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On a Concurrency Calculus for Design of Mobile Telecommunication Systems

Sendai National College of Technology,
1, Kitahara, Kamiayashi, Aoba-ku, Sendai, 989-31
JAPAN.
Telephone: +81-22-392-4761, Fax:+81-22-392-3359.
e-mail:{tando,kato}@info.sendai-ct.ac.jp,
kaoru@cc.sendai-ct.ac.jp

Abstract

Process algebras with name passing can be suitable to describe dynamical changes of connections. To describe mobile communication, however, it is necessary to consider locations at which processes run. We propose a description method to design such systems using a concurrency calculus in this paper. The concept of a field is introduced to model locality. An extension of π-calculus with a field is proposed. A field is given when behaviors of a target system is verified for a particular environment. The aim of the extension is to verify and to test connectivity between processes under various geographical constraints. This method could be design-oriented in this context. Equivalence relations with/without location in this calculus are also discussed.

Keywords

mobile telecommunication, π-calculus, location, field, location bisimulation, location erased bisimulation

Formal Description Techniques and Protocol Specification, Testing and Verification
T. Mizuno, N. Shiratori, T. Higashino & A. Togashi (Eds.)

1 INTRODUCTION

Process algebras are one of the most successful formalisms for specification of concurrent systems. Especially, name passing calculi are useful to describe dynamical changes of connections among processes in mobile systems. π-calculus (Milner et al., 1991 and 1992) is a typical one. Channel names are treated as data that are used to create new channels dynamically and to communicate between processes in π-calculus.

Some issues are raised when π-calculus is applied to mobile telecommunication. Locations and mobility of mobile terminals may be hard to describe using only a name passing technique while behaviors of mobile processes can be influenced by them in many cases. Various approaches have been tried to treat locality in the context of concurrency calculi. Sangiorgi (1994) proposed a method using located processes. A located process is roughly written $l :: P$, where P is a π-calculus process and l is a location at which the process P runs. Location bisimulation based on location transitions, with the form $\overset{a}{\underset{l}{\rightarrow}}$, is an equivalence relation considering not only causality but locations. Amadio et al.(1994 and 1997) focused failures and mobility, and treated detection of failures and mobility of processes using optional functions such as detection of locations and replication of processes. In these approaches, locality is treated within the framework of these languages. Locality may make specification more difficult although locality is needed to be specified.

For simple specification, we take another approach in this paper. Environment is modeled independently of a language, and a calculus consists of π-calculus and the model of an environment in this approach. To model a relation between π-calculus and this model, the concept of a *field* is introduced. A field is considered as a set of constraints on communication, and is set up for each application. In the context of fields, an interesting issue is how the same party of processes behaves for various fields. To discuss an equivalence relation on such behaviors, we introduce two bisimulation relations, i.e. location bisimulation and location erased bisimulation. These bisimulations are almost the same as that of CCS (Milner, 1989) except for focusing on connectivity of processes. The aim of our method is to support design of mobile communication systems. To decide whether processes can similarly behave even if an environment is changed, the above bisimulations are used. Furthermore, these bisimilarities should be invariants when specifications are refined.

The rest of this paper consists as follows. In Section 2, the concept of a field will be introduced. Using a field, we will also define a variant πF of π-calculus in this section. Next, equivalence relations will be discussed in Section 3. Section 4 shows an application of πF to a mobile telecommunication system. Finally, we conclude this paper in Section 5.

2 AN EXTENSION OF π-CALCULUS WITH A FIELD

Processes may be affected by their environment. We model such a situation with a concept of a *field*. π-calculus is extended with a field. To define the extension, we premise the following: (1) Behaviors of processes can be affected by their environment; (2) The environment can not be affected by processes. The first premise is the start point of this paper. We consider environments such as *networks* or *geographical features*, e.g. the configurations of buildings and roads, in this paper. Such environments can be regarded as not changed in the short term that communication processes are running. From the two premises, we take the style that locations are appended to π-calculus processes.

Field and movement

A field presents a set of constraints on communications among processes.

Definition 1 *Field*

Field $\mathcal{F}$ is defined as a pair as follows:
$\mathcal{F} = \langle Loc, RL \rangle$,
where Loc is a set of locations (places at which processes can be located) and $RL \subseteq Loc \times Loc$ is a relation such that a message can be sent from l to m if $(l,m) \in RL$. If $(l,m) \in RL$, then (l,m) is called a road *from l to m, or simply a road.*

Movement of processes can be treated using a higher-order language (see e.g. Milner, 1991). However, we place movement at the outside of the syntax of a language for the simple description and the separation of processes from a field.

Definition 2 *Movement*

Constraints on movement of processes are represented by $MV \subset Proc \times Loc \times 2^{Loc}$, where Proc is the set of all process identifiers. Let $P \in Proc$, $l \in Loc$ and $A \subset Loc-\{l\}$. $(P, l, A) \in MV$ expresses that a process with the process identifier (abbreviated to PID) P may move from the location l to some location $m \in A$. PIDs mean initial process names from which current processes are reduced by the reduction rules in Definition 5.

Example 1 *The following field $\mathcal{F}_1$ is shown as a directed graph in Figure 1. A process at '1' can not communicate with a process at '3', but a process at '2' and '4'. A message can not be sent from '4' to '1' while it can be sent from '1' to '4'. Furthermore, MV represents the situation that a process with the PID R can move '4' to '3'.*

$$\begin{aligned}
\mathcal{F}_1 &= \langle Loc_1, RL_1 \rangle \\
Loc_1 &= \{1, 2, 3, 4\} \\
RL_1 &= \{(1,4), (1,2), (2,1), (2,3), (3,2)\} \\
MV &= \{(R, 4, \{3\})\}.
\end{aligned}$$

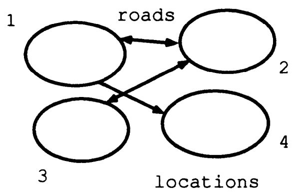


Figure 1 An example of a field: $\mathcal{F}_1$.

Note that no-movements of processes such as $(Q, 4, \{4\})$ must not be written in MV even if other *fixed* processes are located on a field! Readers have to take care that there are no relations between movement of processes and directions of arrows in Fig. 1. The arrows in the figure show transimission directions of data, but not process movement.

πF

An extension of π-calculus with a field is defined here to model behaviors of mobile processes on a particular environment. Syntax of this extension, called πF, is the same as that of the standard poliadic π-calculus(see e.g. Sangiorgi, 1994) except for without matching. In this calculus, locations are appended to π processes as parameters. Such a process with a location is called a *labor*.

In this paper, L, M, $\cdots$ range over the set $\mathcal{LAB}$ of all labors, P, Q, $\cdots$ the set $\mathcal{P}roc$ of all process identifiers, a, b, $\cdots$ the set Ch of all channel names, l, m, $\cdots$ the set Loc of all locations, and $\tilde{b}$, $\cdots$ the set of all channel name vectors.

Definition 3 *Syntax of πF*

$$\begin{array}{llll} \textit{actions} & : \alpha & ::= & a(\tilde{b}) \mid \overline{a}[\tilde{b}] \\ \textit{processes} & : P & ::= & \mathbf{0} \mid \alpha.P \mid P+Q \mid P|Q \mid \nu bP \mid D\langle\tilde{b}\rangle \\ \textit{labors} & : L & ::= & \{P\}l \mid L|M \mid \nu bL \end{array}$$

In the above definition, actions occur through channels, and processes receive ($a(\tilde{b})$) / send ($\overline{a}[\tilde{b}]$) messages (channel names). The definitions of processes represent inaction, action prefix, sum, parallel composition, restriction of a name and constant application respectively. In the definitions of labors, $\{P\}l$ represents that the process P is at the location 'l'. The rest of definitions of labors are corresponding to parallel composition and restriction of a name. If $\tilde{b}$ is empty, brackets [ ] and ( ) will be omitted. D is defined as $D(\tilde{c}) \stackrel{\text{def}}{=} P$, where $\tilde{c}$ is formal parameters. $D\langle\tilde{b}\rangle$ is that formal parameters $\tilde{c}$ is replaced with actual parameters $\tilde{b}$ in D.

Congruence relations on processes are the same as the relations of the standard π-calculus. Additional congruence relations on labors are as follows.

Definition 4 *Congruence of labors*

1. $L|\{\mathbf{0}\}l \equiv L$
2. $L|M \equiv M|L$
3. $\{P|Q\}l \equiv \{P\}l|\{Q\}l$
4. $\nu a \nu b L \equiv \nu b \nu a L$
5. $\nu a\{P\}l \equiv \{\nu aP\}l$
6. $\nu x(L|M) \equiv L|\nu xM$ *if* $x \notin fn(L)$, *where* $fn(L)$ *is the set of all free names in* L.

Labors are reduced according to the following reduction rules. Constraints on communications by locations and movement of processes are reflected in these rules.

Definition 5 *Reduction rules*

$$MOVE: \frac{(P,l,A) \in MV, m \in A}{\{P\}l \stackrel{\tau @\{l,m\}}{\longrightarrow} \{P\}m} \qquad PAR: \frac{L \stackrel{a@Pls}{\longrightarrow} L'}{L|M \stackrel{a@Pls}{\longrightarrow} L'|M}$$

$$RES1: \frac{L \stackrel{a@Pls}{\longrightarrow} L',\ x \neq a}{\nu xL \stackrel{a@Pls}{\longrightarrow} \nu xL'} \qquad RES2: \frac{L \stackrel{a@Pls}{\longrightarrow} L',\ x = a}{\nu xL \stackrel{\tau@Pls}{\longrightarrow} \nu xL'}$$

$$COMM: \quad \frac{(l, l_\lambda) \in RL \ for \ \lambda \in \Lambda, \ \Delta(\neq \emptyset) \subseteq \Lambda}{\{\cdots + \overline{a}[\tilde{b}].P\}l \mid \prod_{\lambda \in \Lambda}\{\cdots + a(\tilde{c}).Q_\lambda\}l_\lambda \stackrel{a@(\{l\} \cup \{l_\lambda \mid \lambda \in \Delta\})}{\longrightarrow} \{P\}l \mid \prod_{\lambda \in \Delta}\{Q_\lambda\langle\tilde{b}\rangle\}l_\lambda \mid \prod_{\lambda' \in \Lambda - \Delta}\{\cdots + a(\tilde{c}).Q_{\lambda'}\}l_{\lambda'}}$$

$$STRUCT: \quad \frac{Q \equiv P, P \stackrel{a@Pls}{\longrightarrow} P', P' \equiv Q'}{Q \stackrel{a@Pls}{\longrightarrow} Q'}$$

$L \stackrel{a@Pls}{\longrightarrow} L'$ represents that L is reduced to L' by the occurrence of the action through the channel a, and processes at locations listed in Pls are related to this reduction. In COMM, $\prod_{\lambda \in \Lambda} L_\lambda = L_{\lambda_1} | L_{\lambda_2} | \cdots$ ($\lambda_1, \lambda_2, \ldots \in \Lambda$). Λ is a communicatable process index set. In this case, the arity (number of names) of both $\tilde{b}$ and $\tilde{c}$ must be the same. τ represents an unobservable action.

Communications are restricted by a field such that processes can communicate with each other when these processes are located at communicatable locations. $COMM$ allows broadcast or multicast transmission. Cases $\Delta = \Lambda$ and $\Delta \subset \Lambda$ correspond to broadcast and multicast respectively. Movement of processes is represented with $MOVE$, and the communication by a bounded channel name is represented with $RES2$. Observation of communications is emphasized in this reduction rules, so that restricted communications and movement of processes are regarded as internal actions.

Example 2 *Consider processes P, Q and R, given as follows, running on the field $\mathcal{F}_1$ under MV in Example 1.*
$P \stackrel{\text{def}}{=} \overline{a}[b].\ P'$, $\quad Q \stackrel{\text{def}}{=} a(x).\ \overline{x}.\ Q'$, $\quad R \stackrel{\text{def}}{=} b.\ R'$.
Then, let P, Q and R be located at '1', '2' and '4' respectively. This labor may behave as follows:

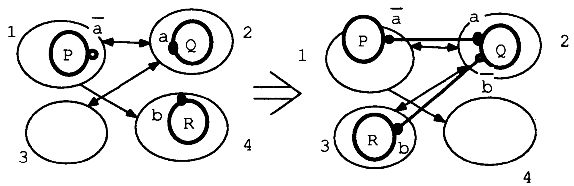


Figure 2 *A behavior of a labor of Example 3.*

$$
\begin{aligned}
\{P\}1 \mid \{Q\}2 \mid \{R\}4 &\overset{a@\{1,2\}}{\longrightarrow} \{P'\}1 \mid \{\bar{b}.\ Q'\}2 \mid \{R\}4 \\
&\overset{\tau@\{3,4\}}{\longrightarrow} \{P'\}1 \mid \{\bar{b}.\ Q'\}2 \mid \{R\}3 \\
&\overset{b@\{2,3\}}{\longrightarrow} \{P'\}1 \mid \{Q'\}2 \mid \{R'\}3
\end{aligned}
$$

3 EQUIVALENCE RELATIONS

Behaviors of located processes described in πF are a subset of behaviors of the standard π-calculus processes. Even if the same processes are given, behaviors of a party of these processes may be different according to fields. In telecommunication systems, it is required that the same communication services are ensured even in the case that the topology of a network changes.

To discuss the equivalence in such a situation, we define bisimulation relations in this section. At first, a *location bisimulation* is defined in terms of located reduction. In this bisimulation, causality of locations is not considered, different from the location bisimulation of Sangiorgi (1994). Next, a *location erased bisimulation* is defined. This bisimulation is that location information is omitted from the above location bisimulation.

Location bisimulation

A *weak reduction* is introduced by omitting reductions with internal actions. If there exists $m, n \geq 0$, location sets $Pls_{1,i} \subseteq Loc$ $(1 \leq i \leq m)$, location sets $Pls_{2,j} \subseteq Loc$ $(1 \leq j \leq n)$, such that $L \overset{\tau@Pls_{1,1}}{\longrightarrow} \cdots \overset{\tau@Pls_{1,m}}{\longrightarrow} \overset{a@Pls}{\longrightarrow} \overset{\tau@Pls_{2,1}}{\longrightarrow} \cdots \overset{\tau@Pls_{2,n}}{\longrightarrow} L'$ for an observable channel name a $(\neq \tau)$ and a location set Pls, we write $L \overset{a@Pls}{\Longrightarrow} L'$.

Now, to compare two labors, we define location bisimulation.

Definition 6 *Location bisimulation*

A binary relation $\mathcal{S} \subseteq \mathcal{LAB} \times \mathcal{LAB}$ over labors is a location bisimulation if $(L, M) \in \mathcal{S}$ implies, for all $a \in Ch$ and all $Pls \in Loc$,

1. *Whenever $L \overset{a@Pls}{\Longrightarrow} L'$, there exists M' such that $M \overset{a@Pls}{\Longrightarrow} M'$ and $(L', M') \in \mathcal{S}$;*
2. *Whenever $M \overset{a@Pls}{\Longrightarrow} M'$, there exists L' such that $L \overset{a@Pls}{\Longrightarrow} L'$ and $(L', M') \in \mathcal{S}$.*

Then, $\approx_l$ is defined as follows, and $L \approx_l M$ if $(L, M) \in \approx_l$.
$\approx_l = \bigcup\{\mathcal{S} \mid \mathcal{S}$ *is a location bisimulation*$\}$

Proposition 1

1. $\{\overline{a}[\tilde{b}].P\}l \mid \{x(\tilde{c}).Q\}m \approx_l \{0\}l'$ *for any* l' *if* $x \neq a$,
2. $\{\nu aP\}l \mid \{Q\}m \approx_l \nu a(\{P\}l|\{Q\}m)$, *if* $a \notin fn(Q)$.

Location erased bisimulation

Location information may not always be important in telecommunication. When mobile terminals can move freely, connection or data transfer becomes a more important problem. To consider such a situation, location erased bisimulation is defined.

A notation of *location erased reduction* is used for the definition of location erased bisimulation, i.e. $L \stackrel{a}{\longrightarrow} L'$ if $L \stackrel{a@Pls}{\longrightarrow} L'$. Weak location erased reduction $L \stackrel{a}{\Longrightarrow} L'$ is also defined similarly.

Definition 7 *Location erased bisimulation*

A binary relation $\mathcal{S} \subseteq \mathcal{LAB} \times \mathcal{LAB}$ *over labors is a location erased bisimulation if* $(L, M) \in \mathcal{S}$ *implies, for all* $a \in CH$,

1. *Whenever* $L \stackrel{a}{\Longrightarrow} L'$, *there exists* M' *such that* $M \stackrel{a}{\Longrightarrow} M'$ *and* $(L', M') \in \mathcal{S}$;
2. *Whenever* $M \stackrel{a}{\Longrightarrow} M'$, *there exists* L' *such that* $L \stackrel{a}{\Longrightarrow} L'$ *and* $(L', M') \in \mathcal{S}$.

Then, $\approx$ *is defined as follows, and* $L \approx M$ *if* $(L, M) \in \approx$.
$\approx = \bigcup\{\mathcal{S} | \mathcal{S}$ *is a location erased bisimulation*$\}$,

We show simple properties on location erased bisimulation.

Proposition 2 $L \approx_l M$ *implies* $L \approx M$.

Proposition 3

1. $\{\overline{a}[\tilde{b}].P\}l \mid \{x(\tilde{c}).Q\}m \approx \{0\}l'$ *if* $x \neq a$.
2. $\{\nu aP\}l \mid \{Q\}m \approx \nu a(\{P\}l|\{Q\}m)$, *if* $a \notin fn(Q)$.

A design method using πF

We simply show an overview of a design method of mobile concurrent systems using πF.

1. Processes and a field are described at first.
2. These processes are located on the field.
3. Necessary properties such as connectability and the detection of failure are verified.

4. If necessary, the design will be more refined: (1) Location bisimulation and/or location erased bisimulation are used as invariants in the refinement; (2) More detailed informations are appended into restricted actions of the previous design.

Location erased bisimulation may be an effective invariant in the case of the design of mobile telecommunication systems. Bisimilarities are difficult to be verified in actual systems as reduction trees may be very complex. Thus, a simulator can be an useful tool in the actual design. A simulator checks a subset of all possible action sequences, so that a part of connectivity and failures could be checked.

4 APPLICATION OF πF TO MOBILE TELECOMMUNICATIONS

An application of πF to mobile telecommunication systems is shown in this section. In mobile telecommunication systems, cellular systems have been employed. Multiplicity of trunks by reuse of frequencies within limited frequency band and the flexibility for increase of users are the reason. The transmission power of a mobile terminal is low, so that a mobile terminal can be connected with only the nearest base station. In cellular systems, each terminal is registered to the area to which the terminal can access every moment (*location registration*). The location of a terminal is traced whenever the terminal moves to other areas (*location tracing control*). A *simultaneous call* technique is used to search a particular terminal in a location registration area (Padgett et al., 1995). We will describe the situation that one calls someone driving a car with a movable terminal from a fixed terminal at home.

A fixed terminal (*Home*) is connected to base stations ($Base_i$, $i = 1, 2, 3$) via the relay station (*Station*) with cables, and base stations communicate with a movable terminal (*Car*) with a radio equipment if the terminal is in its area (cell) (see Figure 3).

At first, a field and movement of processes are set up for this system.

$$
\begin{aligned}
\mathcal{F} &= \langle Loc, RL \rangle \\
Loc &= \{h, s, c_1, c_2, c_3\} \\
RL &= \{(h,s),(s,h),(s,c_1),(c_1,s),(s,c_2),(c_2,s),(s,c_3), \\
&\quad (c_3,s)\} \cup \{(p,p) | p \in Loc\}
\end{aligned}
$$

$$MV \;=\{(Car, c_1, \{c_2, c_3\}), (Car, c_2, \{c_1, c_3\}), (Car, c_3, \{c_1, c_2\})\}$$

'h', 's' and 'c_i' ($i = 1,2,3$) are locations at which the fixed terminal, the relay station and base stations are located respectively. MV represents the situation that $Home$, $Station$ and $Base_i$ ($i = 1,2,3$) can not move while Car can move among cells 'c_i' ($i = 1,2,3$).

Next, these processes are given as follows:

$$\begin{aligned} Home(n) &\stackrel{\text{def}}{=} \overline{call}[n].CallingHome\langle n\rangle, \\ Station &\stackrel{\text{def}}{=} call(n).\overline{search}[n].SearchingStation\langle n\rangle, \\ Base_i &\stackrel{\text{def}}{=} search(n).\overline{n}.RelayingBase_i, \\ Car &\stackrel{\text{def}}{=} num.ReceivingCar. \end{aligned}$$

Car has its own telephone number num. The fixed terminal $Home$ requests for a call to the movable terminal Car with some telephone number. When the relay station $Station$ is requested for a call, the simultaneous call will be done. After each base station receives the number, the corresponding station will connect with Car if Car is in its cell. Then, a connection between $Home$ and Car is established.

We assume that $Home$, $Station$, $Base_i$ and Car are located at 'h', 's', 'c_i' and 'c_1' at the start. This situation is represented as the labor $Call\langle num\rangle$:

$$\begin{aligned} Call\langle num\rangle \stackrel{\text{def}}{=} \; & \{Home\langle num\rangle\}h \mid \{Station\}s \mid \{Base_1\}c_1 \\ & \mid \{Base_2\}c_2 \mid \{Base_3\}c_3 \mid \{Car\}c_1. \end{aligned}$$

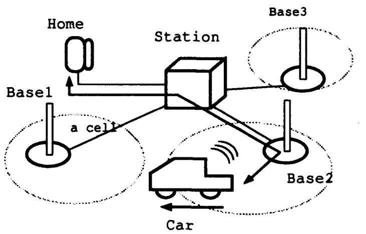
The labor $Call\langle num\rangle$ may be reduced as follows. Then, a connection between $Home$ and Car will be established.

$$\begin{aligned} & Call\langle num\rangle \\ \xrightarrow{call@\{h,s\}} \; & \{CallingHome\langle num\rangle\}h \\ & \mid\{\overline{search}[num].SearchingStation\langle num\rangle\}s \\ & \mid \textstyle\prod_{i=1}^{3}\{search(n).\overline{n}.RelayingBase_i\}c_i \\ & \mid\{Car\}c_1 \\ \xrightarrow{search@\{s,c_1,c_2,c_3\}} \; & \{CallingHome\langle num\rangle\}h \\ & \mid\{SearchingStation\langle num\rangle\}s \\ & \mid \textstyle\prod_{i=1}^{3}\{\overline{num}.RelayingBase_i\}c_i \\ & \mid\{num.ReceivingCar\}c_1 \\ \xrightarrow{\tau@\{c_1,c_2\}} \; \xrightarrow{num@\{c_2\}} \; & \{CallingHome\langle num\rangle\}h \\ & \mid\{SearchingStation\langle num\rangle\}s \\ & \mid\{\overline{num}.RelayingBase_1\}c_1 \\ & \mid\{RelayingBase_2\langle num\rangle\}c_2 \end{aligned}$$

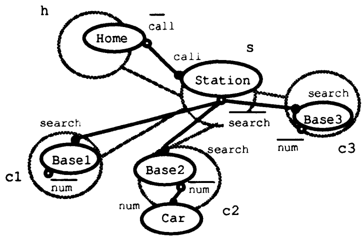
$$|\{\overline{num}.RelayingBase_3\}c_3$$
$$|\{ReceivingCar\}c_2$$

In this reduction sequences, the second reduction shows the simultaneous call. Each base station waits to connect with *Car*. Whenever *Car* connects with one of the base stations, *Car* can communicate by the same channel name *num*. The result of this reduction sequences is shown in Figure 3 (b). Communications with the same names are enabled in various situations, so that process descriptions may become simple. This is an advantage of πF.

Next, consider the accident that the cable between the relay station and one of the base stations, e.g. base station 2, is broken down. How will $Call\langle num\rangle$ behave at that time? Roads (s, c_2) and (c_2, s) are removed from RL in this case. Even if *Car* can not communicate with $Base_2$, *Car* will communicate with $Base_1$ or $Base_3$ by movement to 'c_1' or 'c_3'. So, those behaviors are location erased bisimilar before and after this accident.



(a) An overview



(b) The connection established state.

Figure 3 An example of mobile telecommunication systems.

5 CONCLUSION

We proposed a concurrency calculus for design of mobile telecommunication systems in this paper. By separation of process description from location information, process description can be simple. Verification of features on processes can be flexibly done for various environments. πF may be suitable for mobile telecommunication systems managed in fluidal environments.

Our future works are as follows. A simulator is necessary to support design of mobile communication systems. Using such a simulator, one will be able to check properties such as connectivity of communication processes on particular environments. In addition, effects of fields to behaviors of processes will be investigated. Furthermore, a method of specification from requirement acquisition will be developed based on πF. We have proposed a method based on topology of description techniques (Ando et al., 1996). We plan to apply this topological method to the specification using πF.

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