T_{ad}=\{t_1,t_2,\ldots t_n\}$ is a set of transitions.
- $F\subseteq(A_{ad}\times T_{ad})\cup(T_{ad}\times A_{ad})$ is the flow relations.
- MA_{ad} is a set of MARTE annotations. A MARTE annotation consists of a set of stereotypes, a set of tagged values.
- $a_I\in A_{ad}$ is initial state, $a_F\in A_{ad}$ is final state.

IV. CASE STUDY

A. Case Introduction

The contradiction between the increasing demand for air traffic and the limited airport capacity has led to more and more serious problems with airport traffic congestion and flight delays, which has caused great inconvenience to airlines and passengers. In fact, the airport terminal area is the bottleneck of the entire air traffic network. With the increase in the number of flights, there is an increasing demand for aircraft take-off/landing time. Delays in any stage during the take-off and landing of aircraft will cause flight delay, which will affect other aircraft landing on time and even cause safety problems.

Multi-party coordinated control is usually required to ensure that aircraft lands within the specified time, which is a typical complex system timeliness problem. The above accident case is taken as an example to model and analyze the timeliness of the system.

B. Aircraft Landing Timeliness Modeling

This paper assumes that the system consists of aircraft, radar, air traffic control center (ATC), tower controller and pilot. The radar detects the aircraft's position when the aircraft enters the controller's radar range, and then the ATC transmits the aircraft's track information, meteorological conditions, and airport intelligence to the controller through the tower's display. Through the controller judges the airport conditions, the plane will be given clearance to land if flight landing is allowed and then the pilot operates the aircraft down. Then the tower detects the runway. If the runway is idle, the controller issues a land permit. After the pilot receives the instruction, the aircraft is grounded and parked to the designated location. At last the tower is informed that the aircraft is in place.

According to the foregoing definition of system delays, the delays in the aircraft landing are as follows:

(1)δ_a: radar detection delay, meteorological department monitoring delay and tower detection delay.

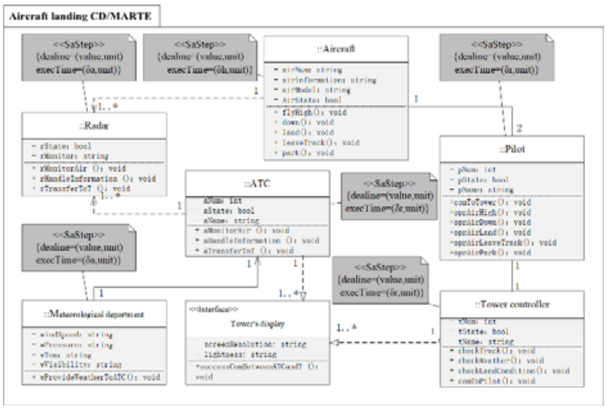
(2)δ_h: ATC handle delay, controller judgment delay and tower calculation delay.

(3)δ_c: data transmission delay between radar, meteorological departments and ATC, and communication delay between the controller and the pilot.

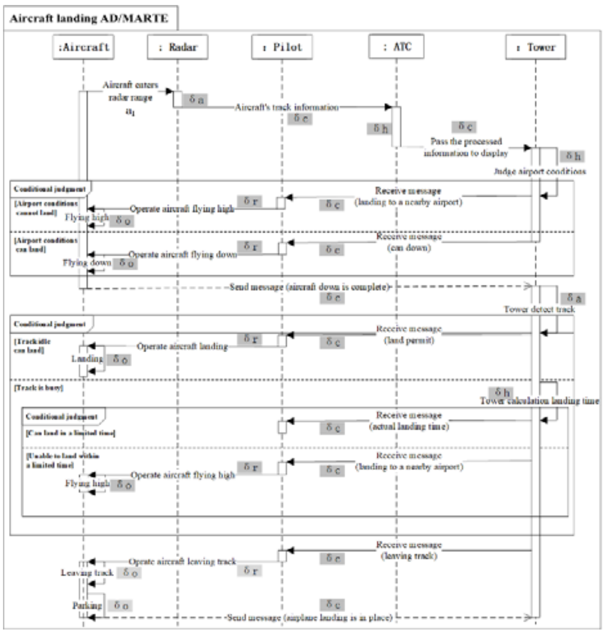
(4)δ_r: pilot operation delay.

(5)δ_o: aircraft implement delay.

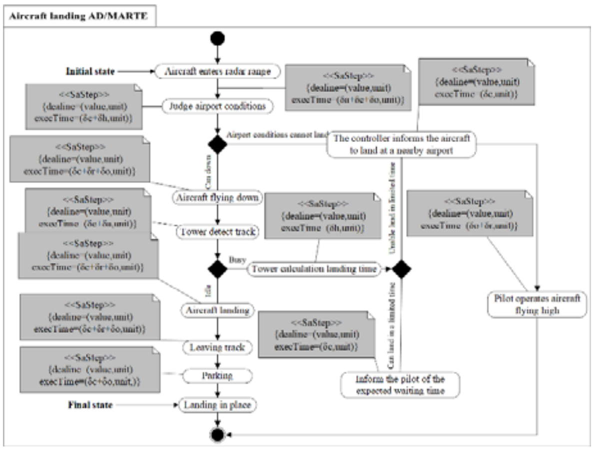
The aircraft landing process was modeled using CD/MARTE, SD/MARTE and AD/MARTE, as shown in FIGURE IV (a), (b) and (c). CD/MARTE describes the attributes, operations of the subsystems, and relationships between them; SD/MARTE describes the messages interaction process in chronological order; AD/MARTE describes the entire process of aircraft landing. By random delay, the random value of the time taken to perform the specified task on each element can be analyzed.



(a) AIRCRAFT LANDING CD/MARTE MODEL



(b) AIRCRAFT LANDING SD/MARTE MODEL

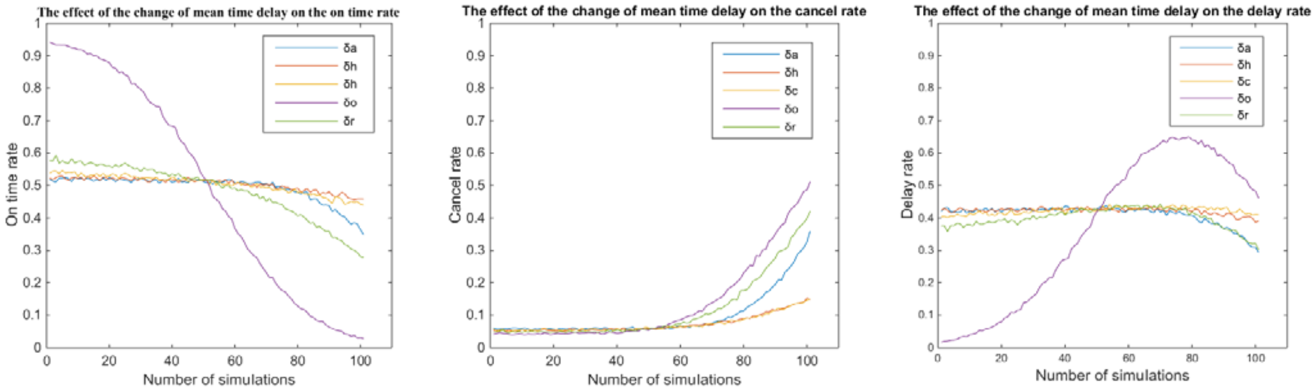


(c) AIRCRAFT LANDING AD/MARTE MODEL

FIGURE IV. AIRCRAFT LANDING PROCESS MODEL

C. Timeliness Analysis of Aircraft Landing

Based on the model, the Monte Carlo simulation method is used for analysis. The main inputs of the simulation include two categories: (1) the distribution and deadline of various delays existing in the system; (2) the distribution of each state selection switch. It is considered that all delays obey the normal distribution, and the state selection switch obeys the binomial distribution [12]. The delay values of different aircraft types are slightly different. The Civil Aviation Administration of China divides the aircraft into small, medium and large aircraft according to the number of passengers. The optimal landing time is 720s, 780s and 900s respectively. All simulation input data are obtained according to the statistics of the daily running production of the airline.



(a) (b) (c)

FIGURE V. SENSITIVITY ANALYSIS OF EACH DELAY MEAN VALUE

10000 simulations were carried out, among which 5057 were on time, 612 were canceled, 4331 were delayed, and the flight landing timeliness was 0.5057. The simulation results show that in the landing process, the impact on aircraft delay cannot be ignored only because of the delays and the complex landing environment.

Moreover, some sensitivity analyses were carried out as well to understand the effect of various delays on timeliness. The simulation results are shown in Figure V (a), (b), and (c).

The following conclusions can be drawn from the sensitivity simulation results:

As the mean value of delay increases, the rate of on time is likely to decrease gradually, as shown in Figure V (a). It can be seen from the trend of the curve that the impact of δ_a, δ_h and δ_c on punctuality is small, while that of δ_r is large, and the effect of δ_o is the most significant.

As the mean value of delay increases, the overall trend of the cancel rate is firstly maintained and then increases sharply, as shown in Figure V (b). It can be seen from the trend of the curve that the influence of the five types of delays is not much different. As each delay value increases, it not lead to cancel flight but delay; when the delays continue to increase beyond the acceptable security range, the landing will be cancelled to avoid accidents, so at that time the cancel rate increases dramatically.

With the increase of the mean value of delay, the delay rate gradually increases firstly and then decreases. It shows that the increase of the delay value at the beginning leads to increased delay. Large enough to exceed the acceptable security range, the landing will be cancelled, and the delay rate begins to decrease, as shown in Figure V (c). It can be seen from the trend of the curve that the influence of δ_a, δ_h, δ_c and δ_r on delay rate is relatively small, and the influence of δ_o is most obvious.

Different delay values in the aircraft landing process lead to different landing times. If at least one type of delay of a aircraft is delayed for a long time, it will affect the other flights normal landing and even cause collision accident. According to the above simulation results, we found that during the landing process, the system response and the system operation phase are weak links. It is necessary to focus on monitoring these two links and reduce their abnormal delays, which can effectively improve the timeliness of the whole system.

V. CONCLUSION

Aiming at the timeliness problem in complex system, this paper proposes a UML/MARTE-based timeliness modeling method of complex systems by using MARTE's extension of time modeling capabilities on UML. The method divides the system delays and adds them to the UML model elements in the form of stereotypes and tagged values. In addition, the formal definitions of CD/MARTE, SD/MARTE and AD/MARTE are given. Finally, using the proposed modeling method, the aircraft landing process is taken as an example to model and simulate, and the influence of delays on the system timeliness is analyzed.

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