Cooperative Motion and Task Planning Under Temporal Tasks

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Royal Institute of Technology, KTH, Sweden

Licentiate Seminar

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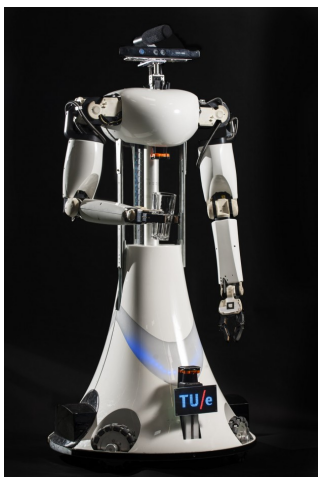
Motivation

Industrial and domestic robots[1] boosted by

- Development of digital processing units
  - more powerful, in speed and capacity
  - more affordable



[1] Gostai, Roomba, Romo, Amigo service robots

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Motivation

Industrial and domestic robots[1] boosted by

- Development of digital processing units
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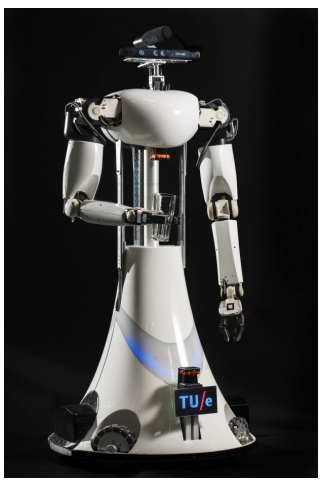
  - more affordable
- Wireless communication technology
  - potentially connects the robots
  - integrates with other "smart" devices



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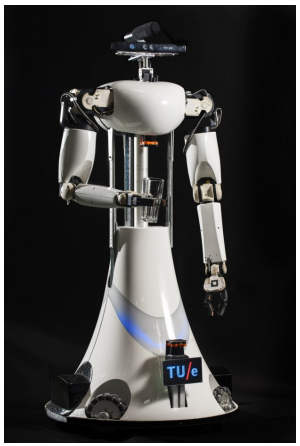
- Imagine ... several care robots in your house



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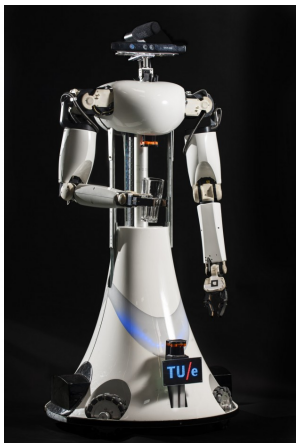

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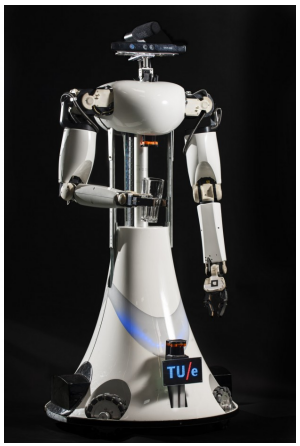

- "Amigo, go to the kitchen, find an apple and bring it to me"
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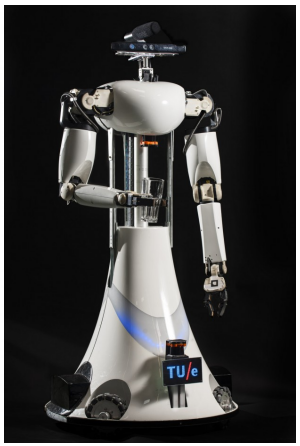

- "Amigo, go to the kitchen, find an apple and bring it to me"
- "Gostai, keep an eye on the kids in the living room and bedroom"
- "Amigo, put all the toys in the basket"
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Challenges

Challenges for system engineers (us)

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- Design algorithms for robots that

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  - a formal but flexible way to specify daily tasks
  - task execution status as feedback
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- Design algorithms for robots that
  - synthesize and execute a plan to satisfy the task
  - without or with minimal human intervention

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- Design algorithms for robots that
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  - without or with minimal human intervention
  - accommodate changes in the workspace
  - initiate communication with other devices
  - handle collaborative tasks

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Background

- Motion and task planning

[2] S. M. LaValle. *Planning algorithms*, 2006.
[3] M. Ghallab et al., *Automated planning: theory & practice*, 2004.
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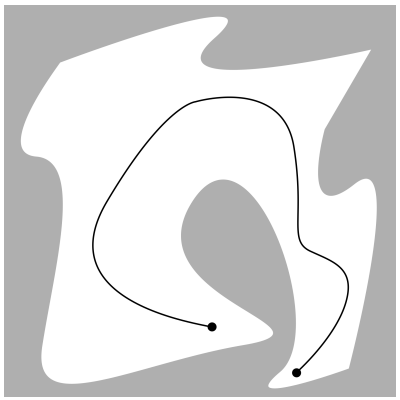
Background

- Motion and task planning
  - motion plan of dynamic systems[2]



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- Motion and task planning
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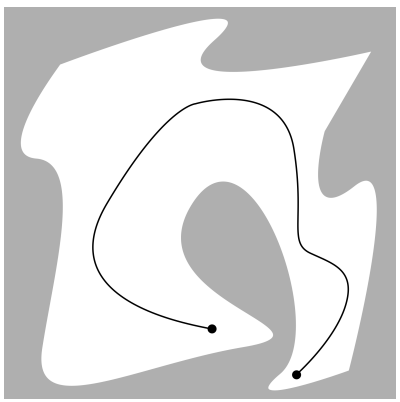
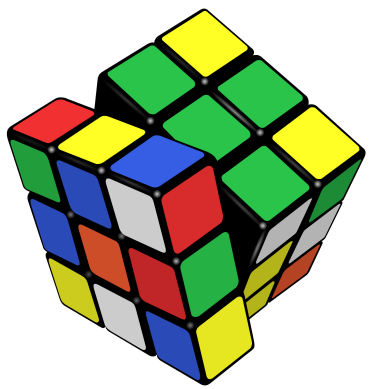
  - task plan for discrete-event systems[3]





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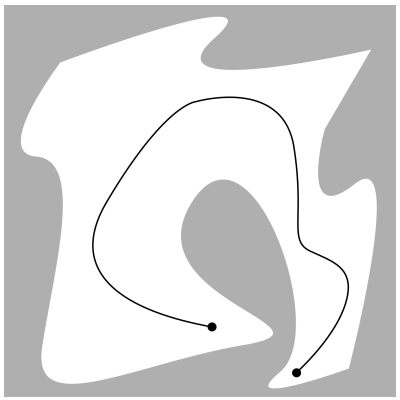

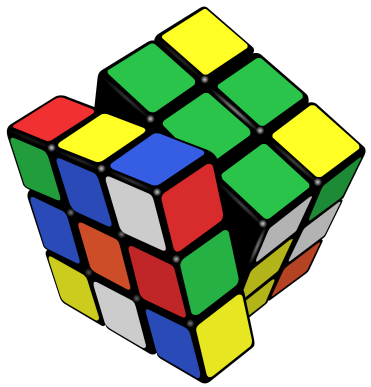

- Model checking
  - for verification[4]
  - for plan synthesis

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Multi-agent System

- Multi-agent system to solve a global task
  - decompose into sub-tasks
  - top-down, tightly-coupled
- Multi-agent system with local tasks
  - favour individual interests
  - bottom-up, loosely-coupled

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Main Contributions

- Reconfiguration for single- and multi-agent systems
  - M. Guo, K. H. Johansson and D. V. Dimarogonas. Motion and Action Planning under LTL Specification using Navigation Functions and Action Description Language. *IROS*, Japan, 2013.
  - M. Guo and D. V. Dimarogonas. Reconfiguration in Motion Planning of Single- and Multi-agent Systems under Infeasible Local LTL Specifications. *CDC*, Italy, 2013.
- Real-time adaptation for single- and multi-agent systems
  - M. Guo, K. H. Johansson and D. V. Dimarogonas. Revising Motion Planning under Linear Temporal Logic Specifications in Partially Known Workspaces. *ICRA*, Germany, 2013.
  - M. Guo and D. V. Dimarogonas. Distributed Plan Reconfiguration via Knowledge Transfer in Multi-agent Systems under Local LTL Specifications. *ICRA*, Hongkong, 2014.
  - M. Guo and D. V. Dimarogonas. Multi-agent Plan Reconfiguration under Local LTL Specifications. *IJRR*. Submitted.

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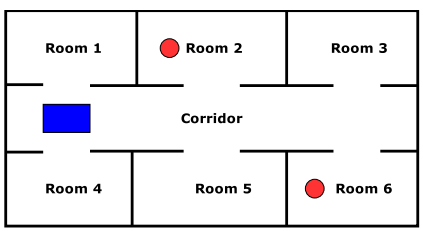
Motion Abstraction

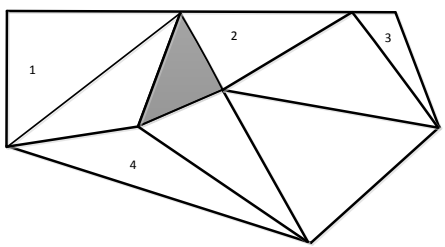
- Abstracted as the weighted finite transition system (FTS)

$$\mathcal{T}_c = (\Pi, \longrightarrow_c, \Pi_0, AP, L_c, W_c)$$

where the finite regions $\Pi = \{\pi_1, \pi_2, \cdots, \pi_W\}$

- Examples:





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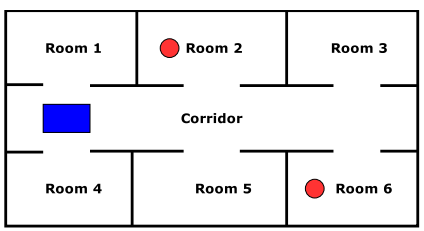
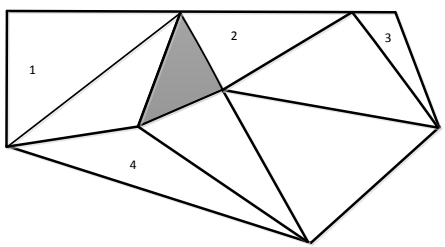
where the finite regions $\Pi = \{\pi_1, \pi_2, \cdots, \pi_W\}$

  - properties of interest $AP = AP_r \cap AP_p$
  - Π_0 initial states
  - $\longrightarrow_c \subseteq \Pi \times \Pi$, control-driven transition
  - $L_c : \Pi \to 2^{AP}$, labelling function
  - $W_c : \Pi \times \Pi \to \mathbb{R}^+$, weight function

- Examples:





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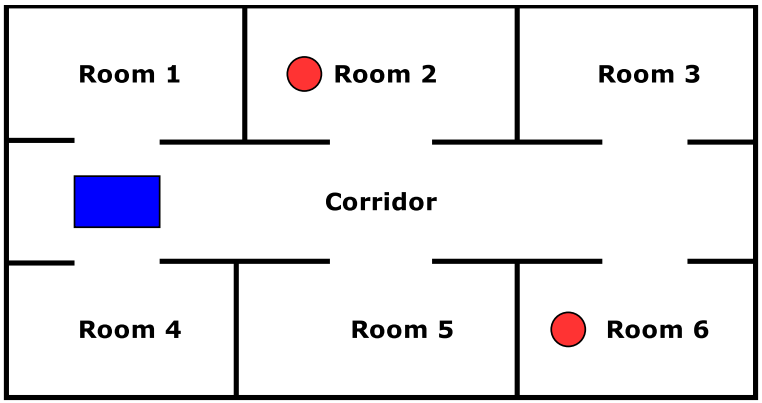
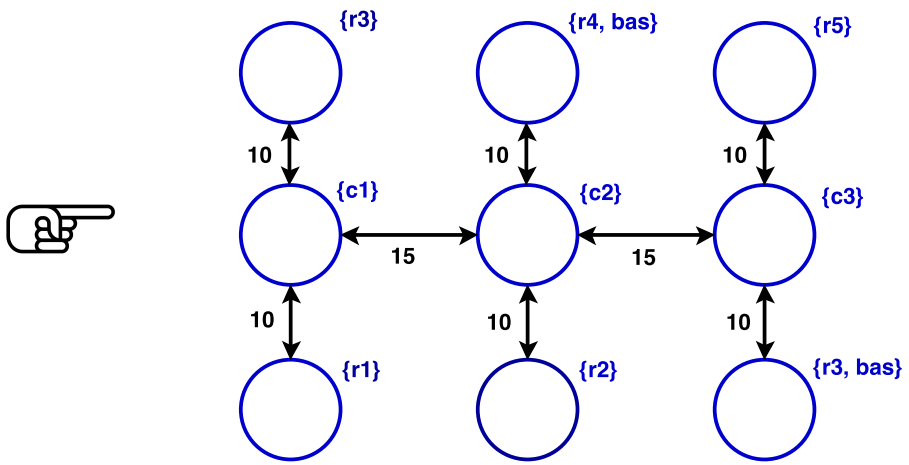
Abstraction Outcome





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Temporal Task Specification

How to formally specify the task?

- Language: Linear-time Temporal Logic (LTL) formula
- Syntax:

$$\varphi ::= \texttt{True} \mid a \mid \varphi_1 \vee \varphi_2 \mid \neg\varphi \mid \bigcirc \varphi \mid \varphi_1 \,\mathsf{U}\, \varphi_2$$

- Semantics[5]
- Specified over AP

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- Semantics[5]
- Specified over AP
- To specify control tasks:
  - Safety: $\Box\neg\,\varphi_1$. Order: $\Diamond(\varphi_1 \wedge \Diamond(\varphi_2 \wedge \Diamond\varphi_3))$.
  - Response: $\varphi_1 \Rightarrow \varphi_2$. Liveness: $\Box\Diamond\varphi_1$.

[5] C. Baier, J.-P Katoen. *Principles of model checking*, 2008.

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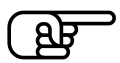
Task Interpretation

- "go to the kitchen, find an apple and bring it to me"



- $\varphi = \Diamond\big((\texttt{Kit} \wedge \texttt{PickApp}) \wedge \Diamond(\Box\texttt{Liv})\big)$

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Task Interpretation

- "go to the kitchen, find an apple and bring it to me"
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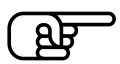

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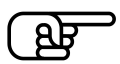

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- $\varphi = \Box\Diamond\texttt{Liv} \wedge \Box\Diamond\texttt{Bed}$
- $\varphi = \Box\Diamond\Big(\texttt{PickToy} \rightarrow \big(\neg\texttt{PickToy}\,\mathcal{U}\,(\texttt{Bas} \wedge \texttt{DropToy})\big)\Big)$
- ...

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Problem Formulation

Given the FTS $\mathcal{T}_c$ and the LTL task φ

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- Synthesize a discrete plan that satisfies φ

$$r1\, c1\, c2\, c3\, r3$$
$$c3\, c2\, r2\, c2\, r5$$
$$c2\, r2\, c2\, c1 (r1)^{\omega}$$

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Problem Formulation

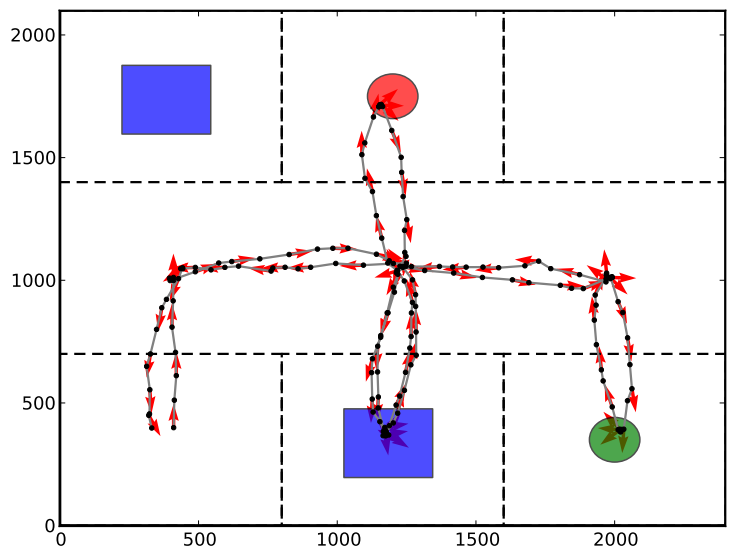
Given the FTS $\mathcal{T}_c$ and the LTL task φ

- Synthesize a discrete plan that satisfies φ
- Construct the hybrid control strategy to execute the derived plan

$$r1\, c1\, c2\, c3\, r3$$

$$c3\, c2\, r2\, c2\, r5$$

$$c2\, r2\, c2\, c1 \left(r1\right)^{\omega}$$



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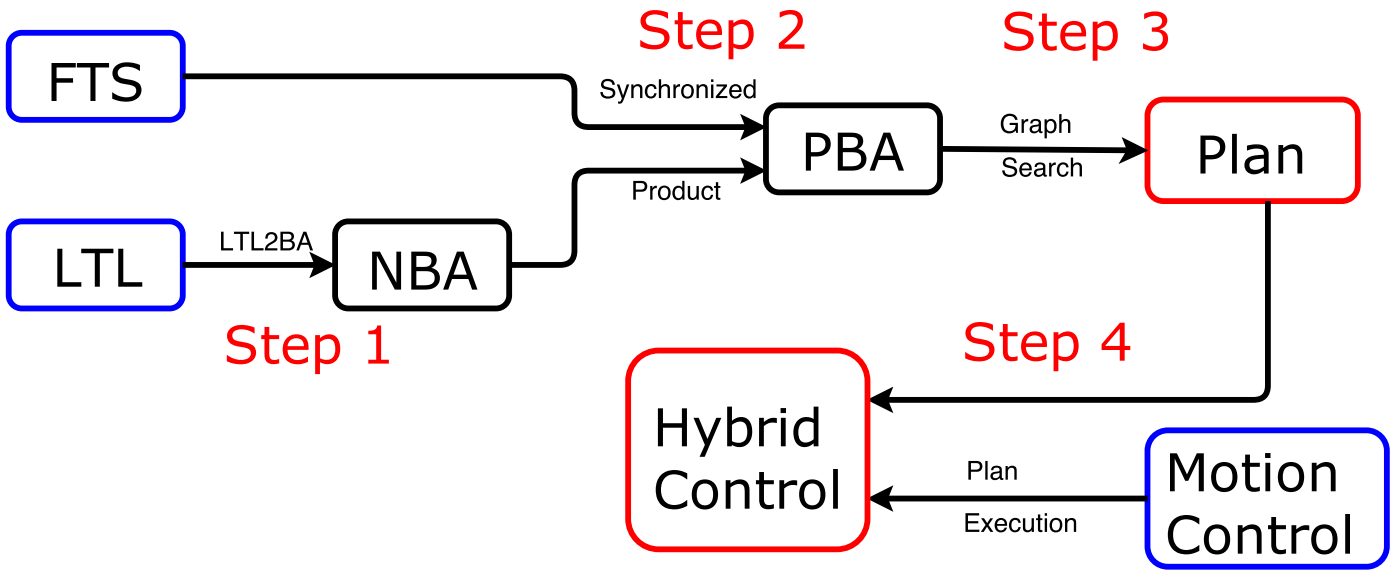
Nominal Solution Outline



- Automata-based model-checking algorithm[6]
- Hybrid controller synthesis[7]

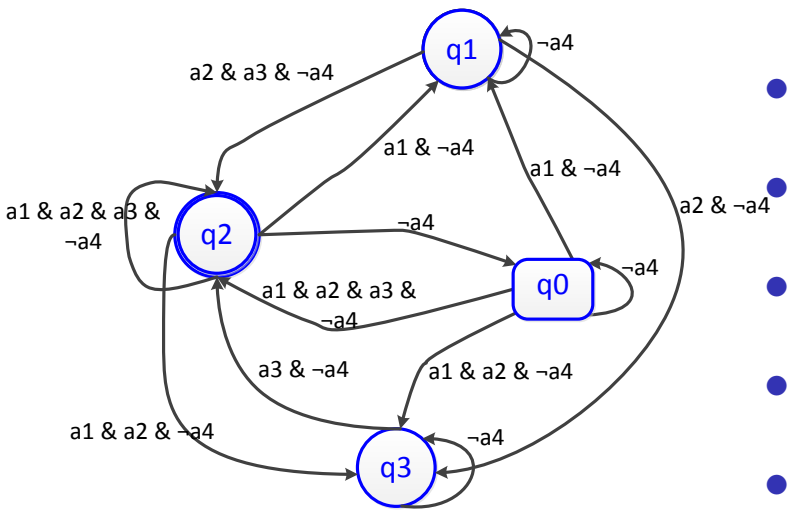
[6] C. Baier, J.-P Katoen. *Principles of model checking*, 2008.

[7] G. E. Fainekos et al., Temporal logic motion planning for dynamic robots. *Automatica*, 2009

Step 1. Translation

- Translate φ into the Nondeterministic Büchi automaton (NBA) $\mathcal{A}_\varphi$ over 2^{AP}:

$$\mathcal{A}_\varphi = (Q, 2^{AP}, \delta, Q_0, \mathcal{F}),$$



- Q is a finite set of states
- 2^{AP} are alphabets.
- $\delta \subseteq Q \times 2^{AP} \times Q$.
- Q_0, $\mathcal{F}$ are initial, accepting states.
- $\chi(q_m, q_n) = \{l \in 2^{AP} | (q_m, l, q_n) \in \delta\}$.

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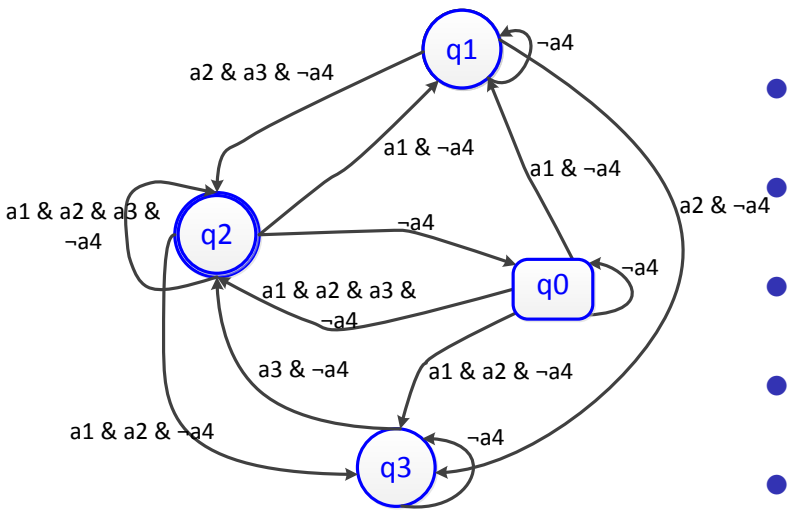

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- Automated
- Fast translation algorithm[8]

[8] D. Oddoux, P. Gastin. *LTL2BA software*, 2009.

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Step 2. Product Automaton

- Construct the weighted product automaton $\mathcal{A}_p = \mathcal{T}_c \otimes \mathcal{A}_\varphi$:

$$\mathcal{A}_p = (Q', \delta', Q'_0, \mathcal{F}', W_p)$$

where $Q' = \Pi \times Q$; $Q'_0 = \Pi_0 \times Q_0$; $\mathcal{F}' = \Pi \times \mathcal{F}$

- $\delta' \subseteq Q \times Q$, where $(\langle \pi_i, q_m \rangle, \langle \pi_j, q_n \rangle) \in \delta'$ iff $(\pi_i, \pi_j) \in \longrightarrow_c$ and $(q_m, L_c(\pi_i), q_n) \in \delta$
- $W_p : \delta' \to \mathbb{R}^+$. $W_p((\langle \pi_i, q_m \rangle, \langle \pi_j, q_n \rangle)) = W_c(\pi_i, \pi_j)$

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- Algorithms
  - static construction
  - on-the-fly construction

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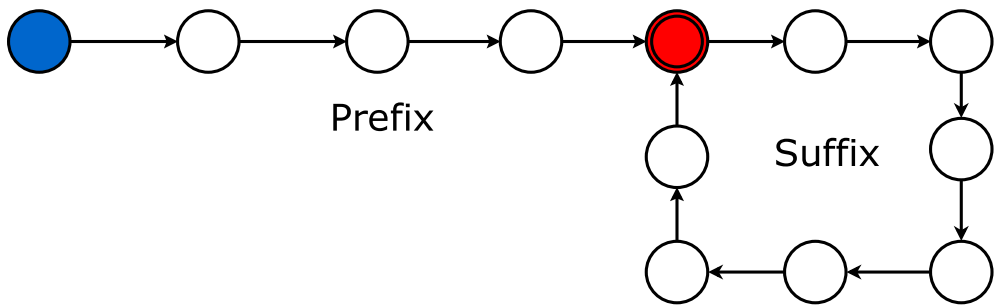
Plan Structure and Cost

- Accepting run R of $\mathcal{A}_p$ with the prefix-suffix structure

$$R = R_{\text{pre}} \, (R_{\text{suf}})^{\omega} = q'_0 \, q'_1 \cdots q'_{f-1} \, \left[\, q'_f \, q'_{f+1} \cdots q'_n \, \right]^{\omega}$$



- The total cost:

$$\texttt{Cost}(R, \mathcal{A}_p) = \sum_{i=0}^{f-1} W_p(q'_i, \, q'_{i+1}) + \gamma \sum_{i=f}^{n-1} W_p(q'_i, \, q'_{i+1})$$

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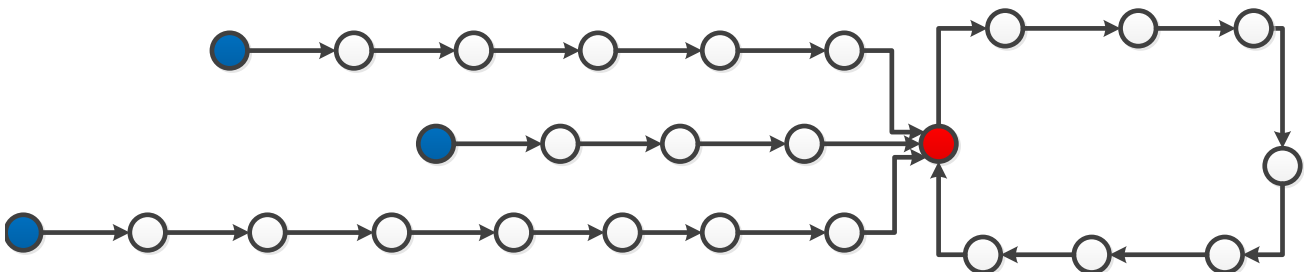
Step 3. Graph Search

- Algorithm based on Nested-Dijkstra shortest path
  - shortest path from every $q'_0 \in Q'_0$ to every $q'_f \in \mathcal{F}'$
  - shortest cycle from q'_f and back



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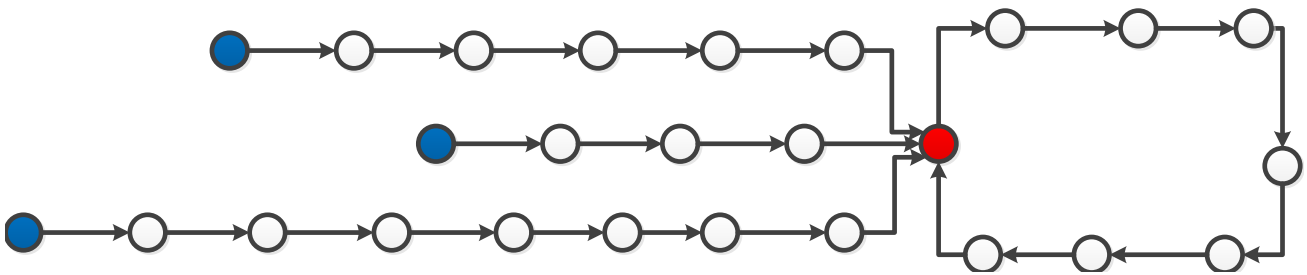
  - shortest cycle from q'_f and back



- The derived accepting run R_{opt} with minimal cost
- Corresponding plan $\tau = R_{\text{opt}}|_{\Pi}$
- Complexity $\mathcal{O}(|\delta'| \cdot \log_2 |Q'| \cdot (|Q'_0| + |\mathcal{F}'|))$

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Step 4. Hybrid Control Strategy

To execute $\tau = R_{\text{opt}}|_{\Pi}$ using $\mathcal{U}(x(t), \pi_i, \pi_j)$

- generate an infinite execution with finite representation
- monitor the execution status
- record past motions

$r1\, c1\, c2\, c3\, r3$

$c3\, c2\, r2\, c2\, r5$

$c2\, r2\, c2\, c1 (r1)^{\omega}$

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Shortcomings of Nominal Solution

- Reconfiguration
  - plan as sequence of motion (no actions)
  - feasible task
- Real-time adaptation
  - fully-known workspace
  - plan synthesized once off-line
  - executed regardless of the real observation

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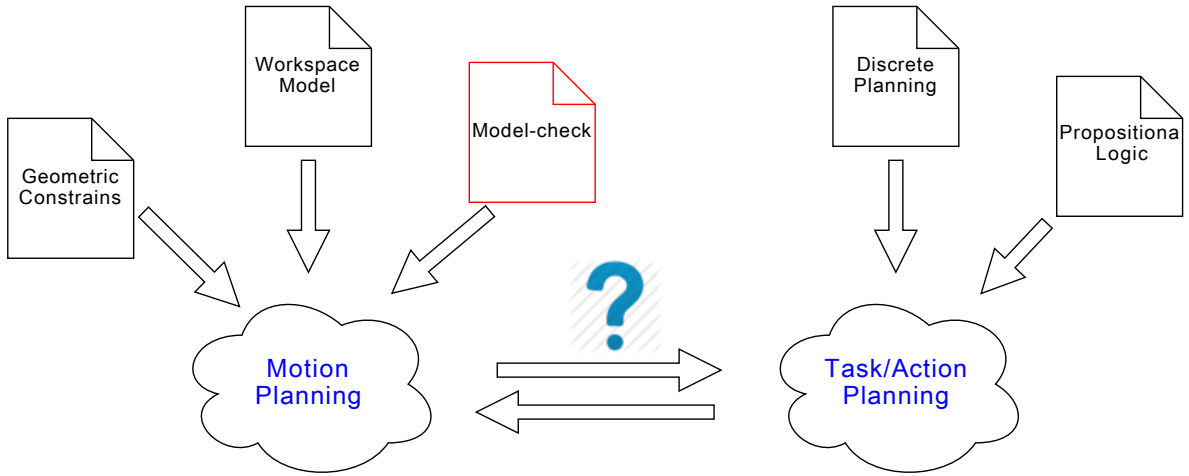
Motion and Action Planning



- Why is it necessary?
  - to automate the choice of actions
  - plan as sequence of motion and actions
- Why plan motion and action together?
  - the purpose of "going somewhere" is to "do something"
- Why model motion and action separately?
  - robot's mobility: depend on the workspace structure
  - robot's capable actions: relatively fixed

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Model of Mobility and Action

- Mobility abstraction is given by (similarly as $\mathcal{T}_c$):

$$\mathcal{M} = (\Pi_{\mathcal{M}}, act_{\mathcal{M}}, \longrightarrow_{\mathcal{M}}, \Pi_{\mathcal{M},0}, \Psi_{\mathcal{M}}, L_{\mathcal{M}}, W_{\mathcal{M}}),$$

- Capable action set $Act_{\mathcal{B}} = \{act_{\mathcal{B},0}, act_{\mathcal{B},1}, \cdots, act_{\mathcal{B},K}\}$
- Precondition function:

$$\texttt{Cond} : Act_{\mathcal{B}} \times 2^{\Psi_p} \times 2^{\Psi_s} \longrightarrow \mathsf{True/False}$$

- Effect function:

$$\texttt{Eff} : Act_{\mathcal{B}} \times (2^{\Psi_s} \times \Psi_b) \longrightarrow (2^{\Psi_s} \times \Psi_b),$$

- Mimic action description language (ADL)

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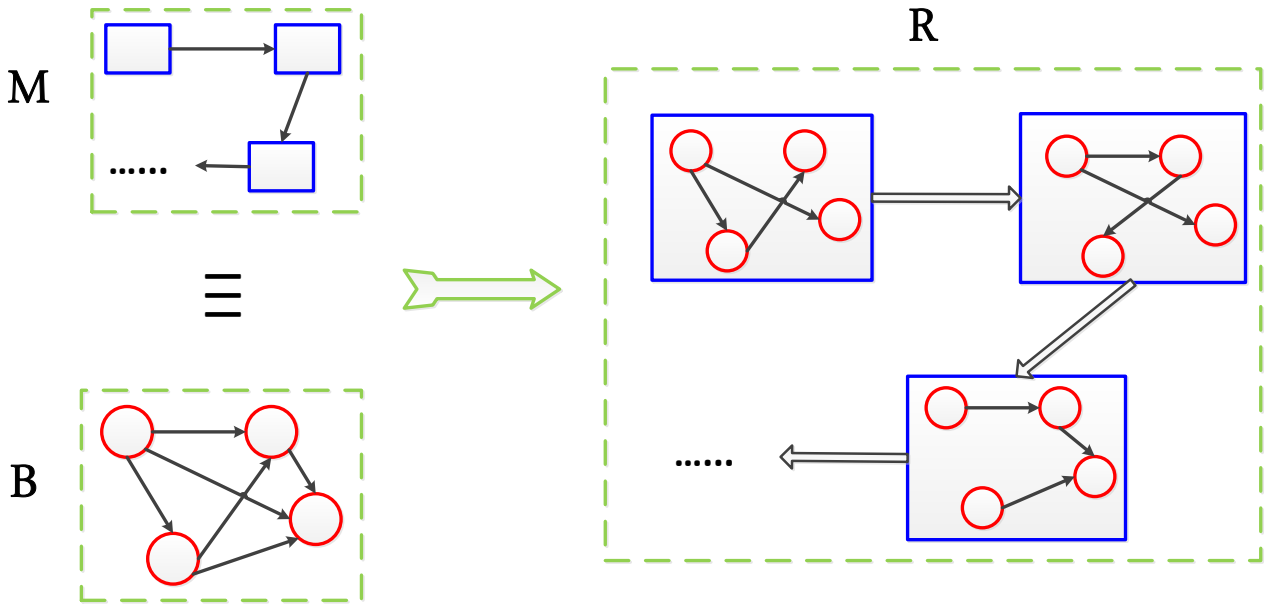
Model of Complete Functionalities



- Complete functionalities by composing $\mathcal{M}$ and $\mathcal{B}$

$$\mathcal{R} = (\Pi_{\mathcal{R}}, Act_{\mathcal{R}}, \longrightarrow_{\mathcal{R}}, \Pi_{\mathcal{R},0}, \Psi_{\mathcal{R}}, L_{\mathcal{R}}, W_{\mathcal{R}}),$$

- Automated algorithm

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Results

- Much richer task specifications
- Given φ over robot motion, action and internal states
- Accepting run with prefix-suffix structure with similar definition for cost

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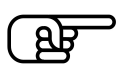

$r1\, c1\, c2\, c3\, r3$ PickG
$c3\, c2\, r2$ Drop $c2\, r5$ PickR
$c2\, r2$ Drop $c2\, c1 (r1)^{\omega}$

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Potentially Infeasible Task

- Def. 2.6: φ is infeasible for $\mathcal{T}_c$ if no accepting run of $\mathcal{A}_p$ can be found.
- Closely related to partially-known workspace
- Example:
  - "go to the kitchen, find an apple and bring it to me"
    $\Rightarrow$ infeasible if no apple
  - "keep an eye on the kids in the living room and bedroom"
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Solution

- Relaxed product automaton $\mathcal{A}_r = \mathcal{T}_c \times \mathcal{A}_\varphi$:

$$\mathcal{A}_r = (Q', 2^{AP}, \delta', Q'_0, \mathcal{F}', W_r)$$

where $Q' = \Pi \times Q$; $Q'_0 = \Pi_0 \times Q_0$; $\mathcal{F}' = \Pi \times \mathcal{F}$;

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  - $\delta' \subseteq Q' \times Q'$. $(\langle \pi_i, q_m \rangle, \langle \pi_j, q_n \rangle) \in \delta'$ iff $(\pi_i, \pi_j) \in \longrightarrow_c$ and $\exists\, l \in 2^{AP}$ such that $(q_m, l, q_n) \in \delta$.
  - $W_r : \delta' \to \mathbb{R}^+$ is the weight function:

$$\begin{aligned} &W_r(\langle \pi_i, q_m \rangle, \langle \pi_j, q_n \rangle) \\ &= W_c(\pi_i, \pi_j) + \alpha \cdot \texttt{Dist}(L(\pi_i), \chi(q_m, q_n)). \end{aligned}$$

- $\alpha \geq 0$: user-defined balance

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Balanced Cost

- Accepting run R with prefix-suffix structure:

$$\begin{aligned} R &= q'_0\, q'_1 \cdots [\, q'_f\, q'_{f+1} \cdots q'_n \,]^\omega \\ &= \langle \pi_0, q_0 \rangle \langle \pi_1, q_1 \rangle \cdots [\, \langle \pi_f, q_f \rangle \cdots \langle \pi_n, q_n \rangle \,]^\omega \ , \end{aligned}$$

- The balanced cost of an accepting run:

$$\begin{aligned} \texttt{Cost}(R, \mathcal{A}_r) &= \sum_{i=0}^{f-1} W_r(q'_i, q'_{i+1}) + \gamma \sum_{i=f}^{n-1} W_r(q'_i, q'_{i+1}) \\ &= \texttt{cost}_\tau + \alpha \cdot \texttt{dist}_\varphi \end{aligned}$$

- $\texttt{cost}_\tau$: implementation cost; $\texttt{dist}_\varphi$: distance to φ
- $\texttt{dist}_\varphi = 0 \Rightarrow R|_\Pi \models \varphi$

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Results

- The balanced accepting run

$$R_{\text{bal}} = \min_{R} \ \texttt{Cost}(R, \mathcal{A}_r)$$

- The balanced plan $\tau_{\text{bal}} = R_{\text{bal}}|_{\Pi}$

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Results

- The balanced accepting run

$$R_{\text{bal}} = \min_{R} \texttt{Cost}(R, \mathcal{A}_r)$$

- The balanced plan $\tau_{\text{bal}} = R_{\text{bal}}|_{\Pi}$
- Proposed algorithms:
  - synthesize R_{bal}, given γ and α
  - computes the associated $\texttt{cost}_\tau$ and $\texttt{dist}_\varphi$ for τ_{bal}
- Theorem 3.1: If φ is feasible over $\mathcal{T}_c$, the balanced plan τ_{bal} satisfies φ if $\alpha > \underline{\alpha}$.

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Feedback by Tuning α

- α: tunable balance between $\texttt{cost}_\tau$ and $\texttt{dist}_\varphi$
  - $\alpha \uparrow \quad \Rightarrow \quad \texttt{dist}_\varphi \downarrow \quad \Rightarrow \quad$ satisfy φ more
  - $\alpha \downarrow \quad \Rightarrow \quad \texttt{cost}_\tau \downarrow \quad \Rightarrow \quad$ cheaper

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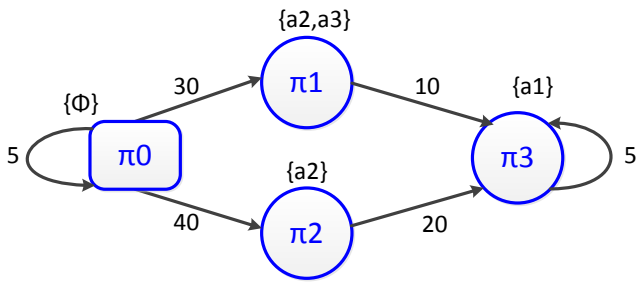
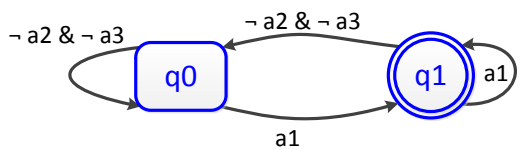
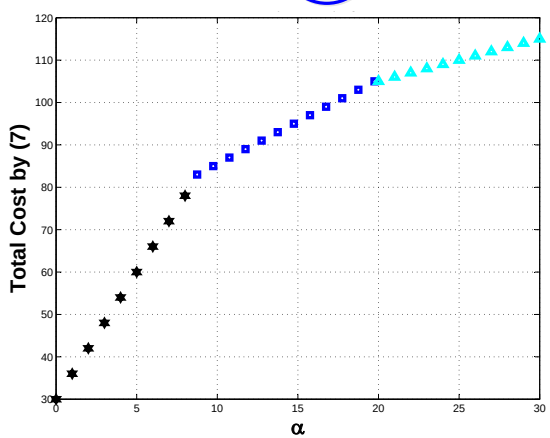
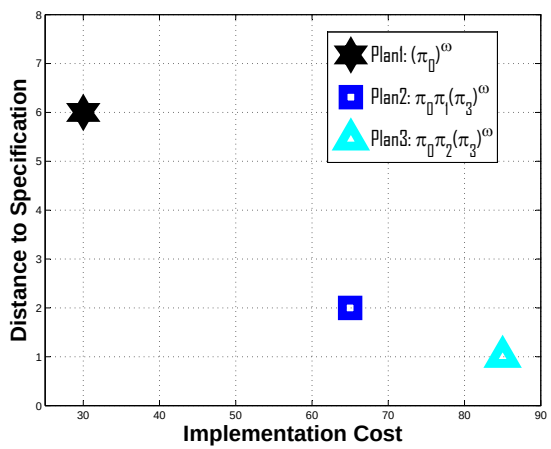
- Example: $\varphi = \Box\Diamond a_1 \wedge \Box\neg(a_2 \wedge a_3)$









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Soft and Hard Specification

- Specification with two distinctive parts:

$$\varphi = \varphi^{\text{hard}} \wedge \varphi^{\text{soft}}$$

- φ^{hard}, for safety or security
  - "do not go to the balcony", "always alarm if see fire"
- φ^{soft}, for additional achievement (maybe infeasible)
  - "collect the toys in all rooms"

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  - synthesize the plan satisfies φ^{hard} completely and φ^{soft} partially
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Solution

- Relaxed intersection of $\mathcal{A}^{\text{soft}}$ and $\mathcal{A}^{\text{hard}}$ as $\tilde{\mathcal{A}}_\varphi$, by Alg. 9

$$\tilde{\mathcal{A}}_\varphi = (Q,\, 2^{AP},\, \delta,\, Q_0,\, \mathcal{F})$$

- Safety-ensured and relaxed product automaton

$$\tilde{\mathcal{A}}_r = \mathcal{T}_c \times \tilde{\mathcal{A}}_\varphi = (Q',\, \delta',\, Q'_0,\, \mathcal{F}',\, W_r)$$

where $Q' = \Pi \times Q$, $Q'_0 = \Pi_0 \times Q_0$, $\mathcal{F}' = \Pi \times \mathcal{F}$

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$$\begin{aligned} &W_r(\langle \pi_i,\, q_m \rangle,\, \langle \pi_j,\, q_n \rangle) \\ =&W_c(\pi_i,\, \pi_j) + \alpha \cdot \texttt{Dist}(L_c(\pi_i),\, \chi_{\text{soft}}(q_2,\, \check{q}_2)) \end{aligned}$$

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Results

- Theorem 3.3: Assume R is an accepting run of $\tilde{\mathcal{A}}_r$.
  $\tau = R|_\Pi$ is safe for $\mathcal{T}_c$ and φ.
- Balanced cost of accepting runs:

$$\texttt{Cost}(R, \tilde{\mathcal{A}}_r) = \texttt{cost}_\tau + \alpha \cdot \texttt{dist}_{\varphi^{\text{soft}}}$$

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- The safe accepting run

$$R_{\text{safe}} = \min_R \ \texttt{Cost}(R, \tilde{\mathcal{A}}_r)$$

- The safe plan $\tau_{\text{safe}} = R_{\text{safe}}|_\Pi$
- Similar algorithms to synthesize R_{safe}
- Lemma 3.2: $\texttt{dist}_{\varphi^{\text{soft}}} = 0 \Rightarrow \tau_{\text{safe}} \models \varphi$

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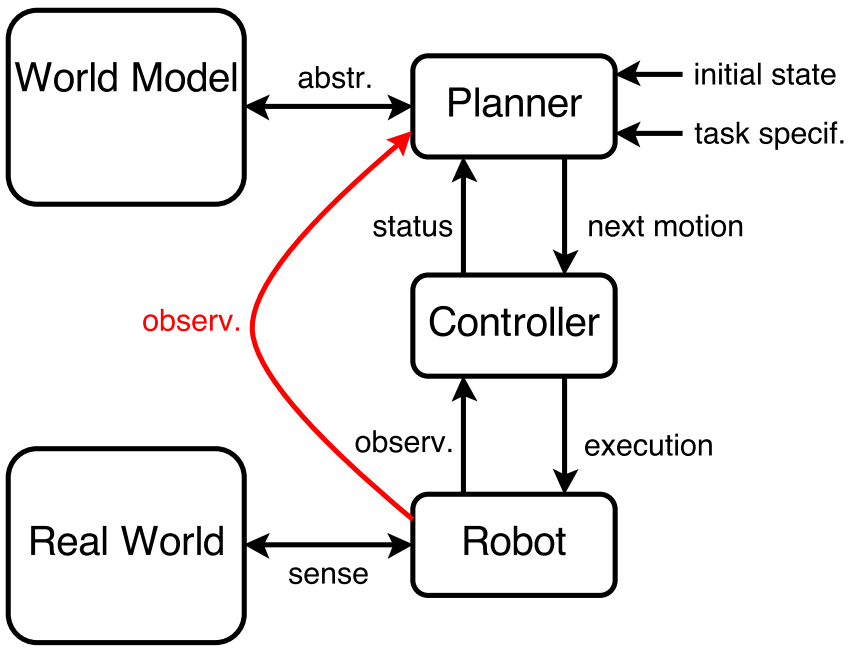
On-line Planning

Why put planner on-line?

- To handle partially-known workspace
- Plan may not be executed as expected
- Plan could be improved
- Feed real-time observation back to planner



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Problem Formulation

- The agent's FTS at time $t \geq 0$:

$$\mathcal{T}_c^t = (\Pi, \longrightarrow_c^t, \Pi_0, AP, L_c^t, W_c^t)$$

- Task specification

$$\varphi = \varphi^{\text{soft}} \wedge \varphi^{\text{hard}}$$

- Our goal:
  - model the robot's sensing
  - update the system model
  - guarantee the plan is always valid and safe

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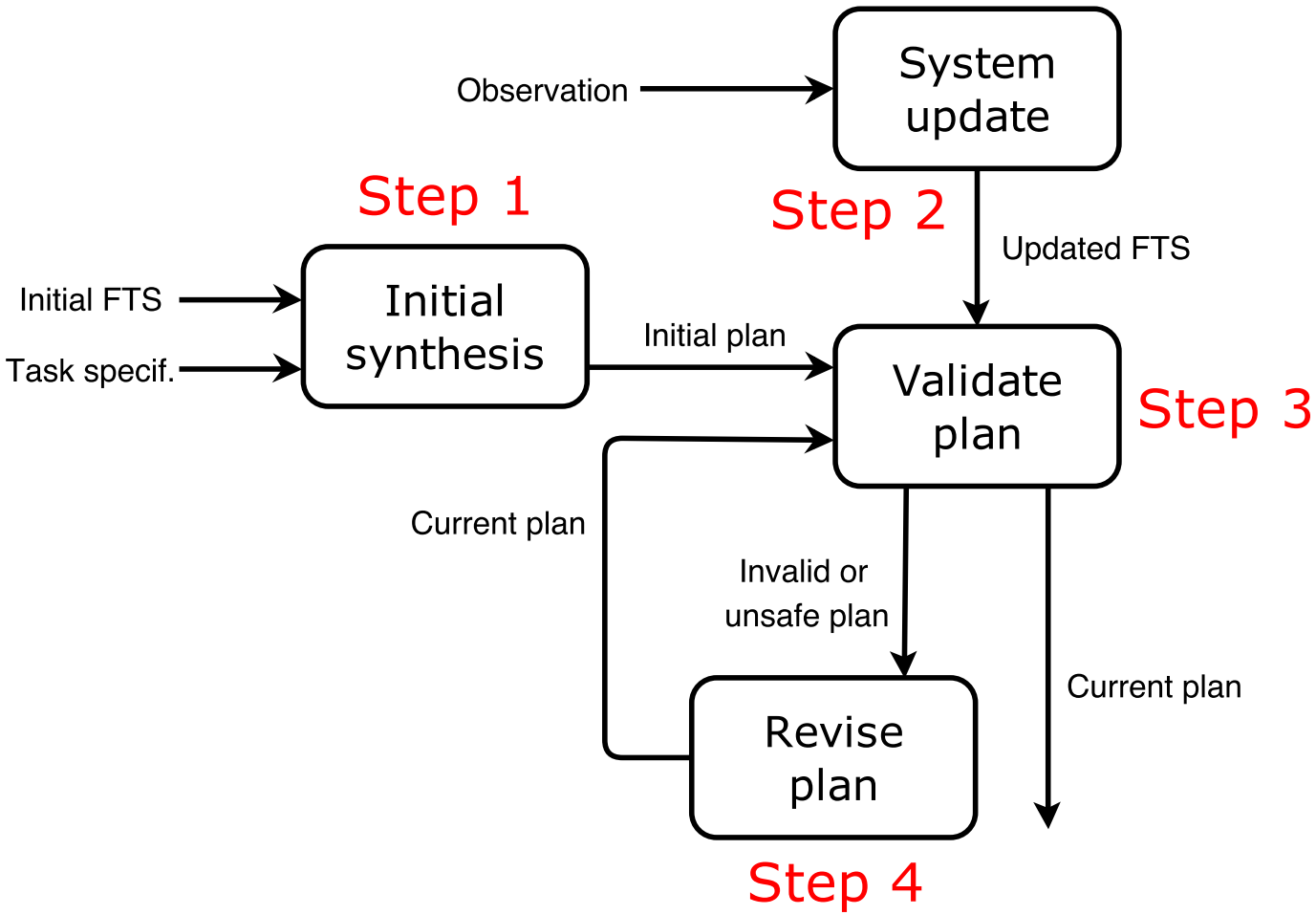
Solution Framework



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Initial Synthesis and System Update

- Step 1. initial synthesis at $t = 0$
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- Step 2. update $\mathcal{T}_c^t$ based on $\mathbf{Sense}^t$

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Plan Verification and Revision

- Step 3. validate the current plan
  - validity $\Longleftrightarrow$ invalid transitions
  - safety $\Longleftrightarrow$ unsafe transitions

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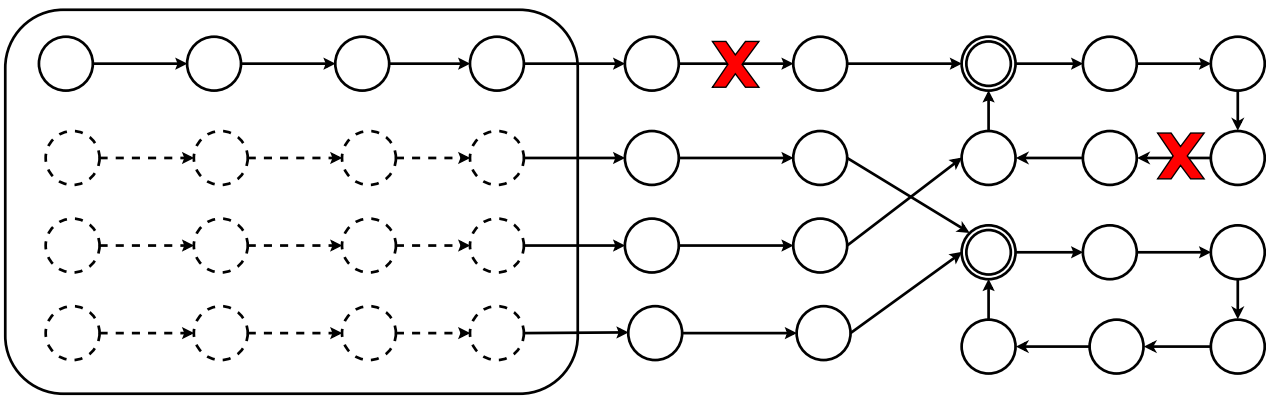

Plan Verification and Revision

- Step 3. validate the current plan
  - validity $\Longleftrightarrow$ invalid transitions
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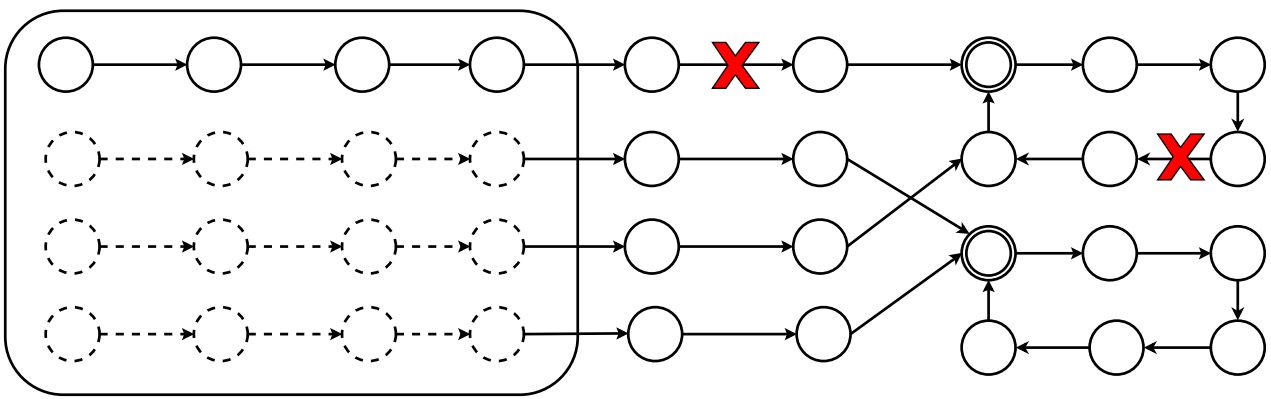
- Step 4. local revision, instead of full synthesis
- Low complexity, suitable for real-time applications
- Theorem. 3.5: validity and safety of the revised plan guaranteed



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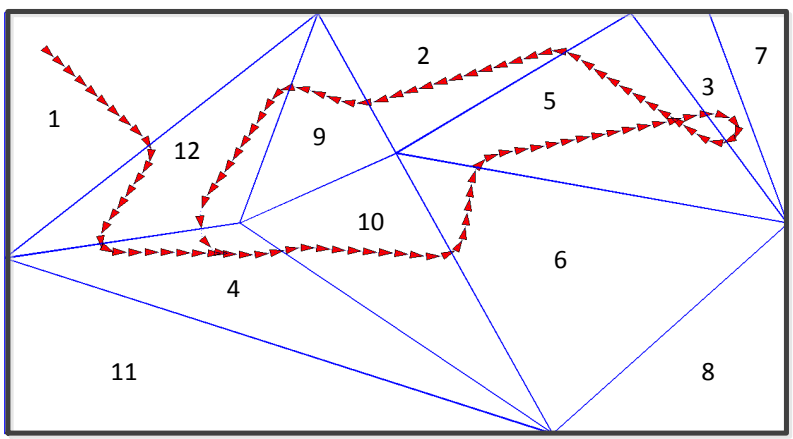
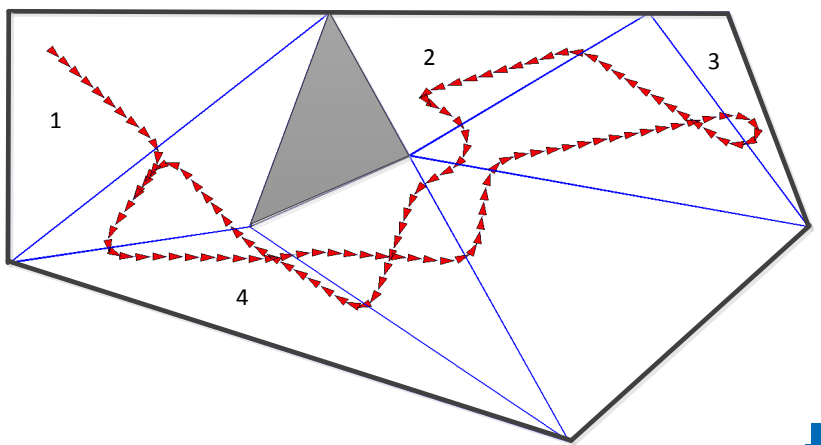
Simulation Example

- Nonholonomic ground vehicle
- Potential filed-based navigation controller[9]
- Surveillance over regions 2, 3, 4
- Detect walls and obstacles in real-time





[9] S. R. Lindemann, I. I. Hussein, S. M. LaValle. Real time feedback control for nonholonomic mobile robots with obstacles. CDC, 2006

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Dependent Local Tasks

- System of N agents, $i = 1, \cdots, N$:

$$\mathcal{T}_i = (\Pi_i, \longrightarrow_i, \Pi_{i,0}, AP_i, L_i, W_i)$$

- Locally-assigned LTL specification by φ_i
- φ_i may contain requirements on other agents $j \neq i$
  - constraints, e.g., "do not be in the same room with agent 1"
  - collaborations, e.g., "move the desk together with agent 1"

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  - collaborations, e.g., "move the desk together with agent 1"
- Difficulties:
  - the joined execution may not be mutually feasible even though the individual one is.
  - the priority of each agent plays an important role.

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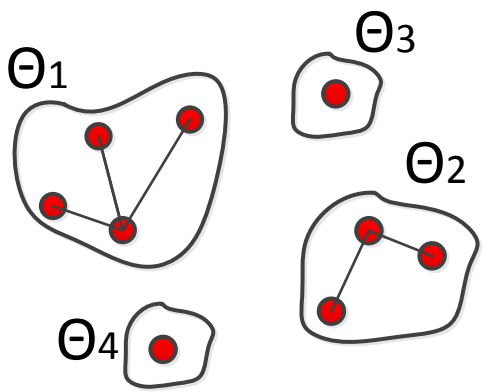
Dependency Cluster

- Dependency: Agents i and j are called dependent if:



(1) agent i depends on agent j if $AP_{\varphi_i} \wedge AP_j \neq \emptyset$, or

(2) agent j depends on agent i if $AP_{\varphi_j} \wedge AP_i \neq \emptyset$.

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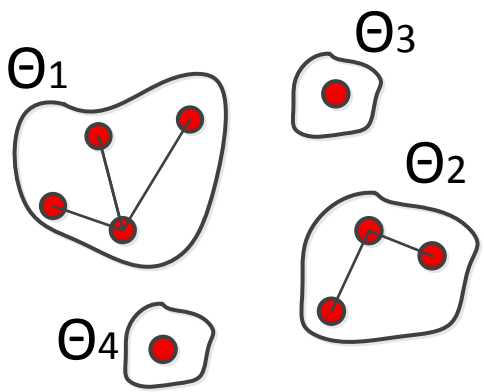

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- Dependency graph: $G_d = (V, E)$, $V = 1, 2 \cdots, N$ and $E \subseteq V \times V$ is the dependency relation
- Dependency cluster: $\Theta \subseteq V$, $\forall i, j \in \Theta$ there is a path from i to j in G_d.

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Mutual Infeasible

Within one cluster $\Theta = \{1, 2, \cdots, M\}$

- The composed FTS $\mathcal{T}_\Theta = \mathcal{T}_1 \times \cdots \mathcal{T}_M$ is:

$$\mathcal{T}_\Theta = (\Pi_\Theta, \longrightarrow_\Theta, \Pi_{\Theta,0}, AP_\Theta, L_\Theta, W_\Theta)$$

- The mutual specification is

$$\varphi_\Theta = \varphi_1 \wedge \varphi_2 \cdots \wedge \varphi_M$$

- Mutually infeasible if φ_Θ is infeasible over $\mathcal{T}_\Theta$.

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Within one cluster $\Theta = \{1, 2, \cdots, M\}$

- The composed FTS $\mathcal{T}_\Theta = \mathcal{T}_1 \times \cdots \mathcal{T}_M$ is:

$$\mathcal{T}_\Theta = (\Pi_\Theta, \longrightarrow_\Theta, \Pi_{\Theta,0}, AP_\Theta, L_\Theta, W_\Theta)$$

- The mutual specification is

$$\varphi_\Theta = \varphi_1 \wedge \varphi_2 \cdots \wedge \varphi_M$$

- Mutually infeasible if φ_Θ is infeasible over $\mathcal{T}_\Theta$.
- The relaxed intersection of $\mathcal{A}_{\varphi_i}$ of $\{\varphi_i, i \in \Theta\}$:

$$\tilde{\mathcal{A}}_{\varphi_\Theta} = (Q, 2^{AP_{\varphi_\Theta}}, \delta, Q_0, \mathcal{F}),$$

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Solution

- The relaxed product automaton

$$\mathcal{A}_{r,\Theta} = \mathcal{T}_\Theta \times \tilde{\mathcal{A}}_{\varphi_\Theta} = (Q', \delta', Q'_0, \mathcal{F}', W_r)$$

where $Q' = \Pi_\Theta \times Q$, $Q'_0 = \Pi_{\Theta,0} \times Q_0$, $\mathcal{F}' = \Pi_\Theta \times \mathcal{F}$

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Solution

- The relaxed product automaton

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where $Q' = \Pi_\Theta \times Q$, $Q'_0 = \Pi_{\Theta,0} \times Q_0$, $\mathcal{F}' = \Pi_\Theta \times \mathcal{F}$

- $\delta' \subseteq Q' \times Q'$. $(\langle \pi_\Theta, q_a \rangle, \langle \pi'_\Theta, q_b \rangle) \in \delta'$ iff $(\pi_\Theta, \pi'_\Theta) \in \longrightarrow_\Theta$ and $(q_a, q_b) \in \delta$.
- $W_r : \delta' \to \mathbb{R}^+$ is the weight function:

$$W_r(\langle \pi_\Theta, q_1, \cdots, q_M, t \rangle, \langle \pi'_\Theta, q'_1, \cdots, q'_M, t' \rangle)$$
$$= W_\Theta(\pi_\Theta, \pi'_\Theta) + \alpha \sum_{i=1}^{M} \beta_i \, \texttt{Dist}(L_\Theta(\pi_\Theta), \chi_i(q_i, q'_i))$$

- α: penalty on violating φ_Θ
- β_i: priority of agent i' task

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Results

- Synthesize the balanced accepting run of $\mathcal{A}_{r,\Theta}$
- Projection onto $\mathcal{T}_i$ as the individual plan, $i \in \Theta$

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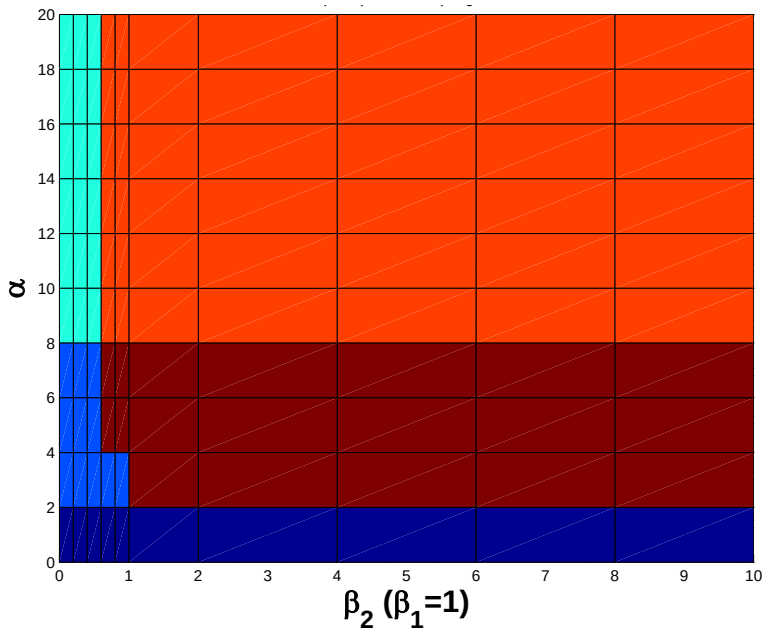
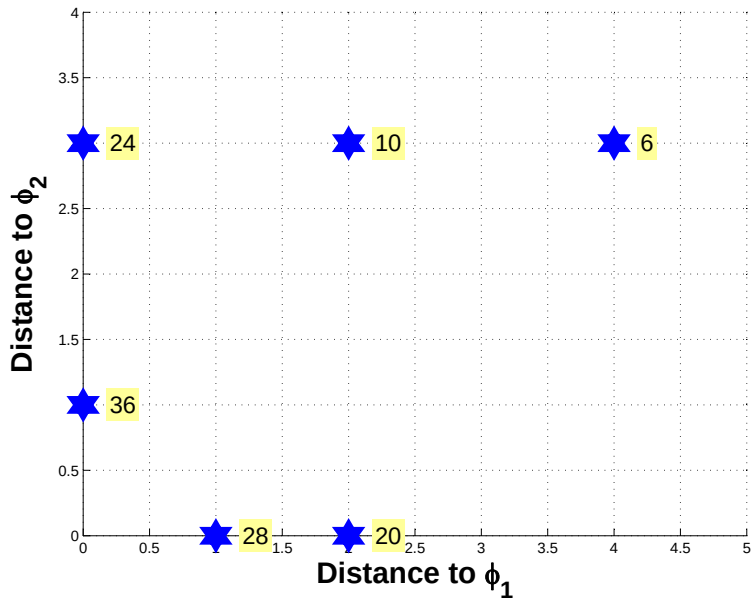
Results

- Synthesize the balanced accepting run of $\mathcal{A}_{r,\Theta}$
- Projection onto $\mathcal{T}_i$ as the individual plan, $i \in \Theta$
- Change α and β
- Example





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Independent Local Tasks

- System of N agents coexisting within a partially-known workspace:

$$\mathcal{T}_i^t = (\Pi_i, \longrightarrow_i^t, \Pi_{i,0}, AP_i, L_i^t, W_i^t)$$

- Locally-assigned task specification and independent

$$\varphi_i = \varphi_i^{\text{soft}} \wedge \varphi_i^{\text{hard}}$$

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- Locally-assigned task specification and independent

$$\varphi_i = \varphi_i^{\text{soft}} \wedge \varphi_i^{\text{hard}}$$

- Motivation:
  - agents located at various locations within the workspace
  - observe up-to-date information
  - beneficial to communicate

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Knowledge Update and Transfer

- Knowledge update by
  - own sensing ability $\mathbf{Sense}_k^t = \{(\pi, S, S_\neg),\ E,\ E_\neg\}$
  - communication with others

Knowledge Update and Transfer

- Knowledge update by
  - own sensing ability $\mathbf{Sense}_k^t = \{(\pi, S, S_\neg),\ E,\ E_\neg\}$
  - communication with others
- Communication network: $\mathcal{N}_k \in \mathcal{N}$ (static or dynamic)
- Transfer knowledge:
  - request once: $\mathbf{Request}_{k,g}^t = (k,\ \varphi_k|_{AP_k})$
  - event-based reply: $\mathbf{Reply}_{h,k}^t = (\pi,\ S',\ S'_\neg)$, where $S' = S \cap (\varphi_h|_{AP_h})$ and $S'_\neg = S_\neg \cap (\varphi_h|_{AP_h})$.
- Update $\mathcal{T}_k^t$ based on $\mathbf{Sense}_k^t$ and $\mathbf{Reply}_{g,k}^t$
- Validate and revise the current plan

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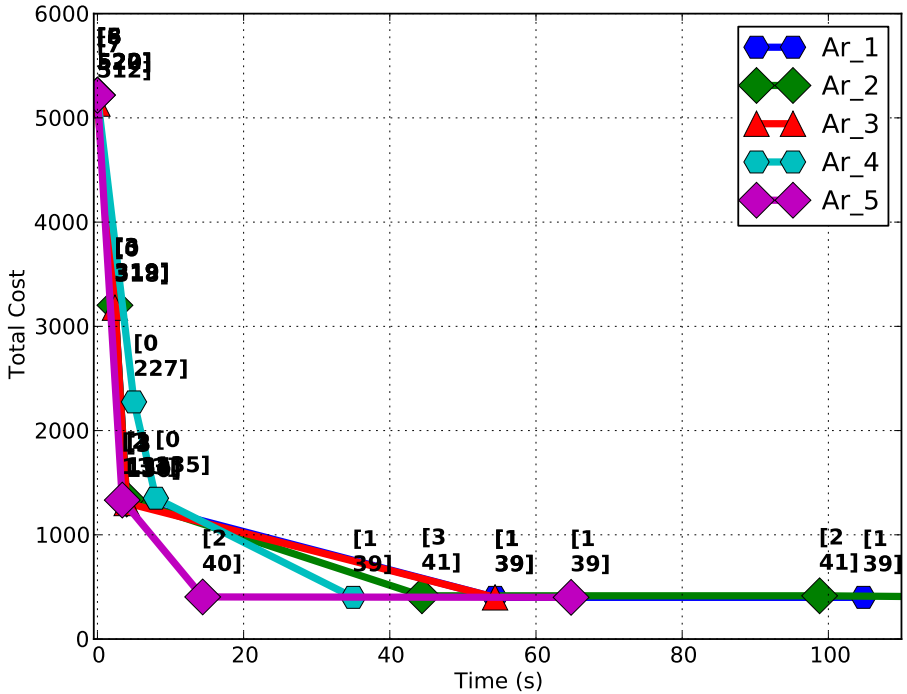
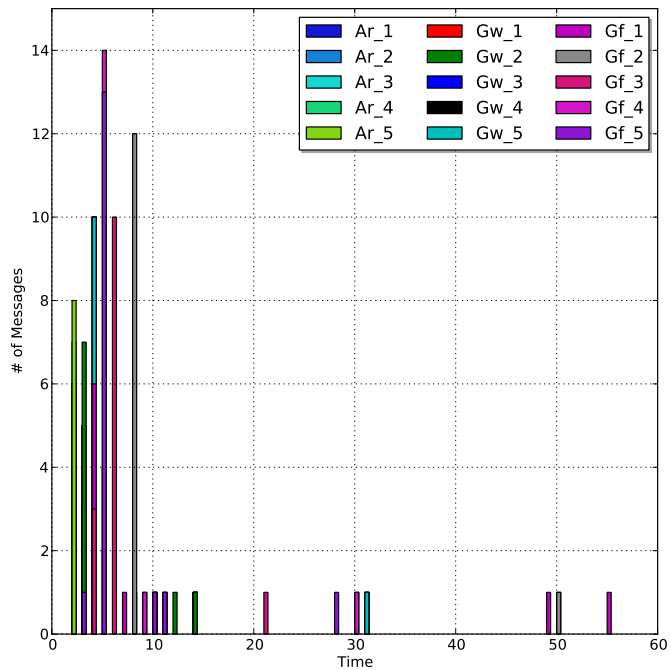
Results

- Full synthesis or local revision
- Event-based trigger to re-synthesize the plan





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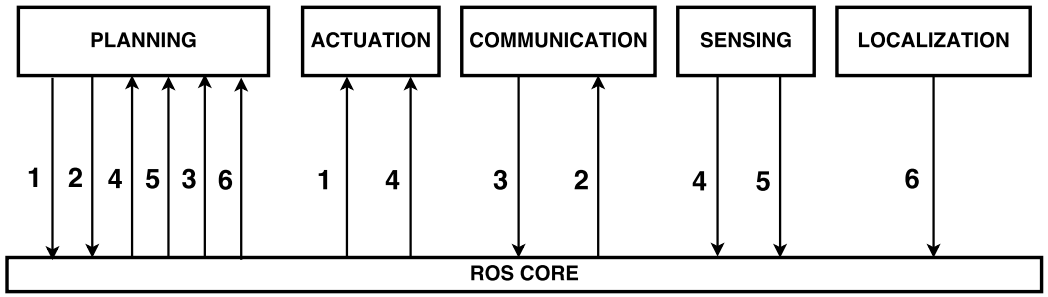
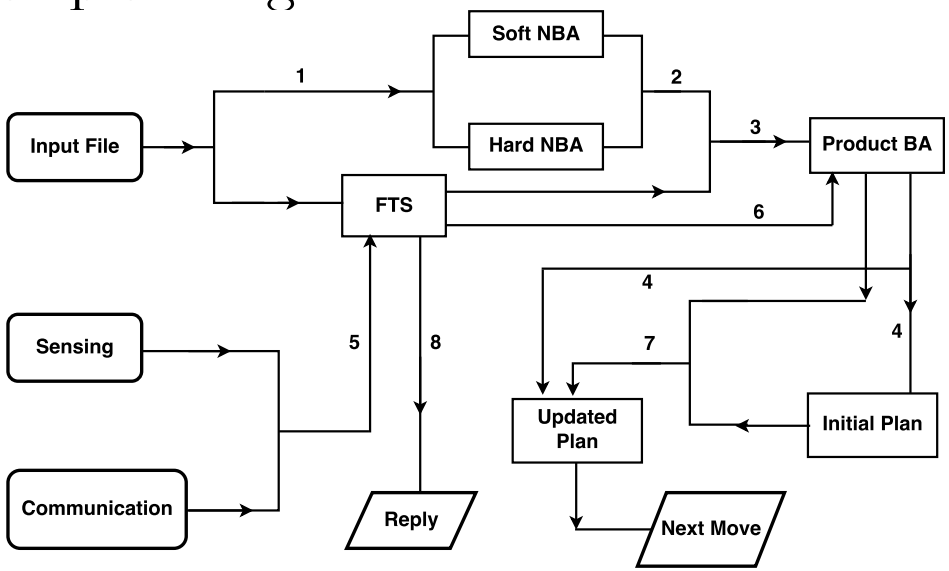
Software Implementation

- Robot operating system(ROS)-based
- ROS core + ROS nodes



- ROS node for planning



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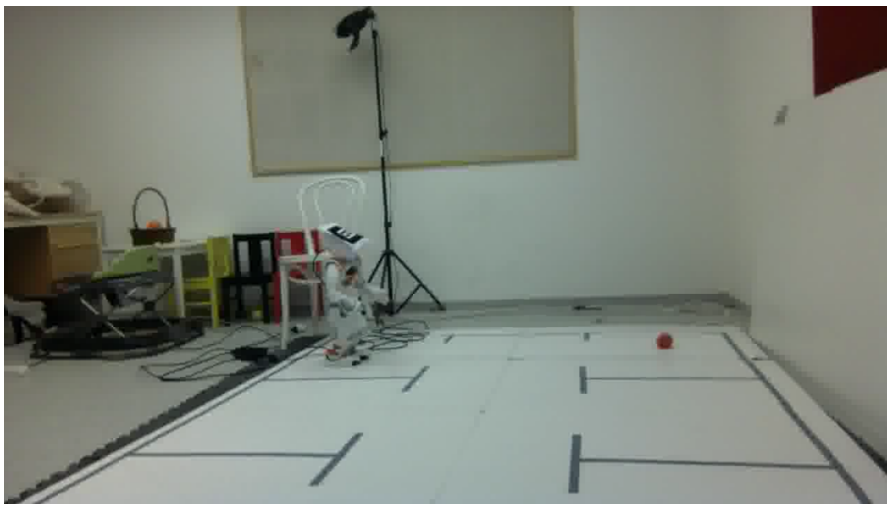
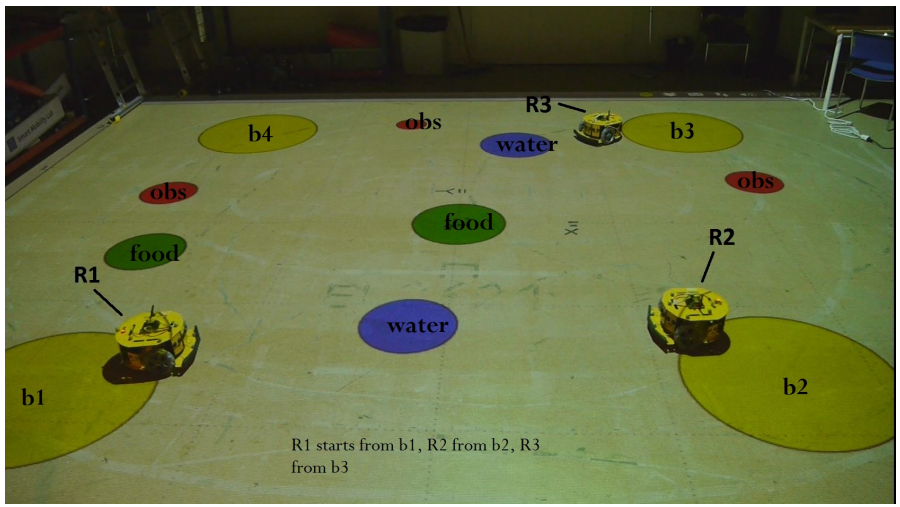
Experiments

- NAO humanoid
- MAS Lab @CVAP



- NEXUS ground vehicle
- Smart Mobility Lab @ACL



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Summary

- Motion and task planning
  - Discrete motion and task plan with minimal cost
  - Hybrid control strategy

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- Motion and task planning
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  - Hybrid control strategy
- Reconfiguration and real-time adaptation
  - Potentially infeasible task
  - Soft and hard specifications
  - Partially-known workspace
  - Motion and action planning

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Summary

- Motion and task planning
  - Discrete motion and task plan with minimal cost
  - Hybrid control strategy
- Reconfiguration and real-time adaptation
  - Potentially infeasible task
  - Soft and hard specifications
  - Partially-known workspace
  - Motion and action planning
- Multi-agent systems with local tasks
  - Dependent tasks
  - Independent tasks
  - Software implementation

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Future Work

- Automated abstraction
- Natural language to LTL, graphic interface
- Trade-off between computational complexity and optimality
- Robustness and fault tolerance (both motion and action)
- Continuous constraints, coupled dynamics

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Thank you!

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