Smart Home Planning Programs

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Service Oriented Computing and Service Composition

- SOC paradigm [ACKM04]:
  - existing software modules are fundamental blocks
  - new modules are built from existing ones
  - main advantages: software re-use; extensibility; low-cost and rapid development

Typical Scenario

- available services instructed (by clients) to execute operations
- operations affect service state
- operations affect the world-model
The SM4All Project
(Smart hoMes for All)

Pervasive Environments

- sensors and actuators spread throughout the house
- sensors \textit{access} the state of the house (world-model)
- actuators \textit{affect} the state of the house
- both have their own \textit{internal state}

IDEA: sensors and actuators play as \textit{services}

GOAL: assist people in carrying out desired tasks
The SM4All Architecture
Service Abstraction

How are services described?

- *behavioral* [BCG+03] perspective: focus on dynamics (vs. in/out description)
- services offer basic operations, which affect the world-model
- operations have, in general, (partial) order constraints (protocol specification)
- captured by finite-state transition systems

Example

![Diagram of bathtub operation states]

OBS: the bathtub cannot be filled if cold air is on
House Model

- A simplified model: finite-state transition system
  - finite-state (discrete and finite measures)
  - transitions triggered by service operations
- States feature propositional properties (same as in planning)

Example

All parts (e.g., window, door, etc.) controlled by some service
State: state of all components (sensors/actuators)
Target Service Model

Target Service: description of user’s desired service

- **goal-based**: at each step (transition), the user requests a goal
- **generic form**: achieve $\varphi$ while maintaining $\psi$
  - goals to achieve in the house (e.g., window open)
  - goals to maintain (e.g., keep door closed)

Essentially, a deterministic transition system where goals label transitions

Example

\[
\begin{align*}
\psi_1 &= (\text{temp\_bedroom} = \text{warm} \land \\
&\quad \text{temp\_livingroom} = \text{warm} \land \\
&\quad \text{temp\_kitchen} = \text{warm} \land \\
&\quad \text{temp\_guestroom} = \text{warm}) \\
\phi_1 &= ((\text{temp\_toilet} = \text{hot} \land \\
&\quad \text{temp\_bathroom} = \text{warm}) \oplus \\
&\quad (\text{temp\_bathroom} = \text{hot} \land \\
&\quad \text{temp\_toilet} = \text{warm})) \\
\psi_2 &= (\text{temp\_bedroom} = \text{warm} \land \\
&\quad \text{temp\_livingroom} = \text{warm} \land \\
&\quad \text{temp\_kitchen} = \text{warm} \land \\
&\quad \text{temp\_guestroom} = \text{warm} \land \\
&\quad \text{temp\_toilet} = \text{hot}) \\
\phi_2 &= (\text{temp\_bathroom} = \text{hot} \land \\
&\quad \text{bath\_state} = \text{bathtub\_filled}) \\
\psi_3 &= (\neg \text{guest\_disturbed}) \\
\phi_3 &= (\text{way\_clear\_bedroom\_kitchen}) \\
\psi_5 &= (\text{temp\_kitchen} = \text{warm}) \\
\phi_5 &= (\neg \text{kitchen\_smell}) \\
\phi_4 &= (\text{breakfast\_ready})
\end{align*}
\]
The Problem

Goal-Based Service Composition Problem [DGPS10]

- **Given**
  - A finite set of available services
  - A finite-state *world-model*
  - A goal-based target service

- **Control** the available services so as to *realize* the target service

  *Realizing:* being always able to fulfill target goal requests

- **Main novelty:** request for goals, instead of operations

- **Flavor of Planning:**
  - transitions realized by conditional plans, through operation delegation
  - goal *routines:* requests can be chained
  - step-by-step planning fails (future requests are neglected)
Can the available services be coordinated so as to fulfill all user goal requests?

If so, how can it be done?
The available services are usual ND transition systems \( S = \langle S, s_0, A, \delta \rangle \)

- \( S \): finite set of states
- \( s_0 \in S \): initial state
- \( A \): set of operations
- \( \delta \subseteq S \times A \times S \): transition relation

The world model is an ND labelled transition system \( B = \langle P, B, b_0, A, \rho \rangle \)

- \( P \): finite set of propositions
- \( B \subseteq 2^P \): finite set of states
- \( b_0 \in B \): initial state
- \( A \): set of operations (same as above)
- \( \rho \subseteq B \times A \times B \): transition relation

The target service is a deterministic TS with edges labelled by propositional (goal) formulae built from \( P \)

Observe: TSs are usually represented compactly (no state enumeration)
Plan-Based Simulation Relation

- How to formalize the notion of \textit{realization}?

\textbf{Definition (Plan-Based Simulation Relation)}

Consider:
- a set of available services $S_i = \langle S_i, s_{i0}, A, \delta_i \rangle$
- a world-model $B = \langle P, B, b_0, A, \rho \rangle$
- a target service $T = \langle T, t_0, G, \varrho \rangle$, with $G \subseteq \text{PROP}(P)$

Let $T_S = S_1 \otimes \cdots \otimes S_n$ be the asynchronous product of all available services.

$\preceq \subseteq (S_1 \times \cdots \times S_n) \times T \times B$ is a \textit{Plan-Based Simulation Relation} iff:
- $\langle \langle s_1, \ldots, s_n \rangle, t, b \rangle \in \preceq$ implies:
  - \textbf{(Local realization)} for all possible target transitions $t \xrightarrow{\phi} t'$ there exists a \textit{conditional plan} (local witness!) $\pi$, \textit{compliant} with $T_S$, leading $B$ to a state satisfying $\phi$.
  - \textbf{(Preservation)} for all possible $B$ states $b'$ and all possible $T_S$ states $\langle s_1', \ldots, s_n' \rangle$, both reached after the same $\pi$ execution, $\langle \langle s_1', \ldots, s_n' \rangle, t', b' \rangle \in \preceq$

This is a \textit{coinductive} definition (gfp) —simulation— with calls to a nested \textit{inductive} definition (lpf) —reachability—.
Realizable Target Services

Intuition:
\[ \langle \langle s_{10}, \ldots, s_{n0} \rangle, t_0, b_0 \rangle \in \preceq: \text{the available services can be coordinated so as to fulfill,} \]
\[ \text{in an } \textit{online} \text{ fashion, all sequences of goals the target service may request} \]

Remarks:
- sequences can be \textit{infinite}, when loops are present (naïve use of planning avoided!)
- \textit{online}: requests not known in advance (all possible futures must be considered)

Definition (Realizable Target Service)

- A target service \( T \) is \textit{realizable} by a set of available services \( S_1, \ldots, S_n \) on a shared blackboard \( B \) iff a Plan-Based simulation relation \( \preceq \) exists such that
\[ \langle \langle s_{10}, \ldots, s_{n0} \rangle, t_0, b_0 \rangle \in \preceq \]
Plan-Based Compositions (cont.)

By choosing and executing a plan at each request, a composition is defined.

**Definition (Plan-Based Service Composition, Informal)**

A composition is a function $comp : ((S_1 \times \cdots \times S_n) \times T \times B)^+ \times \varrho \rightarrow \Pi$ that returns a good plan for each target request:

- $(S_1 \times \cdots \times S_n) \times T \times B)^+$: histories of the (whole) system
- $\varrho$: target requests
- $\Pi$: all conditional plans definable on $(S_1 \otimes \cdots \otimes S_n)$

A good plan is one that:

- never delegates an operation to a service unable to perform it
- guarantees the achievement of the current goal request
Computing Plan-Based Compositions

Compositions are computed by resorting to \textit{LTL synthesis}

\begin{itemize}
  \item Limit state space explosion (BDD-based approach)
  \item Actual technology available (e.g., TLV)
\end{itemize}
LTL Synthesis Overview

System
\[ \Phi_S(\mathcal{X}, \mathcal{Y}) \]

Controller
\[ \Phi_C(\mathcal{X}, \mathcal{Y}) \]

Game perspective

From current state \( \langle \bar{x}, \bar{y} \rangle \) (initially, fix \( \langle \bar{x}_0, \bar{y}_0 \rangle \)):
- (Move) the system chooses a valuation \( \bar{x}' \) for \( \mathcal{X} \) propositions, that satisfies \( \Phi_S \)
- (Reply) the controller chooses a valuation \( \bar{y}' \) for \( \mathcal{Y} \) propositions, that satisfies \( \Phi_C \)
- (Play) moves and replies alternate creating (infinite) runs \( \rho = \langle \bar{x}_1, \bar{y}_1 \rangle \langle \bar{x}_2, \bar{y}_2 \rangle \cdots \)

Goal:
- Find a controller winning strategy \( f : \mathcal{X}^+ \rightarrow \mathcal{Y} \) such that
  - all possible plays \( \rho \) compliant with \( f \) are s.t. \( \rho \models \varphi \)
  - (compliant: the controller plays according to \( f \))

Intuition:
- The controller has a strategy to force \( \varphi \), no matter how the system plays
Complexity:

- For arbitrary $\varphi$, the problem is 2EXPTIME-complete [PR89]
- Generalized Reactivity (1) specifications yield an EXPTIME bound [PPS06, KPP05]

GR(1) specification form

$$\varphi = \varphi_a \land \bigwedge_{m} \square \Diamond \phi_i \rightarrow \varphi_r \land \bigwedge_{\ell} \square \Diamond \psi_j$$

- $\varphi_a$: system structural assumptions (transition relation)
- $\varphi_r$: controller structural assumptions (transition relation)
- $\phi_i, \psi_j$: boolean formulae

Synthesis for GR(1) formulae is enough to capture our problem!
Results

Theorem (Soundness & Completeness)

Given a composition problem instance \((S_1, \ldots, S_n, B, T)\), there exists a plan-based composition \(comp\) iff there exists a controller winning strategy \(f\) for the LTL specification \(\varphi\), obtained from the above reduction:

\[
\varphi = (\bigwedge_n \text{Init}_{S_i} \land \text{Init}_B \land \text{Init}_T \land \square(\bigwedge_n \text{Trans}_{S_i} \land \text{Trans}_T)) \rightarrow (\square \text{good} \land \square \Diamond \text{last})
\]

Moreover, extracting \(comp\) from \(f\) is straightforward!
Theorem (Complexity)

The problem of checking the existence of a plan-based composition for a target service $\mathcal{T}$ by a set of available services $S_1, \ldots, S_n$ on a blackboard $B$ is EXPTIME-complete.

Same complexity class as Conditional Planning w/ Full Observability!
Conclusions

1. A new service composition framework exploited
2. Problem reduced to LTL synthesis:
   - connection with Formal Methods: exploit MC symbolic approach
   - existing technology available
3. Sound & complete approach, same complexity class as Conditional Planning under full observability
Research Directions

1. Extensions:
   ▶ strong fairness constraints on services/blackboard dynamics, to capture necessary eventualities (e.g., an ND operations will eventually succeed)

2. Data: what if operations have parameters and actual data are relevant to world-model and/or services?
   ▶ this is the main open issue, as real services typically deal with data
   ▶ often, data yield state-infiniteness: data abstraction required
   ▶ starting point: results on services/artifacts verification & synthesis [DHPV09, PD09]

3. Efficiency (EXPTIME is hard!):
   ▶ general viewpoint: the problem specification affects the search
   ▶ specific viewpoint: GR(1) expressiveness more than needed
   ▶ use/development of other tools and/or ad-hoc solutions
   ▶ other, possibly incomplete, solution strategies, e.g., heuristic-based
Thank You for Listening!

Questions?
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