ROBOTICS SCIENCE AND SYSTEMS 2021

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Formal methods for robot planning

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Why formal methods?

Rigorous techniques for

specification → How do we tell robots what to do?

development, verification, analysis of systems → How do we ensure that they behave as expected?

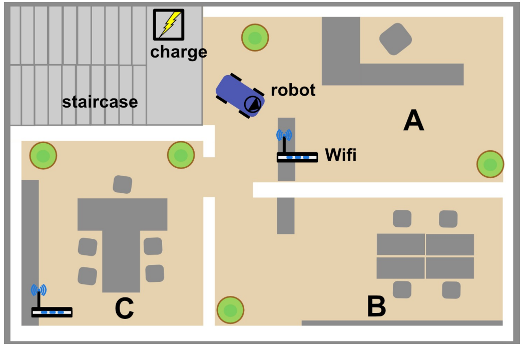
Why temporal logics and formal synthesis?

Temporal logics → How do we tell robots what to do?

- rich
- rigorous
- resemblance to natural language

Formal synthesis → How do we ensure that they behave as expected?

Temporal logic for mission and motion objectives



- Keep patrolling the three offices.

$$GF(A) \wedge GF(B) \wedge GF(C)$$

- Whenever you spot danger, go directly to the staircase and wait for “all clear” signal before continuing.

$$G(danger \Rightarrow X(staircase\ U\ all\_clear))$$

- Make sure to recharge at least every 10 minutes.

$$GF_{[0,10]}recharge$$

- At all times, stay within 5 meters from the wi-fi router.

$$G(Dist(robot, router) \leq 5)$$

Why temporal logics and formal synthesis?

Temporal logics
- rich
- rigorous
- resemblance to natural language

→ How do we tell robots what to do?

Formal synthesis
- correct-by-design plan

→ How do we ensure that they behave as expected?

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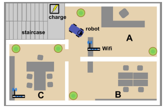
Formal synthesis

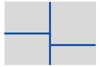
System



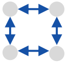
Objective

Patrol offices A and B.

Model $\dot{p}(t) = u(t)$



Abstraction



$GF(A) \wedge GF(B)$ Temporal logic specification

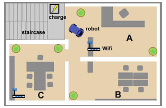
Formal synthesis

A correct-by-design plan

There is no correct-by-design plan

Formal synthesis (2009)

System



Objective

Patrol offices A and B.

Model

Abstraction

DTS, NTS, Petri nets

Temporal logic specification

LTL, GR(1)

Formal synthesis

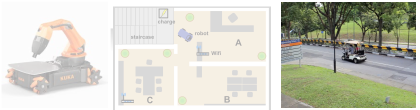
A correct-by-design plan

There is no correct-by-design plan

Some seminal works:
[Kress-Gazit et al, TRO 2009, Kloetzer and Belta, TAC 2008]

Formal synthesis (2013)

System



multi-agent,
partially unknown and
dynamic environments,…

Objective

temporal goals,
additional optimization criteria, deadlines

Model

Non-linear, with disturbance,…

Abstraction

DTS, NTS, Petri nets, roadmaps, trees, WTS, MDPs,…

User-friendly interface

Linguistic, graphical

Temporal logic specification

LTL, GR(1), sc-LTL, PCTL, MTL,…

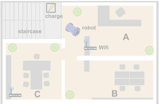
Formal synthesis

A correct-by-design plan

There is no correct-by-design plan

Formal synthesis (today)

System


multi-agent,
partially unknown and
dynamic environments,…

Model

Non-linear, with disturbance,…

Abstraction

DTS, NTS, Petri nets, roadmaps, trees, WTS, MDPs,…

Objective

temporal goals,
additional optimization criteria, deadlines
spatio-temporal goals and constraints,…

User-friendly interface

Linguistic, graphical

Temporal logic specification

LTL, GR(1), sc-LTL, PCTL, MTL, STL,…

Formal synthesis

A correct-by-design plan

There is no correct-by-design plan

Formal synthesis, integrated

4Robots

Multi-robot coordination
for dynamic production assistance

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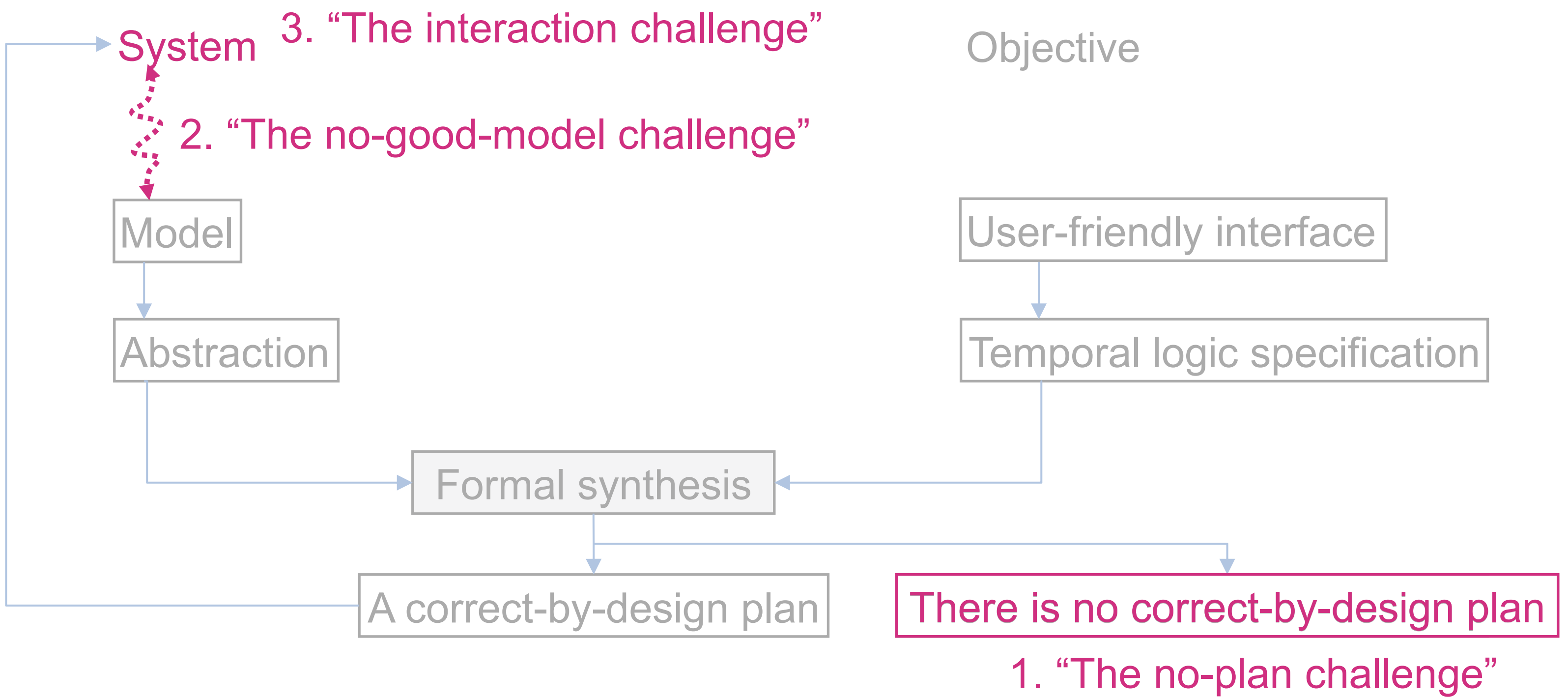
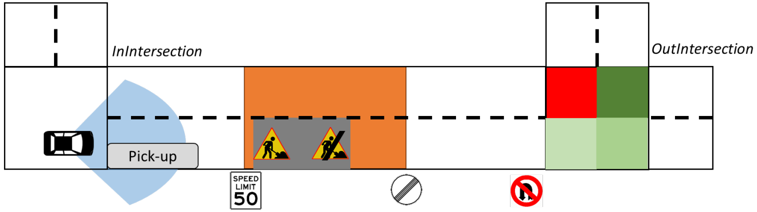
www.co4robots.eu

Three challenges of formal synthesis



1. The no-plan challenge

System



Objective

Obey the traffic rules:

- Do not cross the full lane
- Stay in the right lane
- Do not enter the construction zone
- Do not enter sidewalk

…

Model, abstraction

Temporal logic specification

LTL over finite traces

Formal synthesis

A correct-by-design plan

There is no correct-by-design plan

All the traffic rules cannot be obeyed simultaneously

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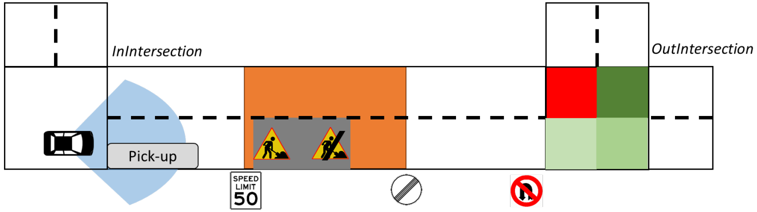
1. The no-plan challenge

System



Model, abstraction

Objective

Obey the traffic rules:

- Do not cross the full lane
- Stay in the right lane
- Do not enter the construction zone
- Do not enter sidewalk

…

Temporal logic specification

LTL over finite traces

Formal synthesis

A plan as correct as possible

The traffic rules are violated only for the absolutely necessary, for the necessary time

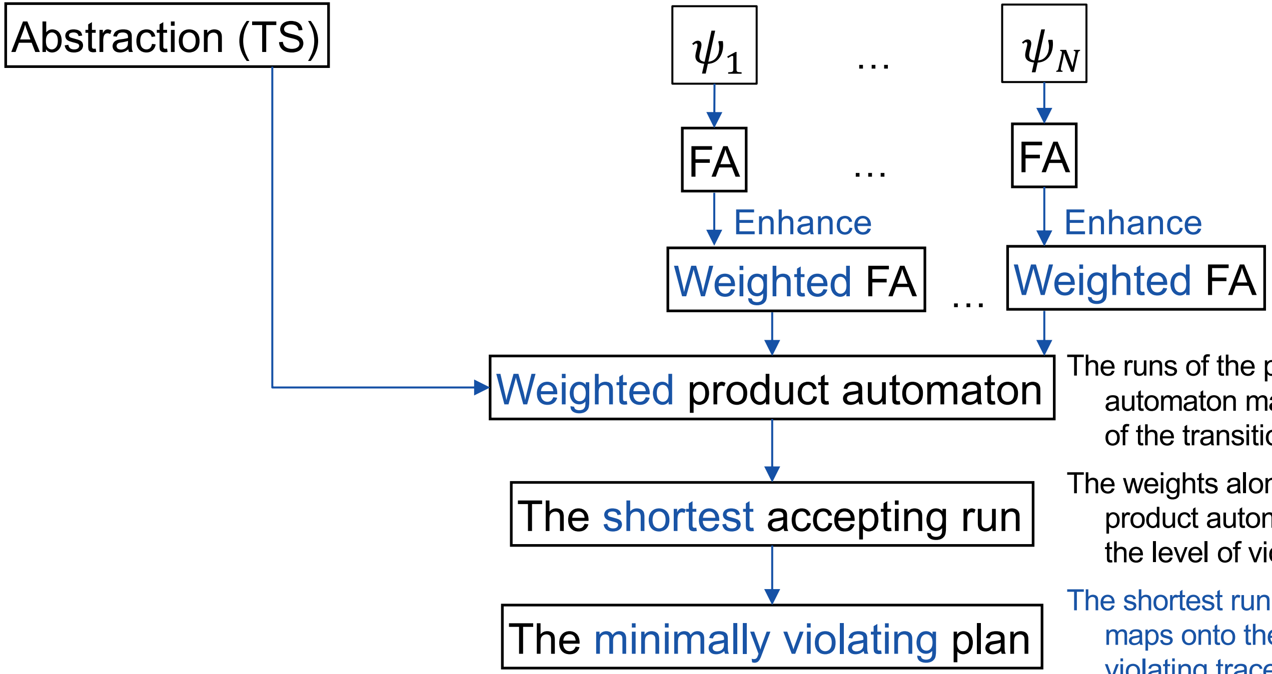
Quantitative evaluation of LTL

Assume a transition system from RRT* or other abstraction

Level of violation $\lambda(trace, LTL\ formula)$**:** the time duration associated with the discrete transitions that need to be removed to make the trace satisfy the LTL formula, weighted by the penalty

[Tumova et al HSCC 2013]

Minimum-violation automata-based FS



- The runs of the product automaton map to the traces of the transition system
- The weights along the run of the product automaton determine the level of violation
- The shortest run of the product maps onto the minimally violating trace of the model

[Tumova et al HSCC 2013]

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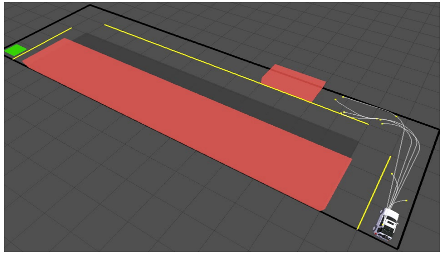
MV-RRT*

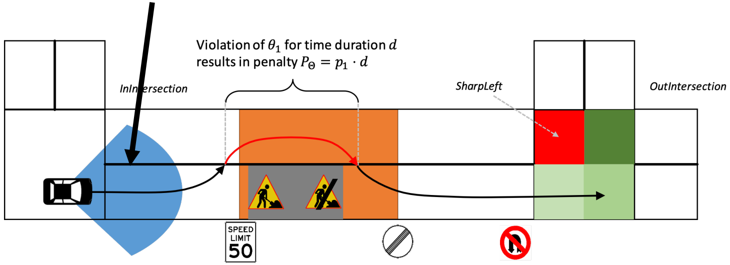
	RRT*	MV-RRT*
• Incrementally build	weighted tree	weighted product automaton
• Incrementally update	shortest path	minimally violating path
• Optimality criterion	distance	primarily level of violation, then distance



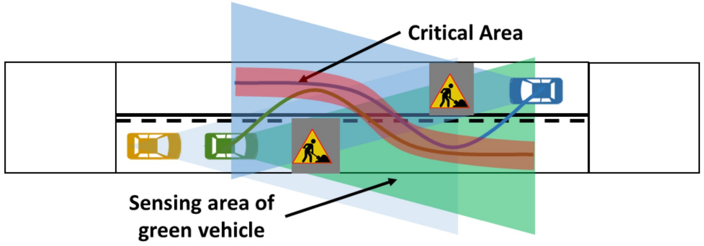
[Reyes-Castro et al CDC 2013]

MV-RRT* in autonomous driving

Limited sensing:



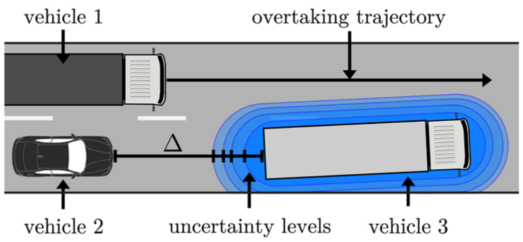
Multi-vehicle settings:



[Reyes-Castro et al HSCC 2013, Vasile et al ICRA 2017, Karlsson et al ICRA 2018, CASE 2020, ICRA 2021]

The no plan challenge under uncertainty

System



Model, abstraction

Objective

Common sense/RSS:

- Keep a safe distance $\Delta(v_e, v_l)$
- …

Temporal logic specification

STL

$G(\Delta(v_e, v_l) - (p_l - p_e) > 0)$

Formal synthesis

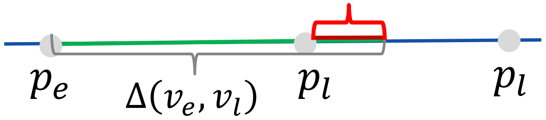
A plan as correct as possible

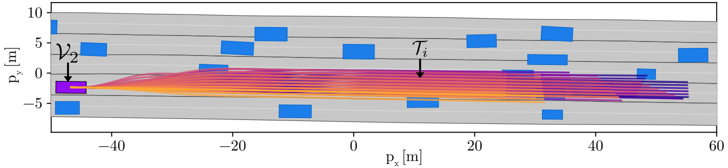
The severity of violation, the probability of violation, and the level of uncertainty are taken into account

Risk-aware planning in autonomous driving

- Safety specification: $G\big(h(x(t)) > 0\big)$
- Severity function: $\ell_h(x) = \begin{cases} \ell\big(h(x(t))\big), h(x(t)) > 0 \\ 0, \text{otherwise} \end{cases}$
- Severity of violation: $L = l_h(\hat{x})$
- Risk: $E[L]$
- Risk-aware planning

$G(\Delta(v_e, v_l) - (p_l - p_e) > 0)$





US101 highway scenario

[Nyberg et al IV 2021]

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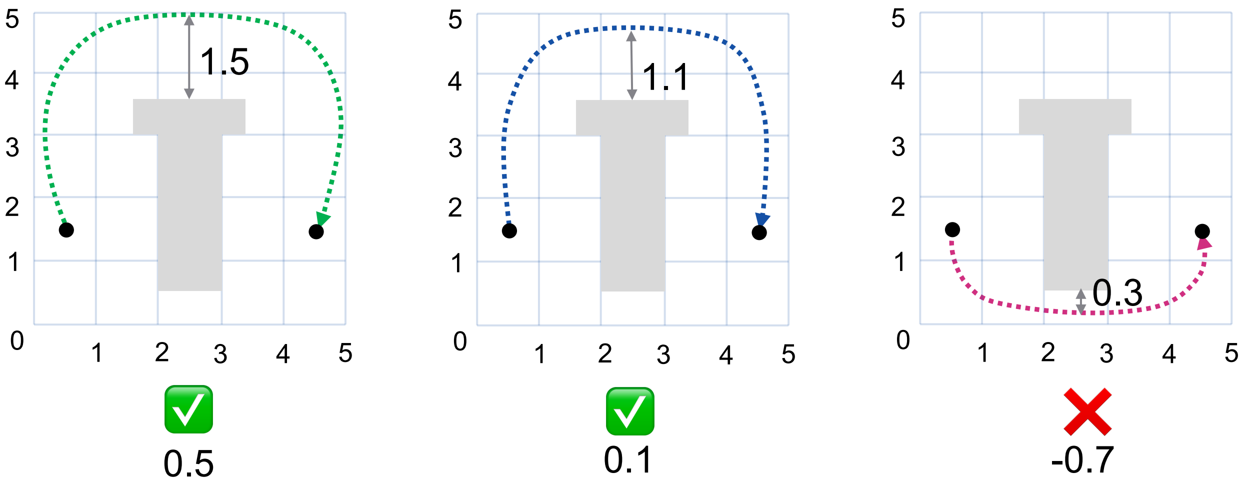
Signal Temporal Logic spatial robustness

$$G(1 - dist(\sigma, M) > 0)$$



See [Donze and Maler, LNCS, 2013]

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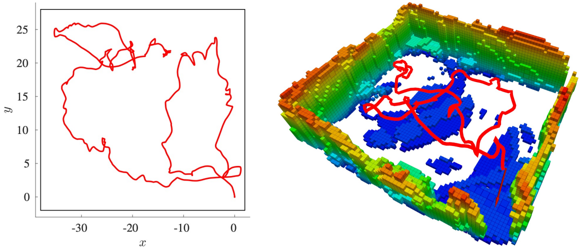
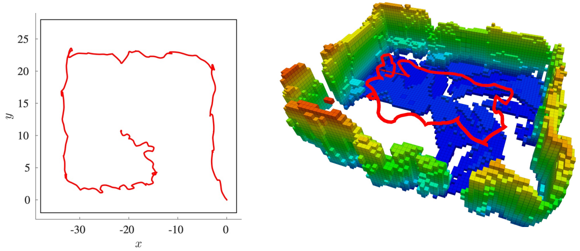
STL as a preference specification

STL-guided autonomous exploration

AEP



AEP + STL $G(dist(\sigma, M) - 1 > 0)$



Guiding Autonomous Exploration with Signal Temporal Logic

Fernando S. Barbosa, Daniel Duberg, Patric Jensfelt and Jana Tumova

[Barbosa et al RA-L 2019]

2. The no-good-model challenge

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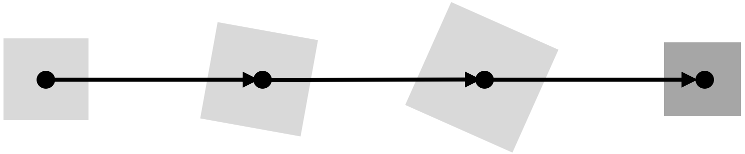
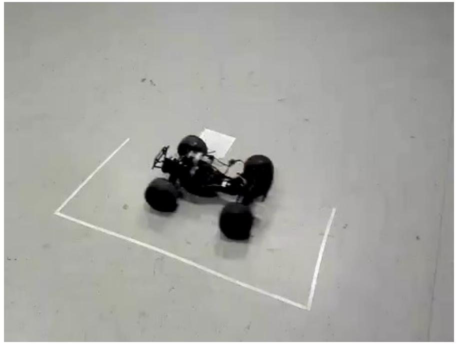
Safe multi-step feedback motion primitives

for non-holonomic system with bounded disturbance

- Divide the input space into regions & linearize
- Linearization introduces error





- The error can be corrected in *k* steps
- The motion primitives can be chained and refined

[Tajvar et al ISSR 2019, CASE 2020, IROS 2021]

LTL planning with motion primitives

System

Objective

LTL specification

BA

Motion primitives

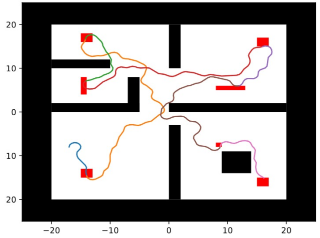
Backward reachability tree

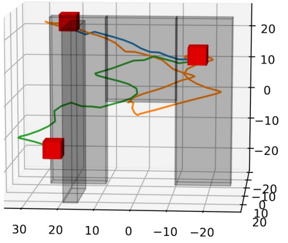
heuristics

Modified A*

refine

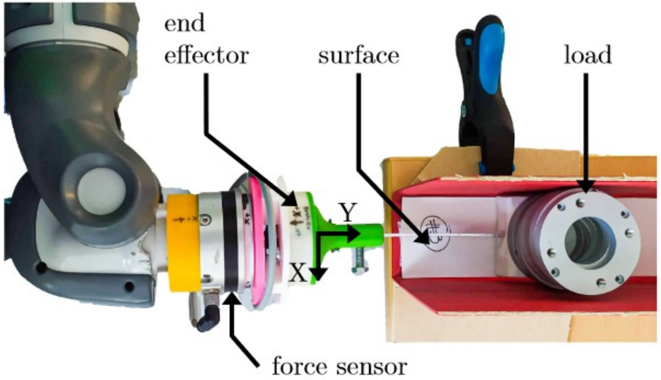
A correct-by-design plan

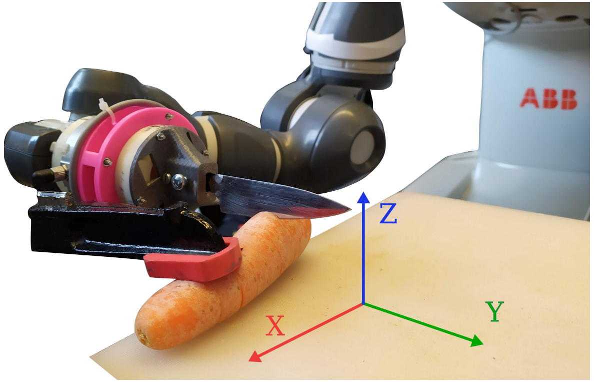




[Tajvar et al CASE 2020]

Towards safe data-driven contact-rich manipulation





[Mitsioni et al Humanoids 2021]

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The social interaction challenge

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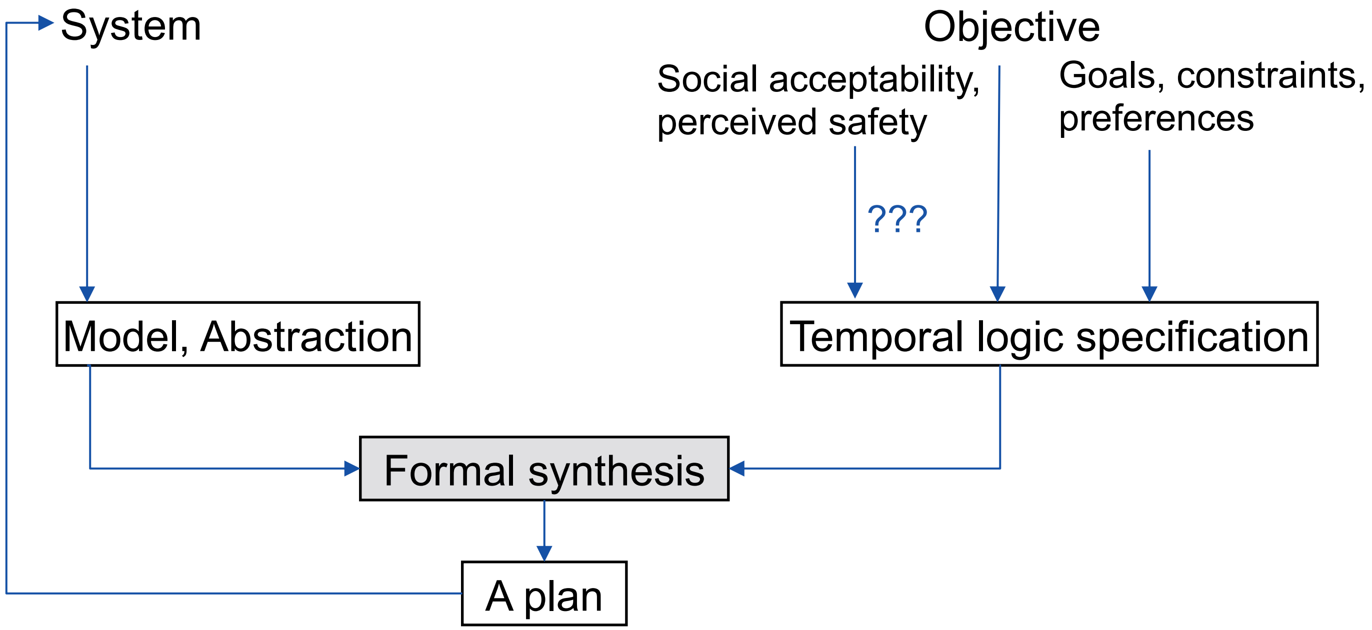
Correct-by-design and socially acceptable plan



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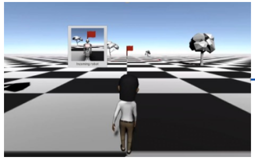
Correct-by-design and socially acceptable plan

System

Interactions



inference

Objective

Social acceptability, perceived safety

Goals, constraints, preferences

STL with probabilistic predicates

Model, Abstraction

Temporal logic specification

Formal synthesis

A plan

Linard et al CASE 2020, IROS 2021

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I wish I had time to talk also about

- Provable safety vs. perceived safety
- Assumption-guarantee synthesis

- Decentralized multi-agent coordination with temporal logic specifications

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Take-aways

- Temporal logics and formal synthesis to address
  - How do we tell robots what to do?
  - How do we ensure that they behave as expected?
- Rigorous, **but not rigid**:
  - Can be used to provide guarantees if that is desired and possible
  - No need to freeze if a correct-by-design plan does not exist
  - Support for preferences, not just mission/safety-critical goals

The future: Moving forward to the wild

- Well-defined mathematical objectives → "Soft" objectives
- Guarantees → Risk-awareness
- Manually created models and specifications → Data-driven models and specifications
- FS or learning → FS and learning

  RL with TL goals, RL with TL constraints,
- Component-view → System-view

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