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A Methodology for the Description of System Requirements and the Derivation of Formal Specifications

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Abstract
A methodology for the description of system requirements and the derivation of formal specifications from system requirements are presented. We will specifically deal with the issues (1) mathematical treatment of system requirements and their relationship with formal specifications represented as state transition systems, (2) a sound and complete system with respect to a system requirement, i.e. a standard system of the system requirement specified as a unique model of the system requirement, (3) derivation of standard systems from system requirements, (4) a support system and an application example, and (5) some comparative discussions on the methodology with partial logical Petri Nets, Production systems, and so on.

Keywords
Function Requirement, System Requirement, Formal Specification, State Transition System, Standard System, Logical Petri Net.

1 INTRODUCTION

For a complex and sophisticated system, operational descriptions might be too tedious to handle for rapid prototyping and analysis of a system's behavior. In such cases, it is more convenient to express the system on a higher level, somehow in a functional manner. This approach yields formal specifications that emphasize the system's general behavioral properties rather than its operational details. Moreover, it has a practical significance if the desired description can be derived or synthesized in a systematic way from the user requirements on system functions.

This paper proposes a new methodology for the description of system requirements and the synthesis of formal specifications from system requirements. The formal specifications can be taken as models of the system requirements. More generally, the main objective is to be able to derive an implementable or operational system description from a given high-level description on system functions. The proposed methodology can be fully automated, hence may/can improve both productivity and quality of system development. We have implemented a support system based on our approach and applied several practical system designs such as a telephone service, a communication protocol, a cable TV system, etc.

In the literature on communicating systems, Formal Description Techniques (FDT), e.g. SDL [5], Estelle [3] and LOTOS [6], have been proposed as high-level specification languages. The conventional state machine oriented approaches such as SDL and Estelle and algebraic approach such as LOTOS are suitable for the purpose of description and investigation of the total behavior of systems. But, these approaches might be not suitable for rapid prototyping and flexible software development. Because we must enumerate and/or determine all system behaviors from an early stage of system design. Our objective is to give theoretical foundations and proposal of a flexible approach on the synthesis of formal specifications from user requirements written in an early stage of system design.

From objectives, our work has some connection with an STR (State Transition Rule) method, which is a specification method based on a production system proposed by Hirakawa and Takenaka in [10]. But, the methodology proposed here differs from their approach mainly in theoretical discussions such as soundness and completeness and formal treatment, rather than practical methodology for description and use. Another related work is a synthesis of communicating processes from temporal logic specification by Manna and Wolper in [11]. Their approach is based on tableau-like method and completely different form ours from technical point of view. Besides those works, no other related works could be found in the literature.

The outline of this paper is as follows: In section 2 after giving some preliminaries, we deal in detail with the issue of system requirements and formal specifications. In section 3, we discuss the key notions, soundness and completeness. Section 4 provides an equivalent transformation on system requirements with the result of determinacy on the resulting transition systems. Section 5 gives an automatic transformation technique from system requirements to formal specifications. Section 6 gives an overview of the support system with an application example followed by the discussions in section 7 and the concluding remarks in section 8.

2 REQUIREMENTS AND FORMAL SPECIFICATIONS

Requirements of a system can be described as expression based on propositional logic. To begin with we will give some preliminaries on propositional logic needed for the description of a system requirement. Let $\mathcal{P}$ be a set of *atomic propositions*. Each atomic proposition describes a specific property of the intended system under the target of design. A *partial interpretation* I is a partial mapping $I : \mathcal{P} \rightarrow \{\textbf{true}, \textbf{false}\}$, where **true** and **false** are the truth values of propositions. If the truth value of a proposition f under I is defined to be **true** then we say that I *satisfies* f, denoted by $I \models f$. $I \not\models f$ denotes that the truth value of f is defined to be **false** and we say I *does not satisfy* f. These can be defined inductively as follows:

(1) $I \models A$ $(I \not\models A)$ if I is defined on A and $I(A) = \textbf{true}$ $(I(A) = \textbf{false})$, where $A \in \mathcal{P}$.
(2) $I \models \neg f$ $(I \not\models \neg f)$ if $I \not\models f$ $(I \models f)$.
(3) $I \models f \wedge g$ $(I \not\models f \wedge g)$ if $I \models f$ and $I \models g$ $(I \not\models f$ or $I \not\models g)$.
(4) $I \models f \vee g$ $(I \not\models f \vee g)$ if $I \models f$ or $I \models g$ $(I \not\models f$ and $I \not\models g)$.

Note that truth value of a proposition under an interpretation is not always defined since we are concerned with partial interpretations. For propositions f and g, $f \Rightarrow g$ denotes the assertion that for any partial interpretation I, $I \models f$ implies $I \models g$.

Definition 21 Let f and g be propositions.
(1) f is *consistent* if $I \models f$ for some partial interpretation I.
(2) f is *inconsistent* if f is not consistent.
(3) f is *dependent* on g if either $g \Rightarrow f$ (in positive) or $g \Rightarrow \neg f$ (in negative).
(4) f is *independent* of g if f is not dependent on g. □

A *literal* is an atomic proposition A of the negation of an atomic proposition $\neg A$. Let γ, γ' be consistent conjunctions of literals. It is clear from the definition that $\gamma \Rightarrow \gamma'$ iff $L(\gamma) \supset L(\gamma')$, where $L(\gamma)$ denotes the set of all literals appearing in γ. This implies the following proposition.

Proposition 21 *Let γ be a consistent conjunction of literals. An atomic proposition A is independent of γ iff A does not appear in γ at all neither in positive nor in negative. The negative literal $\neg A$ is independent of γ iff A is independent of γ.* □

A system can be essentially specified by its fundamental functions and their related constraints for execution. To be more precise, a system function may be invoked by a specific input provided that its pre-condition to be satisfied before execution can hold in the current state. Then, the function is executed, possibly producing some appropriate output. After the execution the current state is changed into the new one. In the new state, other functions (including the same function as well) can be applicable. Taking account into this intuition of system specifications, a function requirement is formally defined in the next definition.

Definition 22 A *function requirement* is a tuple $\rho = \langle id, a, f_{in}, o, f_{out} \rangle$, where

(1) *id* is a *name* of the function;
(2) a is an *input symbol* of the function;
(3) f_{in} is a *pre-condition* of the function to be satisfied before execution, which is represented as a consistent proposition using atomic propositions in $\mathcal{P}$;
(4) o is an *output symbol* of the function;
(5) f_{out} is a *post-condition* of the function to be satisfied after execution, which is represented as a consistent conjunction of literals by atomic propositions in $\mathcal{P}$. □

For simplicity, in what follows we omit the names and the output symbols from the description of function requirements because they do not play the central roles on the theoretical treatment in this paper. A function requirement $\rho = \langle a, f_{in}, f_{out} \rangle$ is often abbreviated as $\rho : f_{in} \overset{a}{\Rightarrow} f_{out}$.

Definition 23 A *system requirement* is a pair $\mathcal{R} = \langle R, \gamma_0 \rangle$, where R is a set of function requirements and γ_0 is an *initial condition* represented as a consistent conjunction of literals in $\mathcal{P}$. □

In this paper, state transition systems are considered as formal specifications. In the literature, a state transition system is an underling structure of Formal Description Techniques, e.g. SDL [5], Estelle [3] and LOTOS [6], and used to give the operational semantics of concurrent processes in process calculi [12], based on the paradigm of SOS (Structural Operational Semantics) by Plotkin [14].

Definition 24 A *state transition system* is a quadruple $M = \langle Q, \Sigma, \rightarrow, q_0 \rangle$, where Q is a set of *states*, Σ is a set of input symbols, $\rightarrow$ is a *transition relation* defined as $\rightarrow \subset Q \times \Sigma \times Q$, and q_0 is an *initial state.* □

The transition relation defines the dynamical change of states as input symbols may be read. For $(p, a, q) \in \rightarrow$, we normally write $p \xrightarrow{a} q$. Thus, the transition relation can be written as $\rightarrow = \{\xrightarrow{a} \mid a \in \Sigma\}$. $p \xrightarrow{a} q$ may be interpreted as "in the state p if a is input then the state of the system moves to q". Now, we assume that for an atomic proposition A and for a state $q \in Q$ it is pre-defined whether or not A holds (is satisfied) in q if the truth value of A in q is defined. $q \models A$ indicates that the truth value of A in q is defined and

A holds in q. Let us define the partial interpretation associated with a state q in M, denoted by $I(q)$, in such a way that

$$I(q)(A) = \begin{cases} \textbf{true} & \text{if } q \models A \\ \textbf{false} & \text{if } q \not\models A \ (q \models \neg A) \\ \text{undefined} & \text{otherwise} \end{cases}$$

for all atomic propositions A. Thus, a state transition system can be treated as a Kripke structure [2], where the interpretation of atomic propositions vary over states. Let

$$Sat(q) = \{\, l \mid \text{the truth value of a literal } l \text{ is defined in } q \text{ and } q \models l\}.$$

Proposition 22 *$q \models f$ iff f is implied from $Sat(q)$ — every interpretation satisfying $Sat(q)$ also satisfies f, for each proposition f.*

Proof: The proof is by structural induction on propositions f. □

By the completeness of propositional logic, we have that $q \models f$ iff $Sat(q) \vdash f$, f is provable from $Sat(q)$.

Two states p and q in M are *logically equivalent* iff $I(p) = I(q)$. A transition system M is *logically reducible* if there exist distinct logically equivalent states in M. Otherwise, the system is *logically irreducible.* To the rest of this paper, unless stated otherwise, a transition system means a logically irreducible system. Thus, $p = q$ iff $I(p) = I(q)$ $(Sat(p) = Sat(q))$. By this assumption, note that a state q in a (an irreducible) transition system M can be equivalently represented as a consistent set X of literals, where $q \models A$ $(q \models \neg A)$ iff $A \in X$ $(\neg A \in X)$.

3 SOUNDNESS AND COMPLETENESS

Definition 31 A state transition $t = \langle p \xrightarrow{a} q\rangle$ *satisfies* (is *correct w.r.t.*) a function requirement $\rho : f_{in} \overset{b}{\Rightarrow} f_{out}$, denoted as $t \models \rho$, if the following conditions hold:

(1) $p \models f_{in}$, $a = b$, and $q \models f_{out}$.

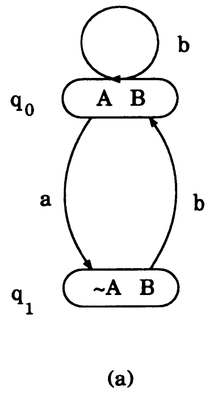
(2) The partial interpretations $I(p)$ and $I(q)$ are identical if atomic propositions independent of f_{out} are only concerned. □

The condition (1) means the precondition and the postcondition must hold in the current state and the next state, respectively. The condition (2) states that for an atomic proposition A independent of f_{out}, $p \models A$ iff $q \models A$. This means that the truth value of independent atomic propositions *w.r.t.* the postcondition remain unchanged through the state transition.

Example 31 Consider the system requirement

$$\mathcal{R}_1 = \langle\{\rho_1 : A \overset{a}{\Rightarrow} \neg A,\ \rho_2 : B \overset{b}{\Rightarrow} A\},\ A \wedge B\rangle$$

and the transition system M_1 given in (a) in Figure 1. Now, consider the transition $t_1 = \langle q_0 \xrightarrow{a} q_1\rangle$ and the function requirement $\rho_1 : A \overset{a}{\Rightarrow} \neg A$. Since $q_0 \models A$ and $q_1 \models \neg A$ the condition (1) in Definition 31 holds for t_1 *w.r.t.* ρ_1. The atomic proposition independent of $\neg A$ is B. Since the truth values of B in q_0, q_1 are defined and $q_0 \models B$, $q_1 \models B$ the condition (2) in Definition 31 holds. Thus, the transition t_1 satisfies the function requirement ρ_1. In the exactly same way, we can easily check that the transitions $q_0 \xrightarrow{b} q_0$, $q_1 \xrightarrow{b} q_0$ satisfy the function requirement $\rho_2 : B \overset{b}{\Rightarrow} A$. □



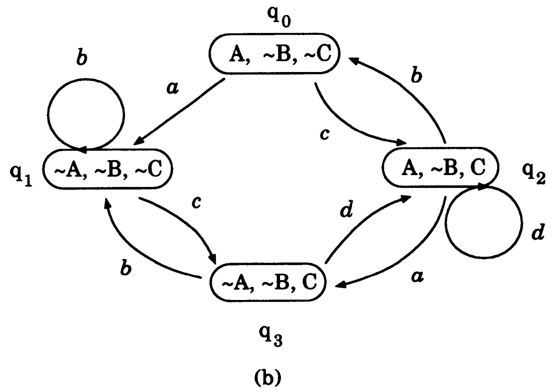


Figure 1 Transition Systems M_1 and M_2

Example 32 As a more involved example, let us consider the system requirement

$$\begin{aligned}\mathcal{R}_2 = \langle\{\ & \rho_1 : A \overset{a}{\Rightarrow} \neg A \wedge \neg B, && \rho_2 : \neg A \wedge \neg B \vee A \wedge C \overset{b}{\Rightarrow} \neg C,\\ & \rho_3 : \neg C \overset{c}{\Rightarrow} C, && \rho_4 : C \overset{d}{\Rightarrow} A\},\\ & A \wedge \neg B \wedge \neg C\rangle\end{aligned}$$

and the transition system M_2 given (b) in Figure 1. In the same way as in Example 31, it is easily checked that:

- the transitions $q_0 \xrightarrow{a} q_1$, $q_2 \xrightarrow{a} q_3$ satisfy ρ_1;
- the transitions $q_1 \xrightarrow{b} q_1$, $q_2 \xrightarrow{b} q_0$, $q_3 \xrightarrow{b} q_1$ satisfy ρ_2;
- the transitions $q_0 \xrightarrow{c} q_2$, $q_1 \xrightarrow{c} q_3$ satisfy ρ_3;
- the transitions $q_2 \xrightarrow{d} q_2$, $q_3 \xrightarrow{d} q_2$ satisfy ρ_4. □

Let γ be a consistent conjunction of literals. We define a partial interpretation $I(\gamma)$ based on γ by

$$I(\gamma)(A) = \begin{cases} \textbf{true} & \text{if } A \text{ appears positive in } \gamma \\ \textbf{false} & \text{if } A \text{ appears negative in } \gamma, \\ \text{undefined} & \text{otherwise} \end{cases}$$

for all atomic propositions A.

Definition 32 A state transition system $M = \langle Q, \Sigma, \rightarrow, q_0 \rangle$ is *sound* with respect to a system requirement $\mathcal{R} = \langle R, \gamma_0 \rangle$ if the following conditions are satisfied:

(1) $I(q_0) = I(\gamma_0)$;
(2) for any transition t in M there exists a function requirement $\rho \in R$ such that $t \models \rho$. □

Note that the transition systems M_1 in Example 31 and M_2 in Example 32 are sound with respect to the system requirements $\mathcal{R}_1$ and $\mathcal{R}_2$, respectively.

Definition 33 Let $M = \langle Q, \Sigma, \rightarrow, q_0 \rangle$ and $M' = \langle Q', \Sigma, \rightarrow', q_0' \rangle$ be state transition systems in common input symbols. A *homomorphism* from M into M' is a mapping $\xi : Q \rightarrow Q'$ such that

(1) $\xi(q_0) = q_0'$.
(2) if $p \xrightarrow{a} q$ in M, then $\xi(p) \xrightarrow{a} \xi(q)$ in M'.
(3) $p \models f$ implies $\xi(p) \models f$, for all states p in M and for all propositions f. □

The third condition (3) in the above definition can be equivalently relaxed:
(3') $p \models l$ implies $\xi(p) \models l$, for all states p in M and for all literals l.

If a homomorphism $\xi : Q \rightarrow Q'$ is a bijection, a one-to-one and onto mapping, and the inverse function ξ^{-1} is a also homomorphism from M' to M, then ξ is called an *isomorphism*. If there is an isomorphism from M to M', then M and M' are *isomorphic*.

Definition 34 Let M be a sound state transition system with respect to $\mathcal{R}$. M is called *complete* with respect to $\mathcal{R}$ if, there is a homomorphism ξ from M' into M for every sound state transition system M' with respect to $\mathcal{R}$. □

Definition 35 A sound and complete transition system with respect to $\mathcal{R}$ is called a *standard system* (*model*) of $\mathcal{R}$. □

Theorem 31 *Let M, M' be standard systems of $\mathcal{R}$, then M and M' are isomorphic.* □

Let $M(\mathcal{R})$ denote a unique standard system of $\mathcal{R}$ up to isomorphism.

4 TRANSFORMATION AND DETERMINACY

Without loss of generality, a proposition f can be equivalently expressed as a *disjunctive normal form* $\gamma_1 \vee \cdots \vee \gamma_n$, where γ_i are conjunctions of literals. Now, consider the following transformation rules on sets of function requirements:

rule 1 $R \cup \{\gamma_1 \vee \cdots \vee \gamma_n \overset{a}{\Rightarrow} \gamma\} \Rightarrow R \cup \{\gamma_1 \overset{a}{\Rightarrow} \gamma, \ldots, \gamma_n \overset{a}{\Rightarrow} \gamma\}$.

rule 2 $R \cup \{\gamma_1 \wedge A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma\} \Rightarrow R \cup \{\gamma_1 \wedge A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma \wedge A\}$
where neither A nor $\neg A$ appears in γ.

rule 3 $R \cup \{\gamma_1 \wedge \neg A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma\} \Rightarrow R \cup \{\gamma_1 \wedge \neg A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma \wedge \neg A\}$
where neither A nor $\neg A$ appears in γ.

Lemma 41 *We have the following results on the transformation rules:*

(1) *A transition t is correct w.r.t. a function requirement $\gamma_1 \vee \cdots \vee \gamma_n \overset{a}{\Rightarrow} \gamma$ iff it is correct w.r.t. some function requirement $\gamma_i \overset{a}{\Rightarrow} \gamma$, for some i.*

(2) *A transition t is correct w.r.t. a function requirement $\gamma_1 \wedge A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma$ iff it is correct w.r.t. the function requirement $\gamma_1 \wedge A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma \wedge A$, where neither A nor $\neg A$ appears in γ.*

(3) *A transition t is correct w.r.t. a function requirement $\gamma_1 \wedge \neg A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma$ iff it is correct w.r.t. the function requirement $\gamma_1 \wedge \neg A \wedge \gamma_2 \overset{a}{\Rightarrow} \gamma \wedge \neg A$, where neither A nor $\neg A$ appears in γ.*

Proof: Obvious from the transformation rules. □

Let $\mathcal{R} = \langle R, \gamma_0 \rangle$ be a system requirement. Let $\hat{\mathcal{R}} = \langle \hat{R}, \gamma_0 \rangle$ denote the resulting system requirement by applying the above transformation rules to $\mathcal{R}$ as much as possible. We call $\hat{\mathcal{R}}$ the *canonical form* of $\mathcal{R}$.

Theorem 41 *Let $\mathcal{R}$ be a system requirement. Suppose that state transition systems M and $\hat{M}$ are standard systems of $\mathcal{R}$ and $\hat{\mathcal{R}}$, respectively, then M and $\hat{M}$ are isomorphic .* □

Example 41 If we apply the above transformation rules to the requirement $\mathcal{R}_2$ in Example 32, we obtain the following requirement $\hat{\mathcal{R}}_2$.

$$\begin{aligned} \hat{\mathcal{R}}_2 = \langle\{ \quad & \rho_1 : A \overset{a}{\Rightarrow} \neg A \wedge \neg B, & \rho_2 : \neg A \wedge \neg B \overset{b}{\Rightarrow} \neg C \wedge \neg A \wedge \neg B, \\ & \rho_2 : A \wedge C \overset{b}{\Rightarrow} \neg C \wedge A, & \rho_3 : \neg C \overset{c}{\Rightarrow} C, \\ & \rho_4 : C \overset{d}{\Rightarrow} A \wedge C\}, & A \wedge \neg B \wedge \neg C\rangle \end{aligned}$$

By Theorem 41, both requirements have the isomorphic standard transition systems. □

Definition 41 Let M be a transition system. M is called *deterministic* if there are no transitions $p \xrightarrow{a} q_1$ and $p \xrightarrow{a} q_2$ for any states p, q_1, q_2 and for any input symbol a such that $q_1 \neq q_2$. □

Proposition 41 *Let $\mathcal{R}$ be a system requirement. If there are no functions $\rho_1 : f_1 \overset{a}{\Rightarrow} f_1'$, $\rho_2 : f_2 \overset{a}{\Rightarrow} f_2'$ with the input symbol in common such that $f_1 \wedge f_2$ is consistent, then the standard system of $\mathcal{R}$ is deterministic.*

Proof: Suppose the standard system $M(\mathcal{R})$ is nondeterministic, then there exist transitions $t_1 = \langle p \xrightarrow{a} q_1 \rangle$, $t_2 = \langle p \xrightarrow{a} q_2 \rangle$ for some states p, q_1, q_2 and for some input symbol a such that $q_1 \neq q_2$. Let $\rho_1 : f_1 \overset{a}{\Rightarrow} f_1'$, $\rho_2 : f_2 \overset{a}{\Rightarrow} f_2'$ be the functions such that $t_1 \models \rho_1, t_2 \models \rho_2$. Then, $p \models f_1$ and $p \models f_2$. Hence, $f_1 \wedge f_2$ is consistent. □

5 SYNTHESIS OF FORMAL SPECIFICATION

Our target is to derive a sound and complete state transition system M from a given system requirement $\mathcal{R} = \langle R, \gamma_0 \rangle$. Now, we state a transformation $\mathcal{T}$ from $\mathcal{R}$ into M. Let us define a transition system $\mathcal{T}(\mathcal{R}) = \langle \Gamma, \Sigma, \rightarrow, q_0 \rangle$, where

(1) $\Gamma = \{\gamma \mid \gamma$ is a consistent conjunction of literals in $\mathcal{P}\}$
(2) $\Sigma = \{a \mid \rho : f_{in} \overset{a}{\Rightarrow} f_{out} \in R\}$
(3) $\gamma \xrightarrow{a} \gamma'$ iff there exists a function requirement $\rho : f_{in} \overset{a}{\Rightarrow} f_{out} \in R$ such that
  (a) $I(\gamma) \models f_{in}$.
  (b) $I(\gamma') \models f_{out}$.
  (c) If an atomic proposition A is independent of f_{out}, then $I(\gamma) \models A$ iff $I(\gamma') \models A$.
(4) $q_o = \gamma_0$.

The partial interpretation associated with a state γ in $\mathcal{T}(\mathcal{R})$ is defined as $I(\gamma)$. In other words, the states correspond possible partial interpretations for all atomic propositions in $\mathcal{P}$. It is trivial from the construction that $\mathcal{T}(\mathcal{R})$ is irreducible.

Theorem 51 *The state transition system $\mathcal{T}(\mathcal{R})$ derived from a requirement description $\mathcal{R} = \langle R, \gamma_0 \rangle$ by $\mathcal{T}$ is a standard system of $\mathcal{R}$.*

Proof: Soundness: This direction is clear from the construction of the transition system $\mathcal{T}(\mathcal{R})$.

Completeness: Let $M = \langle Q, \Sigma, \rightarrow, q_0 \rangle$ be a sound state transition system with respect to $\mathcal{R}$. Let define a mapping $\xi : Q \rightarrow \Gamma$ by $\xi(q) = \gamma$ for $q \in Q$, where γ is a consistent conjunction of literals such that $I(q) = I(\gamma)$. The mapping ξ is well defined.

Now, we will show that ξ is a homomorphism from M into $\mathcal{T}(\mathcal{R})$. It can be easily checked that $\xi(q_0) = \gamma_0$ since M is a sound transition system and the initial state q_0 in M satisfies only literals appearing in γ_0. Let $p \xrightarrow{a} q$ be any transition in M. Suppose $\rho : f_{in} \overset{a}{\Rightarrow} f_{out}$ be the function requirement in R satisfied by this transition. So, we have $p \models f_{in}$ and $q \models f_{out}$. Thus,

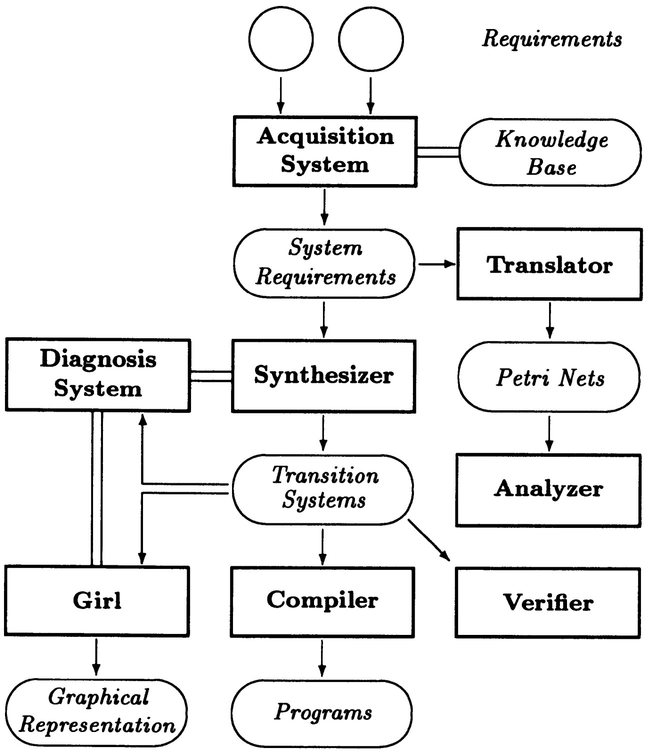


Figure 2 A Support System

$\xi(p) \models f_{in}$ and $\xi(q) \models f_{out}$, by the definition of ξ. The statement "$\xi(p) \models A$ iff $\xi(q) \models A$, for all atomic proposition A independent of f_{out}" can be implied by the statement "$p \models A$ iff $q \models A$, for all atomic proposition A independent of f_{out}". Therefore, we have a transition $\xi(p) \xrightarrow{a} \xi(q)$ in $\mathcal{T}(\mathcal{R})$. By the definition of ξ, $p \models f$ implies $\xi(p) \models f$ for all proposition f. Hence, ξ is a homomorphism from M into $\mathcal{T}(\mathcal{R})$. □

6 SUPPORT SYSTEM AND APPLICATION EXAMPLE

The outline of a support system for the development of (communication) software is briefly stated. The system consists of *Acquisition System* of system requirements with a help of Knowledge Base, *Synthesizer* of transition systems as formal specifications from system requirements, *Compiler* to C^{++} programs (executable codes) from transition systems (not fully implemented), *Diagnosis System* of system requirements with respect to transition systems (not fully implemented), *Verifier* of specifications via Temporal Logic (not fully implemented), *Translator* of system requirements to partial logical Petri Nets, and *Girl* – Visualizer of transition systems on the X-window system —. Figure 2 shows the system structure of our support system.

As a more real example, we will apply our method to a small portion of a simplified CATV system. The terminal of the CATV system is connected with the host computer, we can take several services on TV programs by controlling the buttons of the remote switch of the terminal. A system requirement of the CATV system is briefly stated: Power button enables power on-off of the system alternatively at any time (`[power on/off]` function). By pushing the channel-up, channel-down, or ten-key button, we can select the next, previous, or intended channel directly, respectively (`[channel-change]` functions). As the usual TV systems, the CATV system has muting facility (`[mute on/off]` function). Force tuning and buzzering functions are the characteristics of the CATV system (`[force-tune]` and `[buzzer on/off]` functions). According to the brief description of the system, a system requirement of the CATV system is described by the the following system requirement:

$\texttt{initial\_condition} : \neg muteon \wedge \neg force \wedge \neg poweron \wedge \neg buzzer$
$\texttt{power\_off} : poweron \wedge \neg force \wedge \neg buzzer \overset{power}{\Longrightarrow} \neg poweron$
$\texttt{power\_on} : \neg poweron \overset{power}{\Longrightarrow} \neg muteon \wedge poweron$
$\texttt{channel\_up} : poweron \wedge \neg force \wedge \neg buzzer \overset{chup}{\Longrightarrow} -$
$\texttt{channel\_down} : poweron \wedge \neg force \wedge \neg buzzer \overset{chdw}{\Longrightarrow} -$
$\texttt{channel\_change} : poweron \wedge \neg force \wedge \neg buzzer \overset{tenkey}{\Longrightarrow} -$
$\texttt{mute\_on} : \neg muteon \wedge \neg buzzer \wedge \neg force \wedge poweron \overset{mute}{\Longrightarrow} muteon$
$\texttt{mute\_off} : muteon \wedge \neg buzzer \wedge \neg force \wedge poweron \overset{mute}{\Longrightarrow} \neg muteon$
$\texttt{force\_tune} : \neg poweron \overset{ftune}{\Longrightarrow} force \wedge poweron$
$\texttt{force\_tune} : poweron \overset{ftune}{\Longrightarrow} force$
$\texttt{force\_cancel} : force \wedge \neg buzzer \wedge poweron \overset{power}{\Longrightarrow} \neg force$
$\texttt{buzzer\_on} : \neg buzzer \overset{buzzer}{\Longrightarrow} buzzer$
$\texttt{buzzer\_off} : buzzer \overset{anykey}{\Longrightarrow} \neg buzzer$

In the above description the symbol "–" indicates its own precondition of a function. So, e.g. the channel-up function

$$\texttt{channel\_up} : poweron \wedge \neg force \wedge \neg buzzer \overset{chup}{\Longrightarrow} -$$

is the abbreviation of the regular description

$$\texttt{channel\_up} : poweron \wedge \neg force \wedge \neg buzzer \overset{chup}{\Longrightarrow} poweron \wedge \neg force \wedge \neg buzzer.$$

This means that there are no state change by the channel-up function. The formal specification derived from the requirements is depicted in Figure 3, which is the real output (eps file) of the support system sated in the previous section. In the output function names are used instead of input symbols as labels of transitions.

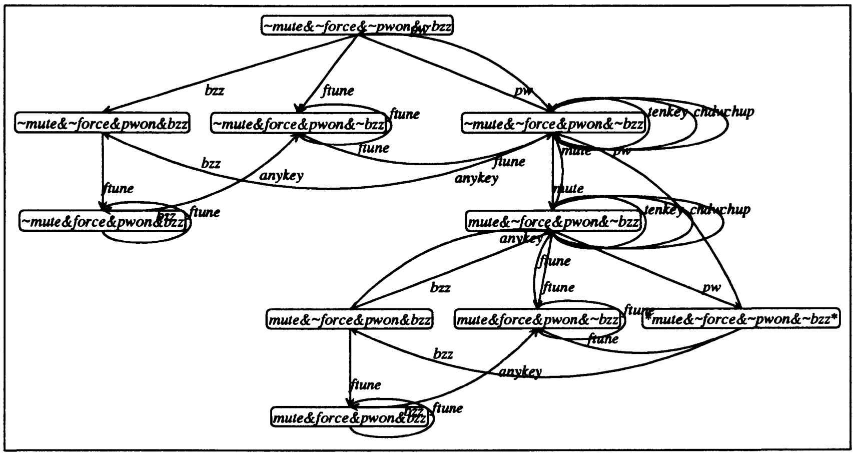


Figure 3 The Derived Formal Specification of the CATV System

7 DISCUSSIONS

The derived state transition system $\mathcal{T}(\mathcal{R})$ from a system requirement $\mathcal{R}$ can be proved to coincide with the reachability graph of a Partial Logical Petri Net. A Partial Logical Petri Net, where inhibited arcs (inhibitor arcs) are allowed in both inputs and outputs of transitions, and two kinds of tokens are provided. The Partial Logical Petri Net is an straight extension of a Logical Petri Net proposed by Song and et al [17].

Definition 71 (Partial Logical Petri Net)
A *Partial Logical Petri Net* is a tuple $PN = \langle P, T, I, O, M_0 \rangle$, where

(1) P is a set of *places*;
(2) T is a set of *transitions*;
(3) $I = \langle I_p, I_n \rangle$ is a pair of *input functions* I_p, $I_n : T \rightarrow 2^P$ such that $I_p(t) \cap I_n(t) = \emptyset$ for all $t \in T$;
(4) $O = \langle O_p, O_n \rangle$ is a pair of *output functions* O_p, $O_n : T \rightarrow 2^P$ such that $O_p(t) \cap O_n(t) = \emptyset$, for all $t \in T$;
(5) $M_0 : P \rightarrow \{0, 1, *\}$ is an *initial marking*. □

A Partial Logical Petri Net can be represented as a bipartite graph in the almost same way as a usual Petri Net [13]. However, in a Partial Logical Petri Net, we have the following extensions and restrictions.

- There are two kinds of arcs, called *positive arcs* and *negative arcs*. If $p \in I_p(t)$ ($p \in O_p(t)$), we make a positive arc, depicted as $\rightarrow$, from p to t (from t to p). If $p \in I_n(t)$ ($p \in O_n(t)$), we make a negative arc, depicted as $\multimap$, from p to t (from t to p).
- There are two kinds of tokens, a *positive token* • and a *negative token* ○ which represent truth constant **true** and **false**, respectively.
- Marking functions are restricted to the functions with the range $\{0, 1, *\}$, where 0, 1, and $*$ means that the associated condition with the place is "not satisfied", "satisfied", and "undefined", respectively.

The graphical representation of a Partial Logical Petri Net is given in Figure 4 (a).

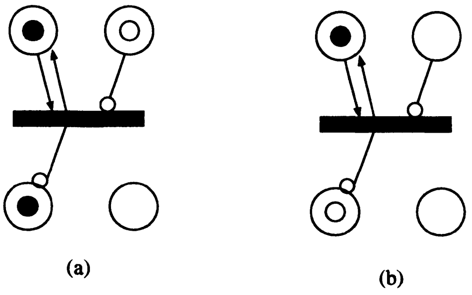


Figure 4 Partial Logical Petri Nets

In a marking M, a transitions t is *fireable* (*executable*) if the following conditions are satisfied:

(1) $M(p) = 1$ for all $p \in I_p(t)$.

(2) $M(p) = 0$ for all $p \in I_n(t)$.

If t is fireable, then t suddenly fires and the marking is changed into the marking M' defined by

$$M'(p) = \begin{cases} 0 & \text{if } p \in O_n(t) \\ 1 & \text{if } p \in O_p(t) \\ * & \text{if } p \in (I_n(t) \cup I_p(t)) \cap O_n(t)^c \cap O_p(t)^c \\ M(p) & \text{otherwise} \end{cases}$$

The transition in the net (a) in Figure 4 is fireable. After firing, the marking is changed into the one (b) in the figure.

Let $\mathcal{R} = \langle R, \gamma_0 \rangle$ be a requirement in canonical form. We can obtain a Partial Logical Petri Net $\langle P, T, I, O, M_0 \rangle$ from $\mathcal{R}$ as follows:
1. $P = \mathcal{P}$: Places correspond atomic propositions.
2. $T = R$: Transitions correspond function requirements.
3. Let $\rho : A_1 \wedge \cdots \wedge A_n \wedge \neg B_1 \wedge \cdots \wedge \neg B_m \overset{a}{\Rightarrow} C_1 \wedge \cdots \wedge C_j \wedge \neg D_1 \wedge \cdots \wedge \neg D_k$ be a function, where capital letters denote atomic propositions. Then, define input functions $I = \langle I_p, I_n \rangle$ and output functions $O = \langle O_p, O_n \rangle$ by

$$\begin{aligned} I_p(\rho) &= \{A_1, \ldots, A_n\} \\ I_n(\rho) &= \{B_1, \ldots, B_m\} \\ O_p(\rho) &= \{C_1, \ldots, C_j\} \\ O_n(\rho) &= \{D_1, \ldots, D_k.\} \end{aligned}$$

4. The initial marking M_0 is defined by

$$M_0(A) = \begin{cases} 0 & \text{if } A \text{ appears negative in } \gamma_0 \\ 1 & \text{if } A \text{ appears positive in } \gamma_0 \\ * & \text{otherwise} \end{cases}$$

Example 71 If we apply the above transformation to the canonical form in Example 41 of the requirement in Example 32, we obtain the Partial Logical Petri Net in Figure 5. The resulting reachability graph of the net coincide with the transition system (b) in Figure 1. This can be guaranteed in general by the next proposition. □

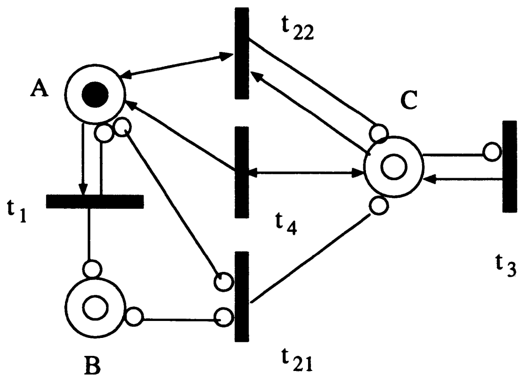


Figure 5 The transformed Partial Logical Petri Net

Proposition 71 *Let M be a standard system of a requirement $\mathcal{R}$. Then, the reachability graph of the Partial Logical Petri Net derived from $\hat{\mathcal{R}}$ is isomorphic to M.* □

The derived transition system $\mathcal{T}(\mathcal{R})$ can be characterized by Production Systems as well. To be more precise, if $\mathcal{R}$ is a requirement in canonical form, then each function requirement $\rho : f_{in} \overset{a}{\Rightarrow} f_{out}$ can be regarded as a production rule $f_{in} \rightarrow f_{out}$. Then, we have the following result.

Proposition 72 *Let $\mathcal{R}$ be a requirement in canonical form. If we take a function requirement $\rho : f_{in} \overset{a}{\Rightarrow} f_{out}$ as a production rule $f_{in} \rightarrow f_{out}$, then the state transition system of the resulting production system is isomorphic to the standard transition system $\mathcal{T}(\mathcal{R})$.* □

8 CONCLUDING REMARKS

A formal methodology for the description of system requirements and the synthesis of formal specifications from them have been presented. We have specifically dealt with the issues (1) mathematical treatment of system requirements and their relationship with formal specifications represented as state transition systems, (2) sound and complete systems, i.e. standard systems, (3) derivation of standard systems from system requirements, (4) a support system and an application example, and (5) some discussions on partial logical Petri Nets, Production systems, and so on . The proposed framework provides theoretical and practical tools for system design.

To conclude the paper, we state some further comments on our methodology.

Extension to Predicate Logic The underlying logic of this paper may be easily extended to first order predicate logic. For example, the function of **channel_up** in the CATV system is expressed more precisely by the function requirement

$$\textbf{channel\_up} : poweron \land \neg force \land \neg buzzer \land ch(x) \overset{chup}{\Longrightarrow} poweron \land ch(x+1)$$

In the above description, the first order variable x is quantified universally.

Branching Time Temporal Logic A function requirement $\rho : f_{in} \overset{a}{\Rightarrow} f_{out}$ can be expressed as a proposition $\Box(f_{in} \supset \langle a \rangle f_{out})$ in an extended branching time temporal logic.

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