Smart Home Planning Programs

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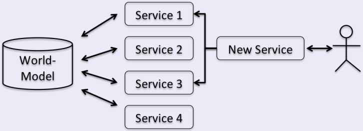
Service Oriented Computing and Service Composition

- 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)

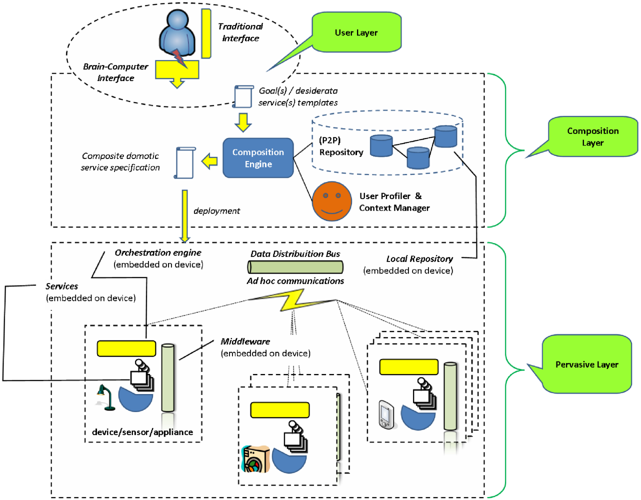
Pervasive Environments

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

IDEA: sensors and actuators play as *services*

GOAL: assist people in carrying out desired tasks

The SM4All Architecture

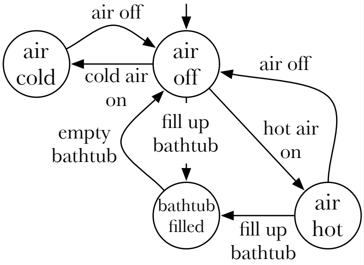


Service Abstraction

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

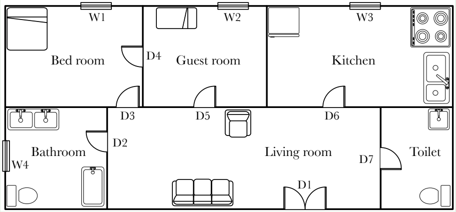


OBS: the bathtub cannot be filled if cold air is on

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)

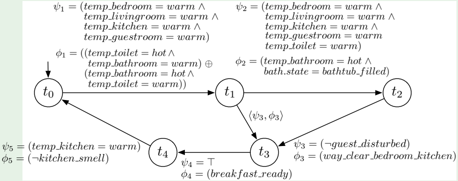
Target Service Model

Target Service: description of user's desired service

- *goal-based*: at each step (transition), the user requests a goal
- generic form: *achieve* φ *while maintaining* ψ
  - 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



The Problem

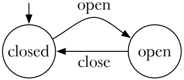
Goal-Based Service Composition Problem [DGPS10]

- 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

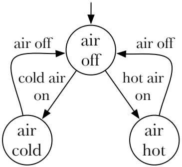
  Realizing: being always able to fulfill target goal requests

- 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)

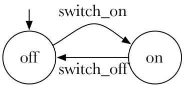
Example



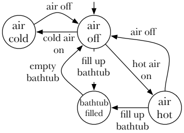
(a) door/window service



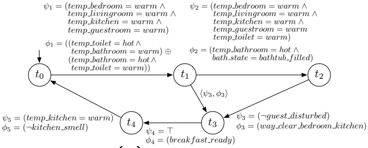
(b) house/toilet heating system



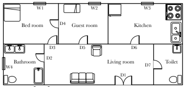
(c) kitchen ventilation



(d) bathroom tub/air controller



(e) target service



(f) world-model

- Can the available services be coordinated so as to fulfill all user goal requests?
- If so, how can it be done?

Formal Model

- The available services are usual ND transition systems $\mathcal{S} = \langle S, s_0, A, \delta \rangle$
  - 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 $\mathcal{B} = \langle P, B, b_0, A, \rho \rangle$
  - 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 *realization*?

Definition (Plan-Based Simulation Relation)

- Consider:
  - a set of available services $\mathcal{S}_i = \langle S_i, s_{i0}, A, \delta_i \rangle$
  - a world-model $\mathcal{B} = \langle P, B, b_0, A, \rho \rangle$
  - a target service $\mathcal{T} = \langle T, t_0, G, \varrho \rangle$, with $G \subseteq PROP(P)$
- Let $\mathcal{T}_S = \mathcal{S}_1 \otimes \cdots \otimes \mathcal{S}_n$ be the asynchronous product of all available services
- $\preceq \subseteq (S_1 \times \cdots \times S_n) \times T \times B$ is a <u>*Plan-Based Simulation Relation*</u> iff:
  - $\langle \langle s_1, \ldots, s_n \rangle, t, b \rangle \in \preceq$ implies:
    - (Local realization) for all possible target transitions $t \xrightarrow{\phi} t'$ there exists a *conditional plan* (local witness!) π, *compliant* with $\mathcal{T}_S$, leading $\mathcal{B}$ to a state satisfying ϕ
    - (Preservation) for all possible $\mathcal{B}$ states b' and all possible $\mathcal{T}_S$ states $\langle s'_1, \ldots, s'_n \rangle$, both reached after the same π execution, $\langle \langle s'_1, \ldots, s'_n \rangle, t', b' \rangle \in \preceq$

This is a *coinductive* definition (gfp) –simulation– with calls to a nested *inductive* definition (lpf) –reachability)

Realizable Target Services

Intuition:

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

Remarks:

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

Definition (Realizable Target Service)

- A target service $\mathcal{T}$ is *realizable* by a set of available services $\mathcal{S}_1, \ldots, \mathcal{S}_n$ on a shared blackboard $\mathcal{B}$ 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 $comp : ((S_1 \times \cdots \times S_n) \times T \times B)^+ \times \varrho \to \Pi$ that returns a *good* plan for each target request

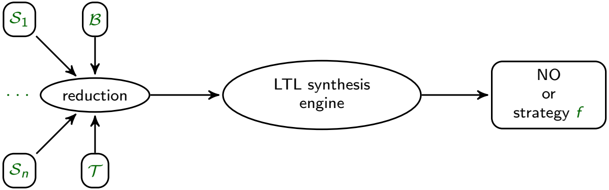
- $(S_1 \times \cdots \times S_n) \times T \times B)^+$: histories of the (whole) system
- ϱ: target requests
- Π: all conditional plans definable on $(\mathcal{S}_1 \otimes \cdots \otimes \mathcal{S}_n)$

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

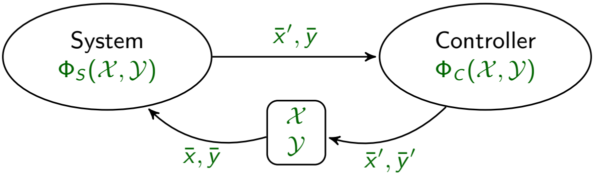
Compositions are computed by resorting to *LTL synthesis*



Advantages:

- Limit state space explosion (BDD-based approach)
- Actual technology available (e.g., TLV)

LTL Synthesis Overview



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 Φ_S
- (Reply) the controller chooses a valuation $\bar{y}'$ for $\mathcal{Y}$ propositions, that satisfies Φ_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 $f : X^+ \to Y$ such that
  - all possible plays ρ *compliant* with f are s.t. $\rho \models \varphi$
  - (*compliant*: the controller plays according to f)

Intuition:

- The controller has a strategy to force φ, no matter how the system plays

LTL Synthesis Overview (cont.)

Complexity:

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

GR(1) specification form

$$\varphi = \varphi_a \wedge \bigwedge_m \Box\Diamond\phi_i \longrightarrow \varphi_r \wedge \bigwedge_\ell \Box\Diamond\psi_j$$

- φ_a: system structural assumptions (transition relation)
- φ_r: controller structural assumptions (transition relation)
- ϕ_i, ψ_j: boolean formulae

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

Results

Theorem (Soundness & Completeness)

Given a composition problem instance $(\mathcal{S}_1, \ldots, \mathcal{S}_n, \mathcal{B}, \mathcal{T})$, *there exists a plan-based composition* comp *iff there exists a controller winning strategy* f *for the LTL specification* φ, *obtained from the above reduction:*

$$\varphi = (\bigwedge_n Init_{\mathcal{S}_i} \wedge Init_{\mathcal{B}} \wedge Init_{\mathcal{T}} \wedge \Box(\bigwedge_n Trans_{\mathcal{S}_i} \wedge Trans_{\mathcal{T}})) \longrightarrow (\Box good \wedge \Box\Diamond last)$$

Moreover, extracting comp from f is straightforward!

Results (cont.)

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 $\mathcal{S}_1, \ldots, \mathcal{S}_n$ on a blackboard $\mathcal{B}$ 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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