Specifying Spatio-Temporal Properties for Mobile Cyber Physical Systems

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***Abstract*—Mobile cyber physical systems, in which the physical system under study has inherent mobility, are a prominent subcategory of cyber-physical systems. Mobile cyber physical systems are spatio-temporal in the sense that correct behavior will be defined in terms of both space and time. Therefore, both temporal and spatial requirements should be taken into consideration when specifying mobile cyber physical systems. However, how to represent spatio-temporal properties is still a huge challenge in the mobile cyber physical development process. In this paper, we propose a method combining clock theory and RCC-8 together indicating spatio-temporal information of CPS, and we present spatio-temporal sequence diagram for change tracking under the specific scene. We take vehicle system as instance to see how the method work in description of spatio-temporal information between vehicles and vehicles, vehicles and people, vehicle and surroundings in different situations.**
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Keywords-spatio-temporal; mobile; CPS; RCC

I. INTRODUCTION

Cyber physical systems(CPS) concludes physical process, communication process and computation process [1], [2]. It requests accurate interaction between moving objects [3], so spatial-temporal information is badly in need. Not only the description of spatio-temporal information, but also the topological relationship changes should be tracked as time passed. Therefore, modeling the unified spatio-temporal model is very necessary [4].

Many spatio-temporal models provides precedent and reference:

Sequent snapshots model regard time as an linear, discrete, absolute attribute of scenario, and mix time information into spatial model by the time stamp [5].

Discrete grid unit model discretizes the spatial dimension in sequent snapshots model, and each spatial unit corresponds to the time list in this unit [6].

The concept of event is first introduced into spatio-temporal model by Peuquet and Wentz, and it defines that event emerges when spatio-temporal information changes. It introduces event to analyze the object and location oriented information. Peu-quet and Duan designed a event-based spatio-temporal data model (ESTDM) which is applied to geoscience [7].

In this paper, we propose a method combining clock theory ［8］ and RCC-8［9］ together indicating spatio-temporal information of CPS, and we extend sequence diagram[10] to spatio-temporal sequence diagram[for change tracking under the specific scene. We take vehicle system as instance to see how the method work in description of spatio-temporal information between vehicles and vehicles, vehicles and people, vehicle and surroundings in different situations.

II. SPATIO-TEMPORAL MODELING

For spatio-temporal modeling, it can be divided into two parts: temporal part and spatial part. In the case of temporal part, we prefer the description of clock theory; while in the case of spatial part, we favor RCC-8.

Clock theory [11]is a hybrid language, and a clock based de-scription for temporal order and time latency as well. CPS contains the continuous physical process and discrete control process, clock theory exactly concludes linking mechanism of continuous and discrete variables, recording event by a clock, and clock at a specific location.

Base on Clarke's work on spatial logic calculus, Randell et al put forward RCC which stands for region connection calculus. The calculus regards region as foundation, and indicates the binary spatial relation. In RCC model, region calculus is divided into sets of relationship, and the elements in the set do not have intersection but jointly exhaustive and pairwise disjoint (JEPD). RCC-8 contains eight topological re-lations as follows, which concludes the relation between border of region: disconnected (DC), externally connected (EC), equal (EQ), partially overlapping (PO), tangential proper part (TPP), tangential proper part inverse (TPPi), non-tangential proper part (NTPP), non-tangential proper part inverse (NTPPi). Figure 1 below shows the topological relations of RCC-8.

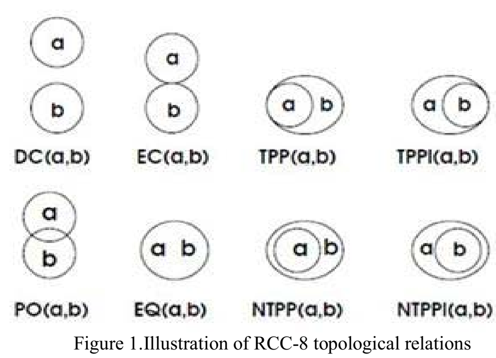

Figure 1.Illustration of RCC-8 topological relations

Regarding what mentioned above, it is urgent to establish contact between clock theory and RCC-8. When tracking a single moving object, its own traveling time and specific location is important. While considering a great number of moving objects in a region, we tend to know the spatio-temporal relationship among them rather

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than a concrete time or location. For that clock theory and RCC-8 bases on respective architecture and topological relations change with timeline, two independent description is not ideal for indicating spatio-temporal relationship. So we divide the region into several sets of relations according to the timeline of clock, and explicate the topological relations in clock theory as Figure 2 shows.

$$DC: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (l_2 : t^+ \preceq k_1 : t^-) \vee (k_2 : t^+ \preceq l_1 : t^-)))$$

$$EC: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (l_2 : t^+ = k_1 : t^-) \wedge (k_2 : t^+ \preceq l_1 : t^-)))$$

$$PO: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (k_1 : t^- \preceq l_2 : t^+) \wedge (l_1 : t^- \preceq k_2 : t^+)))$$

$$EQ: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (l_2 : t^+ = k_2 : t^+) \wedge (k_1 : t^- = l_1 : t^-)))$$

$$TPP: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (k_1 : t^- \preceq l_2 : t^+ \preceq k_2 : t^+) \wedge (k_1 : t^- = l_1 : t^-)))$$

$$TPPI: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (l_1 : t^- \preceq k_2 : t^+ \preceq l_2 : t^+) \wedge (k_1 : t^- = l_1 : t^-)))$$

$$NTPP: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (l_2 : t^+ \preceq k_2 : t^+) \wedge (k_1 : t^- \preceq l_1 : t^-)))$$

$$NTPPI: \exists t_1 \exists t_2 (t_1 \preceq t \preceq t_2 \wedge \forall t^- \forall t^+ (t_1 \preceq t^- \preceq t \preceq t^+ \preceq t_2 \rightarrow (k_2 : t^+ \preceq l_2 : t^+) \wedge (l_1 : t^- \preceq k_1 : t^-)))$$

Figure 2.The logic representation of RCC-8 in clock theory

Through the redefinition of RCC-8 by clock theory, we combine the spatial and temporal elements of moving objects together in CPS. On this basis, a graphical representation is in need for tracing the spatial changes along with timeline. Then the spatio-temporal sequence diagram is shown in Fig.3. As an interaction diagram, sequence diagram indicates how process interact with another in order. In the spatio-temporal sequence diagram, the leftmost vertical arrow in-dicates the clock of event; the parallel vertical lines under objects are lifeline; the vertical bars means activation time of the object; the parallel horizontal arrows means the operations taken and spatio-temporal relationship, and number means the order; message name indicates operations, parameters can be added in the pair of parentheses, and topological relationship is in the square brackets; tail of arrow points at the operator of the operation, and arrowhead points at the other party of the topological relationship.

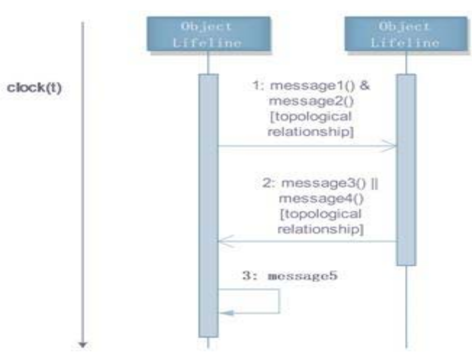

Figure 3. The logic representation of spatio-temporal sequence diagram in RCC-8 and clock theory

III. Case Study: Vehicle System

As a typical case of cyber physical systems, the insurance of safety and security of vehicle system [12][13] all depends on the collection and analysis of spatial and temporal messages among all the traveling vehicles on the road. It is easy to see the importance of representation and demonstration of spatio-temporal relationship changes in given scenarios in such case of CPS. In vehicle system, road conditions are changeable owing to many closely related factors. For example, traffic lights system, lane type, vehicle's operations etc. Here in this paper, lane types consists of single straight lane, double straight lanes, roadside parking station, single bend, double bends, crossroads, confluent roads. Generally, vehicles on the road may accelerate, decelerate, move uniformly, change lanes, make a turn. Table 1 below shows the operation name and abbreviation indicating distance, velocity and location.

TABLE 1. PARAMETER LIST FOR VEHICLE SYSTEM

Parameter and Operation	Value
acc	accelerate
dec	decelerate
uniform	move uniformly
trans	change to another lane
turn	turn left, turn right
d_{xy}	distance between x and y
vx	velocity of x
sx	continuous variable of distance x travelled
lx	discrete variable of location of x

To all the vehicles, acceleration equals to speeding up at high rate(5(c)), while deceleration equals to speeding up at low rate(4(c)). Dynamic features as climb(x,y) and drop(x,y) are used to indicate the temporal relationship according to the travel directions and driving distance. There are some circumstances that one's front or back runs into another, then the binary spatial relationship caused by one's own initiative operation is PO or EC. And among all the operations, the following three ones indicating velocity changes have noninterference.

When there is a single straight lane, all the vehicles on the road are in the same direction in order as Fig.4. Car_A, car_B, and car_C will influence each other when taking different actions. Acceleration, deceleration, and moving uniformly are allowed.

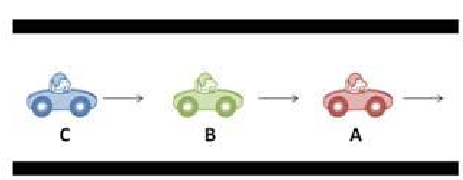

Figure 4.Single straight lane

According to the figure above, the spatial relationship has several conditions: (1) at the beginning, on the premise of v_a v_b v_c car_A, car_B, and car_C will not cause an accident. when car_A accelerates, the spatial relationship with car_B is DC; when car_A decelerates, the spatial relationship with car_B is EC. (3) then car_B accelerates, the spatial relationship with car_A is PO, which is DC with car_C ; when car_B decelerates, the spatial relationship with car_A is DC, which is EC with car_C . (4) when car_C decelerates, the spatial relationship with car_B is DC; when car_C accelerates, the spatial relationship with car_B is PO.

Fig.5 shows the spatio-temporal sequence diagram of the scenario described above.

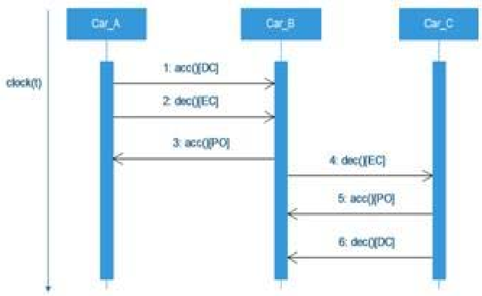

Figure 5.The spatio-temporal sequence diagram of single straight lane

When there are parallel lanes, all the vehicles on the both lanes are in the same direction in order as Figure 6. Car_A, car_B, car_C , and car_D will influence each other when taking different actions. The difference from the single straight lane is that vehicles can changes lane when there is enough space between front and back vehicles. Acceleration, deceleration, moving uniformly, and changing lanes are allowed.

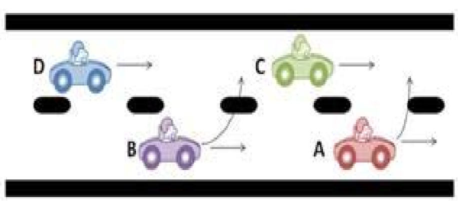

Figure 6. Parallel lanes

According to the figure above, the spatial relationship has several conditions: (car_A and car_B are similar to car_C and car_D when changing lanes) (1) on the basis of v_a v_b and v_c v_d, there will not be any accidents; when two vehicles change to the other lane, if v_a v_b v_c v_d, vehicles will travel safely. (2) when car_A accelerates, the spatial rela-tionship with car_B is DC; when car_A decelerates, the spatial relationship with car_B is EC. (3) when car_B accelerates, the spatial relationship with car_A is PO; when car_B decelerates, the spatial relationship with car_A is DC. (2)(3) are the same as single straight lane. (4) when car_A changes lane, then if it accelerates, the spatial relationship with car_C is DC, if it decelerates, the spatial relationship with car_C is EC. (5) then car_B changes lane, if it accelerates, the spatial relationship with car_C is PO, if it decelerates, the spatial relationship with car_D is EC. (6) now the four vehicles are on the same lane; when car_C decelerates, the spatial relationship with car_B is EC; when car_C accelerates, the spatial relationship with car_A is PO. (7) if car_D decelerates, the spatial relationship with car_B is DC; if car_D accelerates, the spatial relationship with car_B is PO.

Fig. 7 shows the spatio-temporal sequence diagram of the scenario described above.

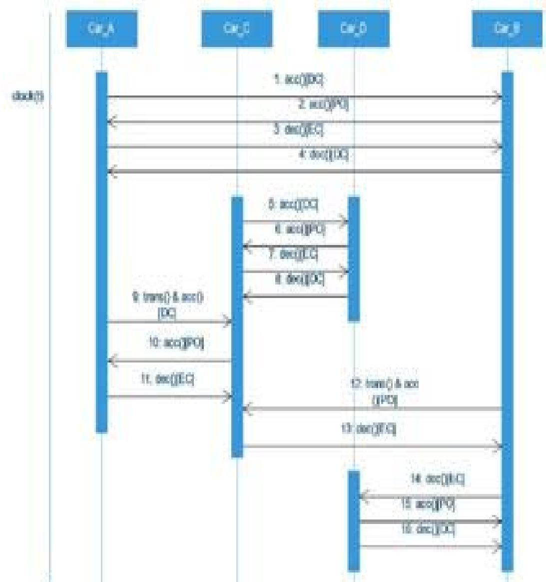

Figure 7.The spatio-temporal sequence diagram of parallel lanes

Roadside parking station can hold only one car at one time as Fig.8 below shows. And if there is a vehicle in the parking station already, another one is not admitted to get in, or there will be a collision. When no vehicles park cars in the parking station, the condition is the same as situation 1. Acceleration, deceleration, moving uniformly, and changing lanes are allowed.

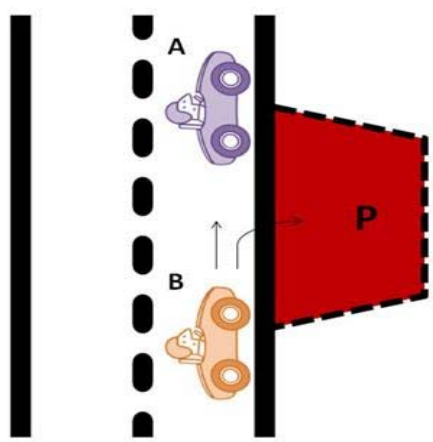

Fig. 8. Roadside parking station

According to the figure above, the spatial relationship has several conditions: (car_A is similar to car_B when parking) (1) on the basis of v_a v_b, there is no accidents. (2) when car_A accelerates, the spatial relationship with car_B is DC; when car_A decelerates, the spatial relationship with car_B is EC. (3) when car_B accelerates, the spatial relationship with car_A is PO; when car_B decelerates, the spatial relationship with car_A is DC. (2)(3) are the same as single straight lane. (4) if car_B changes lane to the parking station, the spatial relationship with parking station is EQ.

Fig. 9 shows the spatio-temporal sequence diagram of the scenario described above.

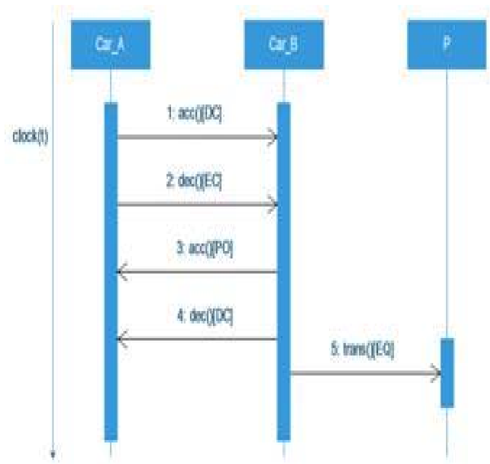

Figure 9. The spatio-temporal sequence diagram of roadside parking station

IV. CONCLUSION

In this paper, we propose a method combining clock theory and RCC-8 together indicating spatio-temporal information of CPS, and we present spatio-temporal sequence diagram for change tracking under the specific scene. We take vehicle system as instance to see how the method work in description of spatio-temporal information between vehicles and vehicles, vehicles and people, vehicle and surroundings in different situations. we analyze the essence and reveal the importance of description of spatio-temporal information in CPS. Then we put forward the logic representation of RCC-8 in clock theory framework, and give a combination of the two conveying the spatio-temporal information of cyber physical systems. Furthermore, we present spatio-temporal sequence diagram for detailed analysis of several situations of vehicle system (as an example of CPS).

In consideration of lack of verification of the method, transformation of the model, development and expansion of the tool is important in the future work. Future work will also integrate Spatio-Temporal Sequence Diagram with Modelicaml and AADL to specify and model complex mobile cyber physical systems.

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