객체전송 이동체의 추적을 위한 실시간 분산, 이동, 상호작용 Calculus

A Calculus of Real-Time Distribution, Mobility and Interaction for Tracing Mobile Agents with Transporting Objects

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요 약

GPS/GIS와 RFID는 유비쿼터스 시대로 가는 우리 사회의 패러다임을 변화시켰다. 특히, 이러한 환경에서 지리적으로 분산되어 있고 운송해야 할 대상이 있는 이동 에이전트들은 자동으로 인식하고추적할 수 있어야 한다. 그렇게 하기 위해서, 지리적 공간에서 에이전트들의 공간적/시간적 행위들을 명세하고 검증하기위한 기본적인 이론과 기술들이 필요하다. 본 논문은 이를 위해 CaRDMI라는 새로운 정형기법을 제안한다. 명세를 위해 CaRDMI는 지도와 운송대상을 가지는 이동 에이전트들을 정의한다. 에이전트의 이동은 지도상의 경로로 표현되고 이들은 공간적/시간적 제약이 있는 노드와 에지들의 리스트들로 구성된다. 에이전트들 사이에서의 운송 대상에 관한 상호작용은 동기화 모드들에 의해 표현된다. 이들이 CaRDMI의 두드러진 특징이다. 특히, 시간 속성을 가진 다대다 동기화는 주목할만하다. CaRDMI는 분석과 검증을 위해 공간적, 시간적 그리고 상호작용을 위한 추론 규칙과 공간적/시간적 동일성 관계들을 제안한다.

Abstract

GPS/GIS and RFID technologies have been changing the paradigm of our society toward ubiquitous era. Especially, geographically distributed mobile agents with transporting objects need to be automatically recognizable and traceable under certain conditions. To do this, fundamental theories and technologies are required to specify and verify spatial and temporal behaviors of agents on geographical space. This paper presents a new formal method, called Calculus of Real-Time Distribution, Mobility, and Interaction (CaRDMI), for this purpose. For specification, CaRDMI defines a map, mobile agents with transporting objects. The movement of an agent is represented by a path on the map, consisting of a list of nodes and a list of edges with spatial and temporal constraints. Interactive constraints among agents are represented by synchronization modes on objects at nodes. These constraints are distinguishable features of CaRDMI from other methods. Especially, many-to-many timed synchronization constraints are noticeable. For verification, CaRDMI presents the spatial, temporal and interactive deduction rules and the spatial and temporal equivalence relations.

☞ keyword : Calculus, mobile agent, CaRDMI, equivalence

1. Introduction

GPS/GIS and RFID technologies have been changing the paradigm of our society toward ubiquitous era [1]. Especially, geographically distributed mobile agents with transporting objects are automatically recognizable and traceable under certain conditions. This fact is the main deriving force for many strategic industries, such as Intelligent Traffic Systems (ITS), Telematics, Location-Based Services (LBS) systems, etc [2], as well as tactical applications, such as a real-time e-delivery system with PDA based on GPS/GIS and

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RFID technologies [3], intelligent supply chain management systems [4], etc. - for convenience, such systems are named as real-time transportation/navigation systems (RTNS).

In order to specify, analyze and verify the correct and consistent timed behavioral properties of such agents for their mobility and transportability on geographical space, fundamental theories and technologies are required. The behavioral properties include concurrency, spatial and temporal constraints, interactive synchronization modes, and so on. These properties are used to analyze and verify system requirements, such as correctness, consistency, safety, deadline, dead/live lock freedom, equivalence, etc.

A number of process algebras, i.e., *CCS* [5], *pi-calculus* [6,7], and *mobile ambient calculus* [8], have been reported to specify, analyze, verify, and predict behavior of distributed real-time systems. However these algebras are not well suitable to represent *real-time transportation/navigation systems* (RTNS) [9, 10, 11, 12] due to the lack of representation of process distributivity over some geographical space or the indistinction of representation of process mobility from process distributivity over the space as follows - note that mobile agents for transportation or navigation in RTNS are geographically distributed over some dynamically re-formable 2 or 3 dimensional space of places with dynamically connectable and disconnectable links between ports of the places, not of agents:

- CCS does not have spatial information where processes belong or interact. Consequently it is not suitable to represent process mobility.
- Pi-calculus does not have the spatial information just as CCS, but process mobility is represented by dynamic change of link connections between processes with ports of processes.
- Mobile ambient calculus represents the spatial information with scopes of ambients where processes belong, and describes process mobility with dynamic changes of scopes among the ambients. However the space information is dependent on the process mobility since the mobility changes the scope relations among the ambients by the definition of the mobility.

To make the process algebra suitable to RTNS, it is inevitable to separate the space representation from the mobility representation.

This paper presents a formal method for this purpose, namely, *Calculus of Real-Time Distribution, Mobility, and Interaction* (CaRDMI) as follows:

- **Space representation.** Space of RTNS is represented by a map, called *hyper-graph*, with a set of nodes and a set of edges between nodes - we call the graph a *map*for convenience. In order to represent scope relations between nodes, an *inclusion*relation is defined between nodes. Note that the relation is changeable and makes the graph dynamically reconfigurable. Similarly, in order to represent the scope of edges between nodes at different scopes,an inclusion relation between edges is defined between edges. The inclusion relations are used for hierarchical abstraction of RTNS. Note that nodes have ports. Consequently edges can be defined between ports of nodes.
- **Mobility representation.** The mobility of agent in RTNS is represented by a pair of a list of nodes on a map, called a path, and a set of delivering objects, if necessary. A path is a sequence of edges between nodes with ports with

spatial, temporal and interactive constraints - note that agents don't have ports. The spatial and temporal constraints are imposed on nodes, and the interactive constraints on delivering objects at nodes, respectively. Further these constraints are hierarchically abstracted with respect to inclusion relations in their scopes.

For analysis and verification, CaRDMI defines a set of the spatial, temporal and the interactive deduction rules and a set of equivalence relations as follows:

- The deduction rules define the semantics of CaRDMI for each sequential, selective, interactive operations with respect to spatial, temporal and interactive constraints. The rules can be abstracted hierarchically.
- The equivalence relations define how similar two mobile agents are in the spatial and temporal space. The relations can be abstracted hiearchically.

The innovative features of CaRDMI are as follows:

- The space and mobility representations are separated.
- The space and mobility representations can be abstracted hierarchically.
- Further the deduction rules and equivalence relations can be abstracted hierarchically, too.

- Agents don't have ports, but nodes have ports instead.
- Agents move through paths and interact with another synchronously or asynchronously by delivering objects at certain nodes on a map.
- Temporal constraints include a set of *ready*, *duration deadline* and *wait* scopes, hierarchically.
- Many-to-many timed synchronization and asynchronization are possible, as well as one-to-one.

This paper consists of sections as follows. Sections 2 and 3 define CaRDMI syntax and semantics, respectively. Section 4 defines temporal semantics of CaRDMI. Section 5defines behavioral equivalences. Section 6 illustrates and analyzes a practical example for RTNS application. Finally Section 7 concludes with some limitations and future researches.

2. Basic CaRDMI Syntax

Definition 2.1 (Preliminaries)

$G=\{V,W,I\}$: a hyper-graph for a map, where $V=\{v_i \mid 1\le i\le n\}$: a set of nodes and hyper-nodes, $W=\{e_i \mid 1\le i\le m\}$: a set of edges and $I=\{(v_i,v_j)\mid v_i,v_j\in V, v_i\subseteq v_j\}$: a set of node inclusion relations. $M=\{m_i \mid 1\le i\le n\}$:a set of symbols representing mobile agents. $X=\{x_i \mid 1\le i\le n\}$: a set of symbols representing transporting objects by a mobile agent. $Act=\{{}_{n^s}\bullet_{n^t} \mid n^s,n^t\in V\}$: A set of symbols representing timed movement actions, where n^s and n^t are the source and target nodes for an action, respectively. $N=\{a_i,b_j \mid 1\le i\le n, 1\le j\le m\}$: a set of symbols representing nodes or places on a space map. $Q=\{f_i \mid 1\le i\le n\}$: a set of relabeling functions, that is, $\forall a\in N,\ f(a)=b,\ \exists b\in N$. If $f(a_i)=a_i'$ for $i\in\{1,\dots n\}$, then it can be represented as $[a_1'/a_1,\dots a_n'/a_n]$.

Note that n^s and n^t in $n^s \bullet n^t$ can be hidden for convenience, especially in the case that their meaning is very trivial, i.e, $a \bullet E'$.

Definition 2.2 CaRDMI Syntax

$$\epsilon := \epsilon | \epsilon \;|\; \epsilon \dot{|} \epsilon \;|\; \epsilon \hat{|} \epsilon \;|\; E$$

$$E := 0 \,|\, a(X) \bullet E \,|\, \neg a(X) \bullet E \,|\, E \setminus a \,|\, (E+E) \bullet E \,|\, E[f] \,|\, E^n \bullet E$$

$$X := x'', X \,|\, x''$$

$$x'' := x' \,|\, \overline{x}' \,|\, \widetilde{x}' \,|\, \overline{\overline{x}}'$$

$$x' := x \,|\, \varepsilon .$$

Definition 2.3 Multiple Composition

Multiple summation and parallel compositions are represented by the following notations:

$$\sum_{i=1}^{n} E_i = E_1 + E_2 + \cdots + E_n$$

$$\prod_{i=1}^{n}{}^{\|} E_i = E_1 \,|\, E_2 \,|\cdots|\, E_n .$$

Basic notations are similar to those of CCS: "0" for inaction, "$\bullet$" for prefixing, "+" for choice, "\" for restriction, "[]" for relabeling, and "|" for parallel composition. However its interpretation is quite different with CCS as follows:

- E is a movement expression, that is, a path of movements, denoted by $B(m_i, X_i) \overset{def}{=} E$, where m_i and X_i are a mobile agent and a set of transporting objects, respectively. Here B implies behavior.
- ϵ is a system expressions consisting of a set of mobile agents, denoted by $B(\sum(m_i, X_i), G) \overset{def}{=} \epsilon$, where $\sum m_i$ and G are a set of mobile agents and a map, respectively.
- "0" implies inaction, interpreted as termination of movements on a map.
- "$\bullet$" implies a movement, interpreted as an edge from a position/area to another position/area.
- "a" implies a location or area to visit in a path. a implies a movement to a $\neg a$ a movement to any position or area except a $a(x)$, a movement to a with x to transport; $a(\overline{x})$ and $a(\widetilde{x})$,synchronous and asynchronous movements with $a(x)$ for an object x to be transported at a, respectively; $a(\overline{\overline{x}})$, a synchronous movements with $a(\overline{x})$ to transport x and to get it back at a, $a(\overline{\varepsilon})$ and $a(\widetilde{\varepsilon})$,pure synchronous and asynchronous movements with $a(\varepsilon)$ without any object to be transported at a, respectively. Note that ε can be omitted and x can be a list of objects.
- "+" implies choice, interpreted as a selection of a movement at a position or area among $\sum_{i \in I} a_i \bullet E$ for the next movement.
- "\" implies restriction on some nodes so that other agents cannot interact with at these nodes. For example, if m_i transfers x to m_j synchronously at a without any interference or intervention by other mobile object, it can be represented by $(a(x) \bullet E \,|\, a(\overline{x}) \bullet F) \setminus \{a\}$.
- "$[f]$" implies a relabeling function to rename a node.
- "E^n" implies the repetition of E, n times. For example, $(a_1 + b_1)^3 \bullet a_2 \bullet b_2 \bullet 0$ implies execution

of a_1 or b_1 three times and $a_2 \bullet b_2$,in sequence.

- "|" implies the parallel composition of two agents.
- "$\dot{|}$" implies the parallel composition of a synchronous interaction between two mobile agents. CaRDMI supports both 1-to-1 and *m*-to-*n* synchronous interaction. For example, $E_1 \,\dot{|}\, \overset{4}{\underset{j=2}{\|}} E_j = a(x_2, x_3, x_4) \bullet E_1' \,\dot{|}\, (a(\bar{x}_2) \bullet E_2' \mid a(\bar{x}_3) \bullet E_3' \mid a(\bar{x}_4) \bullet E_4')$ implies that m_1 synchronously transfer objects (x_1, x_2, x_3) to m_2, m_3 and m_4, respectively. Restriction on a, that is, prevention of other agents from interrupting these transportation can be represented by $a(x_2, x_3, x_4) \bullet E_1' \,\dot{|}\, (a(\bar{x}_2) \bullet E_2' \mid a(\bar{x}_3) \bullet E_3' \mid a(\bar{x}_4) \bullet E_4') \setminus \{a\}$.
- "$\hat{|}$" implies an asynchronous interaction between two mobile agents. Similar to synchronous interaction, CaRDMI supports both 1-to-1 and *m*-to-*n* interaction. For example, $(\overset{3}{\underset{i=1}{\|}} E_i) \,\hat{|}\, (\overset{5}{\underset{j=4}{\|}} E_j) = (a(\bar{x}_1) \bullet E_1' \mid a(\bar{x}_2) \bullet E_2' \mid a(\bar{x}_3) \bullet E_3') \,\hat{|}\, (a(x_1, x_2) \bullet E_4' \mid a(x_3) \bullet E_5')$.
- Precedence order of operators are as follows: $\{.\} > \{+\} > \{\setminus\} > \{\|\} > \{\dot{|}, \hat{|}\} > \{|\}$. For example, $a_1 + a_2 \bullet a_4 \setminus a_4 = ((a_1 + (a_2 \bullet a_4)) \setminus a_4)$.

3. CaRDMI Semantics

The deduction rule for movement of agent is represented as follows:

$$Rule: \frac{premise}{Conclusion}\ condition$$

It can be interpreted as, "If the premise is satisfied under the condition, the conclusion can be derived by this rule."

Definition 3.1 Transition

A movement action from one node a o another b by a mobile agent on a map can be representeda transition $\xrightarrow{\bullet_b}$ as follows:

$$a \bullet_b b \bullet_c E \xrightarrow{\bullet_b} b \bullet_c E.$$

Definition 3.2 Primitive CaRDMI Semantics

Basic: $\dfrac{}{a \bullet E \xrightarrow{\bullet} E}$

Alternative: $\dfrac{a \bullet_i E_i \xrightarrow{\bullet_i} E_i}{a \bullet \sum_{j=1}^{n} E_j \xrightarrow{\bullet_i} E_i}$ Loop: $\dfrac{a \bullet E \xrightarrow{\bullet} E}{a^n \bullet E \xrightarrow{\bullet} a^{n-1} \bullet E}$

Restriction: $\dfrac{a \bullet E \xrightarrow{\bullet} E}{a \bullet E \setminus b \xrightarrow{\bullet} E \setminus b} (a \neq b)$

Relabel: $\dfrac{a \bullet_a E \xrightarrow{\bullet_a} E}{f[a] \bullet_{f[a]} E \xrightarrow{\bullet_{f[a]}} E}$

Parallel: $\dfrac{a \bullet_1 E_1 \xrightarrow{\bullet_1} E_1}{a \bullet_1 E_1 \mid E_2 \xrightarrow{\bullet_1} E_1 \mid E_2}$ or $\dfrac{a \bullet_2 E_2 \xrightarrow{\bullet_2} E_2}{E_1 \mid a \bullet_2 E_2 \xrightarrow{\bullet_2} E_1 \mid E_2}$

Synchronization interaction:

$$\frac{\overset{m}{\underset{i=1}{\|}} (a(X_i) \bullet_{X_i} E_{X_i} \xrightarrow{\bullet_{X_i}} E_{X_i}),\ \overset{n}{\underset{j=1}{\|}} (a(\bar{Y}_j) \bullet_{Y_i} E_{Y_i} \xrightarrow{\bullet_{Y_i}} E_{Y_i})}{(\overset{m}{\underset{i=1}{\|}} (a(X_i) \bullet_{X_i} E_{X_i}) \,\dot{|}\, (a(\bar{Y}_j) \bullet_{Y_i} E_{Y_i}) \xrightarrow{a(X_1 \cup \cdots \cup X_m, \bar{Y}_1 \cup \cdots \cup \bar{Y}_n)} (\overset{m}{\underset{i=1}{\|}} E_{X_i} \,\dot{|}\, \overset{n}{\underset{j=1}{\|}} E_{Y_i}) \setminus \{a\}}$$

where $\{X_i \mid 1 \leq i \leq m\}$ and $\{Y_j \mid 1 \leq j \leq n\}$ is a disjoint set of X and Y, respectively, and $X = Y$.

Asynchronization interaction:

$$\frac{\overset{m}{\underset{i=1}{\|}} (a(X_i) \bullet_{X_i} E_{X_i} \xrightarrow{\bullet_{X_i}} E_{X_i}),\ \overset{n}{\underset{j=1}{\|}} (a(\bar{Y}_j) \bullet_{Y_i} E_{Y_i} \xrightarrow{\bullet_{Y_i}} E_{Y_i})}{(\overset{m}{\underset{i=1}{\|}} (a(X_i) \bullet_{X_i} E_{X_i}) \,\hat{|}\, (a(\bar{Y}_j) \bullet_{Y_i} E_{Y_i}) \xrightarrow{a(X_1 \cup \cdots \cup X_m, \bar{Y}_1 \cup \cdots \cup \bar{Y}_n)} (\overset{m}{\underset{i=1}{\|}} E_{X_i} \,\hat{|}\, \overset{n}{\underset{j=1}{\|}} E_{Y_i}) \setminus \{a\}}$$

where $\{X_i \mid 1 \leq i \leq m\}$ and $\{Y_j \mid 1 \leq j \leq n\}$ is a disjoint set of X and Y, respectively, and $X = Y$.

Note that 1-1synchronization / asynchronization and 1-n synchronization / asynchronization are a subset of m-n synchronization and asynchronization, respectively.

Implications of each rule are briefly described as follows:

- **Basic**: Without any premise, the $\bullet$ action is possible. Note that $\bullet$ can be considered as an edge on a map.
- **Alternative**: In the premise of a transition with $\bullet_i$ action, the only possible transition for choice is to the expression with the action. Note that *alternative* is the rule that express selective movement on paths of an agent.
- **Restriction**: In the premise of a transition with $\bullet$ action, the transition with b restriction is possible only when $a \neq b$.
- **Relabel**: In the premise of a transition with $\bullet_a$ action, the transition of the premised transition for relabelling is possible only when the relabelled node name and the relabelled transition name are equal.
- **Parallel**: In the premise of a transition with $\bullet_1$ action, the transition for parallel composition of two agents is the transition of the premise when the action occurs.
- **Loop**: In the premise of a transition with $\bullet$ action, the transition for loop with n repetition is the transition to the loop with n-1repetition when the action occurs.
- **Synchronous interaction**: In the premise of the transitions of a number of mobile agents transporting X_i and the transitions of a number of agents to receive some objects Y_j in $\bigcup_{i=1}^{m} X_i$ at a, the transition of the *m-n* synchronous interaction is a set of transitions by all related agents for X_i and Y_j at a when all premised transitions occur. The exchange modes for each x in the interaction can be different. That is, x can be given, taken, both given and taken, or both taken and given, synchronously at some position on a map.
- **Asynchronous interaction**: This rule is similar to the *m-n* synchronous interaction, but interaction performs asynchronously.

4. Temporal Semantics

This section defines temporal semantics of CaRDMI. It is assumed that all agents are synchronized by a global clock.

Definition 4.1 Timed action

$$Act_T = \{{}_{[t_r]}\bullet_{i,[t_s,t_e]} \mid 0 \le i \le n, 0 \le t_s \le t_e, 0 \le t_r\}$$

A set of symbols representing timed movement actions, where t_r, t_s and t_e are the ready time before action $\bullet_i$, the lower and upper time bounds of the actions, respectively. Note that $[t_i] = [t_i, t_i]$, $[t_s, -] = [t_s, \infty]$, and $[-, t_e] = [\infty, t_e]$.

For example, a sequence of movements of a mobile agent is defined as $E_1 = a_{1[4]} \bullet_{2,[5,10]} a_2(x_1) \bullet_{3,[0,15]} a_3(x_2) \bullet_{4,[15,20]} E_1'$. It implies that the agent performs an action $\bullet_2$ at the relative time between 5 and 10 time units after waiting for 4 time units.

Definition 4.2 Timed semantics

Timed basic: $\dfrac{}{a\bullet_{[t_s,t_e]} E \xrightarrow{\bullet_{\{t\}}} E}$

Timed Alternative: $\dfrac{a\bullet_{i[t_s,t_e]} E_i \xrightarrow{\bullet_{i\{t\}}} E_i}{a\bullet_{j[t_s^j,t_e^j]} \sum_{j=1}^{n} E_j \xrightarrow{\bullet_{i\{t\}}} E_i}\left(t_s \le t \le t_e\right)$

Timed loop:

$$\dfrac{a\bullet_{[t_s,t_e]} E \xrightarrow{\bullet_{\{t\}}} E}{(a)^n\bullet_{[t_s^n,t_e^n]} E \xrightarrow{\bullet_{\{t\}}} (a)^{n-1}\bullet_{[t_s^n-t_s,\,t_e^n-t]} E}\begin{pmatrix} t_s \le t \le t_e \\ t_s \le t_s^n,\, t_e \le t_e^n \end{pmatrix}$$

Timed restriction:

$$\dfrac{a\bullet_{[t_s,t_e]} E \xrightarrow{\bullet_{\{t\}}} E}{a\bullet_{[t_s,t_e]} E\backslash b \xrightarrow{\bullet_{\{t\}}} E\backslash b}(t_s \le t \le t_e, a \ne b)$$

Timed parallel:

$$\dfrac{a\bullet_{1,[t_s,t_e]} E_1 \xrightarrow{\bullet_{1,\{t\}}} E_1}{a\bullet_{1,[t_s,t_e]} E_1 \mid E_2 \xrightarrow{\bullet_{1,\{t\}}} E_1 \mid E_2}(t_s \le t \le t_e) \quad \text{or}$$

$$\dfrac{a\bullet_{2,[t_s,t_e]} E_2 \xrightarrow{\bullet_{2,\{t\}}} E_2}{E_1 \mid a\bullet_{2,[t_s,t_e]} E_2 \xrightarrow{\bullet_{2,\{t\}}} E_1 \mid E_2}(t_s \le t \le t_e)$$

Timed synchronization interaction:

$$\dfrac{\prod_{i=1}^{m}\left(a(X_i)\bullet_{X_i[t_s,t_e]} E_X \xrightarrow{\bullet_{\{t\}}} E_X\right),\ \prod_{j=1}^{n}\left(a(\bar{Y}_j)\bullet_{Y_j[t_s',t_e']} E_Y \xrightarrow{\bullet_{\{t\}}} E_Y\right)}{\left(\prod_{i=1}^{m}(a(X_i)\bullet_{X_i[t_s,t_e]} E_X\right) \mid \left(a(\bar{Y}_j)\bullet_{Y_j[t_s',t_e']} E_Y\right) \xrightarrow{a(X_1\cup\cdots\cup X_m,\bar{Y}_1\cup\cdots\cup\bar{Y}_n)} \left(\prod_{i=1}^{m} E_X \mid \prod_{j=1}^{n} E_Y\right)\backslash\{a\}}\begin{pmatrix} t_s, t_s' \le t \le t_e, t_e' \\ t \le t_e \text{ or } t \le t_e' \end{pmatrix}$$

where $\{X_i \mid 1 \le i \le m\}$ and $\{Y_j \mid 1 \le j \le n\}$ is a disjoint set of X and Y, respectively, and $\bigcup_{i=1}^{m} X_i = \bigcup_{j=1}^{n} Y_j$.

Timed asynchronization interaction:

$$\dfrac{\prod_{i=1}^{m}\left(a(X_i)\bullet_{X_i[t_s,t_e]} E_X \xrightarrow{\bullet_{\{t\}}} E_X\right),\ \prod_{j=1}^{n}\left(a(\bar{Y}_j)\bullet_{Y_j[t_s,t_e]} E_Y \xrightarrow{\bullet_{\{t\}}} E_Y\right)}{\left(\prod_{i=1}^{m}(a(X_i)\bullet_{X_i[t_s,t_e]} E_X\right) \mid \left(a(\bar{Y}_j)\bullet_{Y_j[t_s,t_e]} E_Y\right) \xrightarrow{a(X_1\cup\cdots\cup X_m,\bar{Y}_1\cup\cdots\cup\bar{Y}_n)} \left(\prod_{i=1}^{m} E_X \mid \prod_{j=1}^{n} E_Y\right)\backslash\{a\}}\begin{pmatrix} t_s' \le t_i \le t_e' \\ t_s' \le t_j \le t_e' \end{pmatrix}$$

where $\{X_i \mid 1 \le i \le m\}$ and $\{Y_j \mid 1 \le j \le n\}$ is a disjoint set of X and Y, respectively, and $\bigcup_{i=1}^{m} X_i = \bigcup_{j=1}^{n} Y_j$.

Proposition 4.1 Composition of Time Bounds

$E_{i\{t_r\}}\bullet_{j,[t_s,t_e]} E_{j[t_r']}\bullet_{k,[t_s',t_e']} E_k$ can be composed by $F_{[t_r+t_r']}\bullet_{k,[t_s+t_s',t_e+t_e']} E_k$, where $F = E_i \bullet E_j$.

Proof. E_i and E_j are subexpressions of E. By Definitions 2.2, $E_i \bullet E_j$ is a subexpression of E, too. In the perspective of F, an agent of this expression must wait $[t_r, t_r']$ time units before executing both E_i and E_j, and the execution time of both E_i and E_j will takes within the summed time values of both time bounds, that is, $[t_s+t_s', t_e+t_e']$. Therefore $F_{[t_r+t_r']}\bullet_{k,[t_s+t_s',t_e+t_e']} E_k$ is possible.

5. Verification of Behavioral Equivalence

This section presents a number of behavioral equivalences between two agents.

- $m_i \equiv m_j$ (*Identical*): Two agents have the same expression.
- $m_i \eqsim m_j$ (*ST-Equivalent*): Two agents have the same path with same timing properties.
- $m_i \doteq m_j$ (*S-Equivalent*): Two agents have the same path with different timing properties.
- $m_i \dot{\approx} m_j$ (*CT-Equivalent*): Two agents have the same critical path of check points with the same timing properties.
- $m_i \dot{\div} m_j$ (*C-Equivalent*): Two agents have the same critical path of check points with different timing properties.

Note the relations among the equivalence relations: $\equiv \subseteq \eqsim \subseteq \doteq \subseteq \dot{\approx} \subseteq \dot{\div}$.

Definition 5.1 ST-equivalence: $m_i \equiv m_j$

For $\forall \bullet \in Act$ and $(E_1, E_2) \in R$, the relation $R \subseteq E \times E$ is ST-equivalent if the following conditions are satisfied. Note that $m_1 := E_1$, $m_2 := E_2$, $t_s \neq t_s'$, $t_e \neq t_e'$.

(i) If $E_1 \xrightarrow{\bullet_{[t_s, t_e]}} E_1'$, $\exists E_2'$ which are $E_2 \xrightarrow{\bullet_{[t_s', t_e']}} E_2'$, $(E_1', E_2') \in R$ and $[t_s, t_e] \cap [t_s', t_e'] \neq \varnothing$.

(ii) If $E_2 \xrightarrow{\bullet_{[t_s', t_e']}} E_2'$, $\exists E_1'$ which are $E_1 \xrightarrow{\bullet_{[t_s, t_e]}} E_1'$, $(E_1', E_2') \in R$ and $[t_s, t_e] \cap [t_s', t_e'] \neq \varnothing$.

Definition 5.2 S-equivalence: $m_i \doteq m_j$

For $\forall \bullet \in Act$ and $(E_1, E_2) \in R$, the relation $R \subseteq E \times E$ is S-equivalent if the following conditions are satisfied. Note that $m_1 := E_1$, $m_2 := E_2$, $t_s \neq t_s'$, $t_e \neq t_e'$.

(i) If $E_1 \xrightarrow{\bullet_{[t_s, t_e]}} E_1'$, $\exists E_2'$ which are $E_2 \xrightarrow{\bullet_{[t_s', t_e']}} E_2'$, $(E_1', E_2') \in R$.

(ii) If $E_2 \xrightarrow{\bullet_{[t_s', t_e']}} E_2'$, $\exists E_1'$ which are $E_1 \xrightarrow{\bullet_{[t_s, t_e]}} E_1'$, $(E_1', E_2') \in R$.

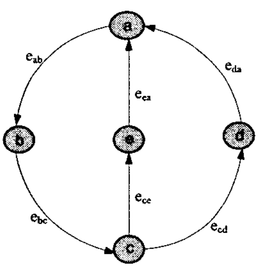

Fig. 1. A Space map Example

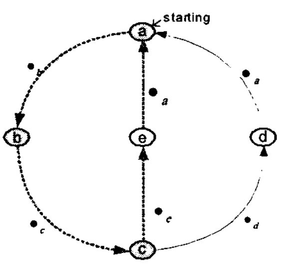

Fig. 2. Transition diagram for m_1 and m_2

For example, two mobile agents m_1 and m_2 can be defined as follows. Its pictorial representation is shown in Fig.2 on a space map in Fig. 1.

$$m_1 := a\bullet_{b,[0,5]}\, b\bullet_{c[0,4]}\, c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0$$

$$m_2 := a_{[9]}\bullet_{b,[10,15]}\, b\bullet_{c[0,5]}\, c_{[4]}\bullet_{e[5,10]}\, e\bullet_{a[0,5]}\, a\bullet 0$$

The binary relation R in Definition 5.2 is as follows:

$$R = \{(a\bullet_{b[0,5]}\, b\bullet_{c[0,4]}\, c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0,\ a_{[9]}\bullet_{b[10,15]}\, b\bullet_{c[0,5]}\, c_{[4]}\bullet_{e[5,10]}\, e\bullet_{a[0,5]}\, a\bullet 0),$$
$$(b\bullet_{c[0,4]}\, c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0,\ b\bullet_{c[0,5]}\, c_{[4]}\bullet_{e[5,10]}\, e\bullet_{a[0,5]}\, a\bullet 0),$$
$$(c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0,\ c_{[4]}\bullet_{e[5,10]}\, e\bullet_{a[0,5]}\, a\bullet 0),\quad (e\bullet_{a[0,9]}\, a\bullet 0,\ e\bullet_{a[0,5]}\, a\bullet 0),$$
$$(a\bullet 0,\ a\bullet 0)\}.$$

$\bullet_b$ actions in E_1 and E_2 occur at [0,5] and [10,15] and respectively, and next actions are defined as $E_1' = b\bullet_{c[0,4]}\, c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0$ and $E_2' = b\bullet_{c[0,5]}\, c_{[4]}\bullet_{e[5,10]}\, e\bullet_{a[0,5]}\, a\bullet 0$. By Definition 5.2, two agents are S equivalent since (E_1', E_2') in R: $m_1 \doteq m_2$.

Definition 5.3 Critical Nodes

A set of critical nodes $N_C \subseteq V$ for a map $G = \langle V, W \rangle$ in Definition 2.1.

Definition 5.4 Transitive Closure

$tc((V, W), N_C) = (V', W')$. The transitive closure of (V, W) for N_C is (V', W'), where $V' = V \cap N_C \wedge V' \subseteq N_C$ and $W' = \{w_i = (n_j, n_k) \mid n_j, n_k \in V'\}$, where there exists a shortest path between n_i and n_j in W.

Definition 5.5 Critical Path

If $(\sigma=(V_i,W_i))\subseteq G$, $\hat{W}_i$ is defined as a critical path of W_i for N_C in $(\hat{\sigma}=(\hat{V}_i,\hat{W}_i))\subseteq G$, where $\hat{V}_i=V_i\cap N_C$ and $\hat{W}_i=tc((V_i,W_i),N_C)$.

Definition 5.6 CT-equivalence: $m_i \dot{\approx} m_j$

For $\forall\bullet\in Act$, $(E_1,E_2)\in R$, the relation $R\subseteq E\times E$ is CT-equivalent if the following conditions are satisfied. Note that $m_1:=E_1$, $m_2:=E_2$.

(i) If $E_1\xrightarrow{\hat{\bullet}_{[t_s,t_e]}}E_1'$, $\exists E_2'$ which are $E_2\xrightarrow{\hat{\bullet}_{[t_s',t_e']}}E_2'$, $(E_1',E_2')\in R$ and $[t_s,t_e]\cap[t_s',t_e']\neq\varnothing$.

(ii) If $E_2\xrightarrow{\hat{\bullet}_{[t_s',t_e']}}E_2'$, $\exists E_1'$ which are $E_1\xrightarrow{\hat{\bullet}_{[t_s,t_e]}}E_1'$, $(E_1',E_2')\in R$ and $[t_s,t_e]\cap[t_s',t_e']\neq\varnothing$.

Definition 5.7 C-equivalence: $m_i \div m_j$

For $\forall\bullet\in Act$ and $(E_1,E_2)\in R$, the relation $R\subseteq E\times E$ is C-equivalent if the following conditions are satisfied. Note that $m_1:=E_1$, $m_2:=E_2$.

(i) If $E_1\xrightarrow{\hat{\bullet}_{[t_s,t_e]}}E_1'$, $\exists E_2'$ which are $E_2\xrightarrow{\hat{\bullet}_{[t_s',t_e']}}E_2'$, $(E_1',E_2')\in R$.

(ii) If $E_2\xrightarrow{\hat{\bullet}_{[t_s',t_e']}}E_2'$, $\exists E_1'$ which are $E_1\xrightarrow{\hat{\bullet}_{[t_s,t_e]}}E_1'$, $(E_1',E_2')\in R$.

For example, two mobile agents m_1 and m_2 can be defined as follows. Its pictorial representation is shown in Fig. 3 on a space map in Fig. 1.

$$m_1 := a\bullet_{b[0,5]}\, b\bullet_{c[0,4]}\, c\bullet_{e[0,5]}\, e\bullet_{a[0,9]}\, a\bullet 0$$

$$m_2 := a_{[10]}\bullet_{b[11,20]}\, b\bullet_{c[0,7]}\, c\bullet_{d[0,3]}\, d\bullet_{a[0,4]}\, a\bullet 0$$

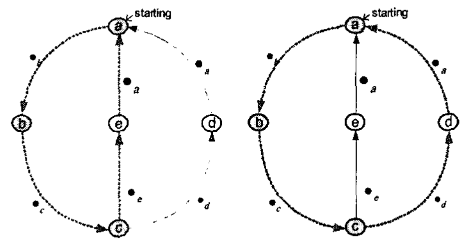

Fig. 3. Transition diagram for m_1 and m_2

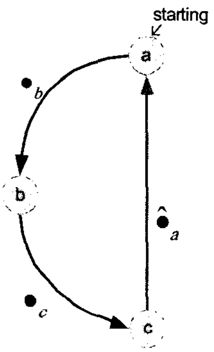

Fig. 4. Critical path for N_C

As shown, m_1 and m_2 are not ST-equivalent. However, if we consider $N_C=\{a,b,c\}$, then m_1 and m_2 can be abstracted as follows by Definition 5.4, 5.5, as shown in Fig.4:

$$m_1 := a\bullet_{b[0,5]}\, b\bullet_{c[0,4]}\, c\hat{\bullet}_{a[0,14]}\, a\bullet 0$$

$$m_2 := a_{[10]}\bullet_{b[11,20]}\, b\bullet_{c[0,7]}\, c\hat{\bullet}_{a[0,7]}\, a\bullet 0$$

Therefore m_1 and m_2 are C-equivalent: $m_2 \div m_2$.

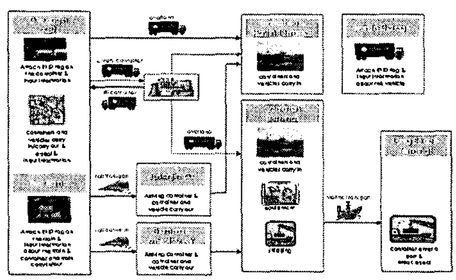

Fig. 5. A scenario for Exporting Supply Chain.

6. An Example

Fig. 5 show a scenario of pilot project for efficient management of Harbor Supply Chain by the Department of Ocean and Marine Products of Republic of Korea during year 2004 and 2007 [13]. Exporting goods are transferred from Euiwang ICD, through Busanjin CY, Gamman Cheongsong CY and Gamcheon and Gamman Terminals, to Long Beach Terminal on East Coast of USA.

Fig. 6 shows a map of paths through which supply containers can be transported. Fig. 7 represents a map for the map in Fig. 6. Assuming that the containers are transported on the map, agents transporting the containers perform the following missions:

- A trailer m_1 loads goods at 'Wonju' Plant, attaching a 'GyeonginICD' tag on the container of the goods, transports it to 'GamcheonHanjin' Terminal by way of 'SeodaejeonJC' and 'Daejeon'.
- A trailer m_2 moves from 'GyeonginICD', through 'SeodaejeonJC' and 'Daejeon', to 'BusanjinCY', where the trailer gets a container of goods from a freight train m_3, and transports it to 'GamcheonHanjin' Terminal'.
- A freight train m_3 moves to 'BusanjinCY' from 'GyeonginICD' by railroad, and transports goods to m_2.
- The critical nodes where agents must passare 'GyeonginICD', 'SeodaejeonJC' and 'GamcheonHanjin'.

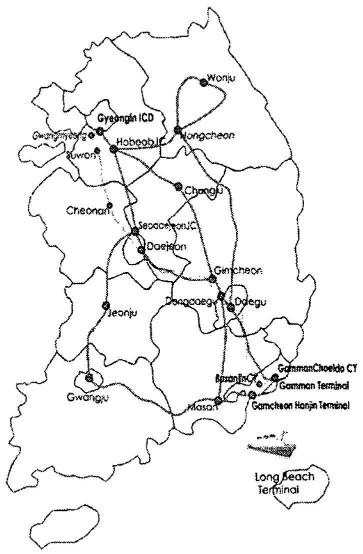

Fig. 6. A map of railroad and express roads

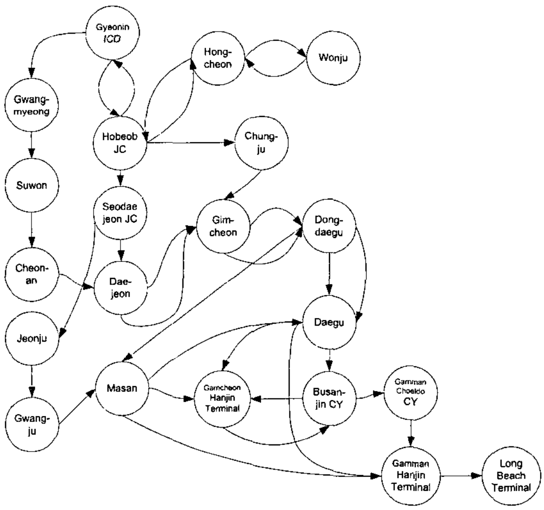

Fig. 7. A space map

The paths of movements for each agents are defined as follows:

- m_1 :Wonju • Hongcheon • HobeobJC • GyeonginICD • HobeobJC • SeodaejeonJC • Daejeon • Gimcheon • Dongdaegu • Masan • GamcheonHanjinTerminal
- m_2 :GyeonginICD • HobeoJC • SeodaejeonJC • Jeonju • Gwangju • Masan • Daegu • BusanCY(x) • GamcheonHanjinTerminal
- m_3 :GyeonginICD • Gwangmyeong • Suwon • Cheonan • Daejeon • Gimcheon • Dongdaegu • Daegu • BusanCY(x).GammancheoldoCY

For convenience, each nodes in the space map are renamed as follows: GyeonginICD(a), HobeobJC(b), SeodaejeonJC(c), Jeonju(d), Gwangju(e), Masan(f), Daeg(g), BusanCY(h), GamcheonHanjinTerminal(i), Wonju(j), Hongcheon(k), Daejeon(l), Gimcheon(m), Dongdaegu(n), Gwangmyeong(o), Suwon(p), Cheonan(q) and GammancheoldoCY(r).

Fig. 8 shows the symbolic representation of the transition diagrams of agents m_1, m_2 and m_3.

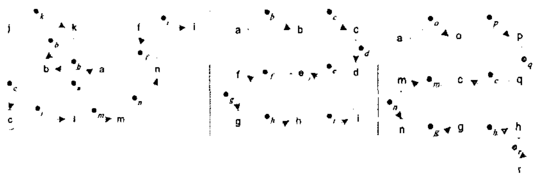

Fig. 8. Transition diagram for m_1, m_2 and m_3

The timed representation of the above movements can be defined as follows in CaRDMI:

$$m_1 := j_{[2]} \bullet_{k[2,5]} k \bullet_{b[0,5]} b \bullet_{a[0,4]} a \bullet_{b[0,4]} b \bullet_{c[0,3]} c \bullet_{l[0,2]} l \bullet_{m[0,3]} m \bullet_{n[0,2]} n \bullet_{f[0,3]} f \bullet_{i[0,2]} i \bullet 0$$

$$m_2 := a_{[2]} \bullet_{b[2,5]} b \bullet_{c[0,5]} c \bullet_{d[0,3]} d \bullet_{e[0,5]} e \bullet_{f[0,4]} f \bullet_{g[0,7]} g \bullet_{h[0,3]} h(\bar{x}) \bullet_{i[0,2]} i \bullet 0$$

$$m_3 := a_{[5]} \bullet_{o[6,10]} o \bullet_{p[0,3]} p \bullet_{q[0,2]} q \bullet_{c[0,3]} c \bullet_{m[0,3]} m \bullet_{n[0,3]} n \bullet_{g[0,4]} g \bullet_{h[0,4]} h(x) \bullet_{r[0,3]} r \bullet 0$$

The system for Export Supply Chain consists of 3 mobile agents in parallel composition, where m_2 and m_3 are synchronous for exchanging goods, as follows:

$$\Theta = E_1 \mid ((E_2 \mid E_3) \setminus \{h\}).$$

The system is required to verify the following two properties:

(1) Behavioral equivalence between m_1 and m_2, and

(2) Timing consistency for synchronous interaction between m_2 and m_3.

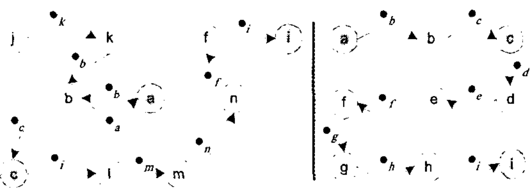

Fig. 9. Transition diagram for critical nodes

- **Behavioral equivalence between m_1 and m_2, and**

As shown in Fig. 9, m_1 and m_2 are not ST-equivalent. However they are C-equivalent to the critical node of $\{a, c, i\}$, as shown in Fig. 10.

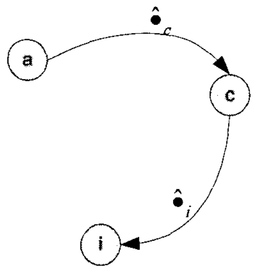

Fig. 10. Transition diagrams with critical paths

- **Timing consistency for synchronous interaction between m_2 and m_3.**

As shown in Fig. 11 for the timing sequences of each movements of m_2 and m_3, there exists a overlapping temporal interval where two agents can interact synchronously to exchange goods.

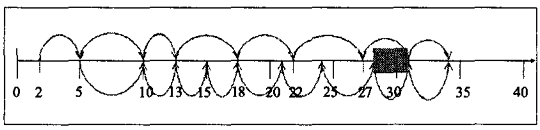

Fig. 11. Timing sequence for movement of m_2 and m_3 and the synchronous temporal interval

• **Discussion**

The example illustrates the capability of specifying the mobile paths of agents, that is, trailers and trains. It also illustrates the capability of specifying the timing requirements for each transporting steps in the paths in order to transport goods safely and synchronously in both spatial sequence and timely manner. Further it illustrates the capability of verifying the spatial and temporal mobility of agents based on ST equivalences. The example demonstrates the capability of applying CaRDMI to the many real applications.

7. Conclusion and Future Researches

In CaRDMI, the movement of a mobile agent is represented by a path on the map, with spatial, temporal and interactive constraints. The spatial constraint occurs with transporting objects at a node or place where the interaction should occur, the temporal constraint is a set of timing requirements, such as, *ready* and *execution* time bounds. Interactive constraint is represented by synchronization modes on transporting objects at a synchronization node. These constraints are distinguishable features of CaRDMI. Especially, the timed many-to-many synchronization constraints are noticeable. Further a set of the spatial, temporal and interactive deduction rules and a set of spatial and temporal equivalence relations are defined in CaRDMI for analysis and verification.

CaRDMI can be practically applied to many real applications, as shown with the example.

Future research will include the probabilistic model for CaRDMI in order to represent probabilistically non-deterministic RTNS, its probabilistic equivalences, the fault-tolerance model for CaRDMI in order to represent autonomous RTNS, and so on.

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