A SYSTEMS THEORY APPROACH TO COOPERATIVE ROBOTICS AND SENSOR NETWORKS

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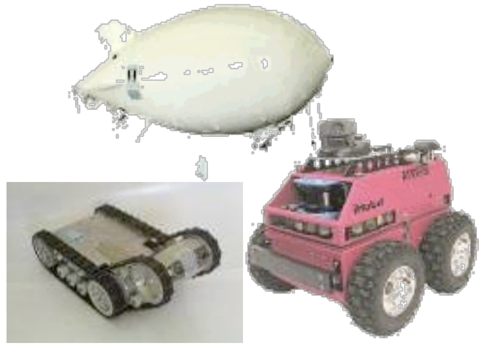
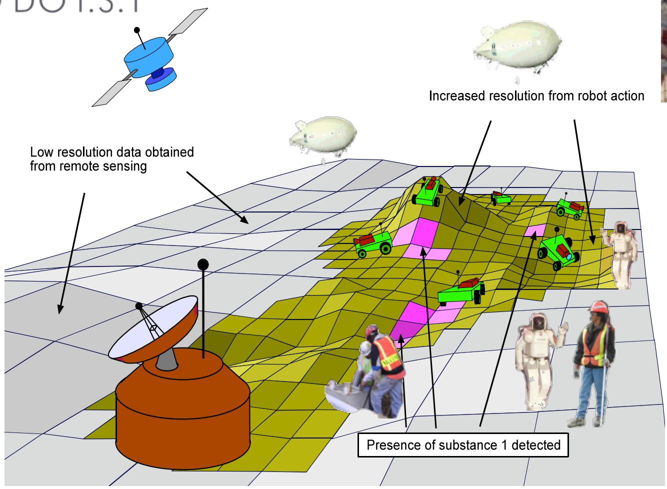
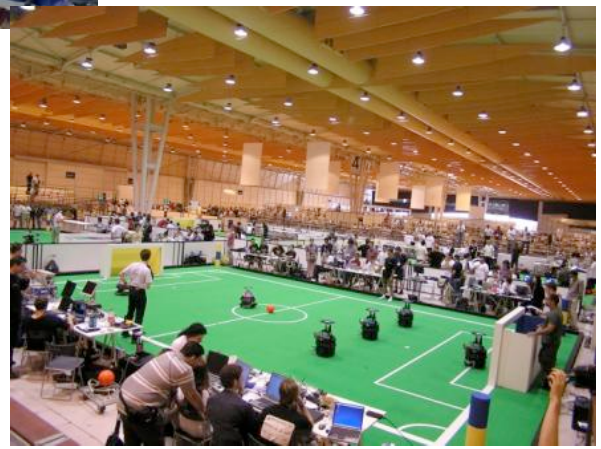
PÓLO DO I.S.T







MOTIVATION

most of the existing robotic task models

- are not based on formal approaches
- concern a small number of behaviors
- are tailored to the task at hand

systems-theory-based task design methods for general robotic tasks can enable

- systematic approach to modeling, analysis and design
- scaling up to realistic applications
- analysis of formal properties
- design from specifications

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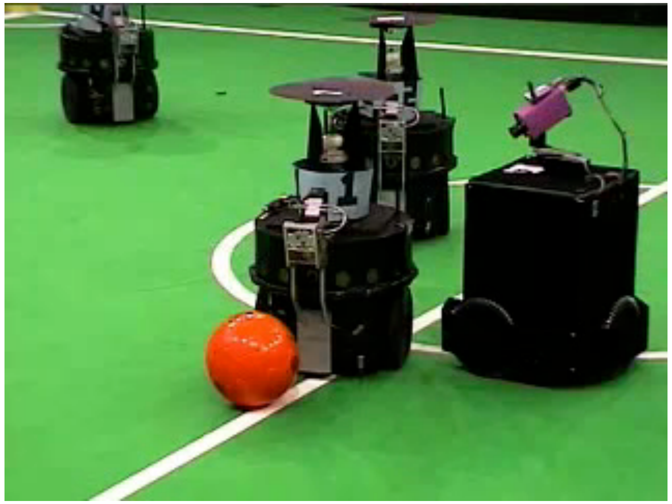
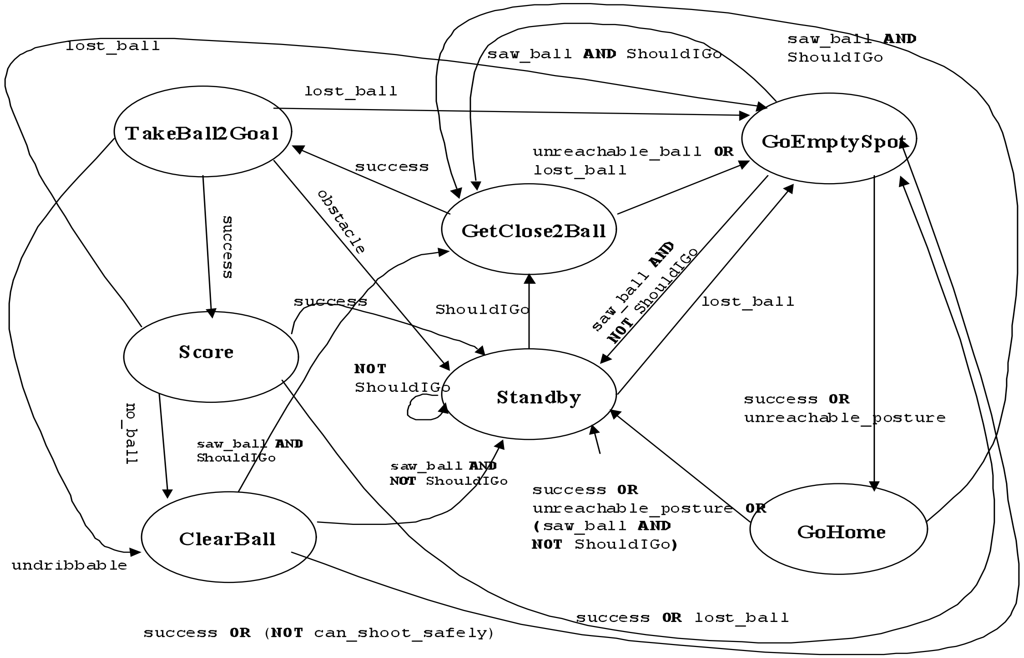
MOTIVATION



How to design the "right" behavior?



?

CR SIG, Lisbon
24-26 Oct 08

Pedro Lima, ISR/IST

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RELATION TO SIG TOPICS

coordination and cooperation among multiple types of robots

also tackling

- common testbed, common research platform for benchmarking (RoboCup MSL)
- formal models and performance metrics (plan reliability, robustness)
- applications of network robot systems (search and rescue, urban scenarios, soccer robots)
- inclusion of humans in robot teams (Institutional Robotics)

DISCRETE EVENT MODELS OF ROBOTIC TASKS

Finite State Automata

Petri Nets

Formal Verification Tools available

Performance Analysis in the presence of uncertainties possible

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PN MODEL OF ROBOTIC TASKS

(Lima *et al*, 1998) (Milutinovic, Lima, 2002)

- Places with tokens represent
  - *predicates*
  - *primitive actions* running

- *State* is distributed over the places with tokens

- *Events* assigned to transitions:
  - *Controllable events*: decision to start an action
  - *Uncontrollable events*: failure, environment change not provoked by the robot (could be by a teammate, or a human)

- Transition fires **when** it is enabled **and** the labeling event occurs

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PN MODEL OF ROBOTIC TASKS

Petri Nets (PN) Robotic Task Model

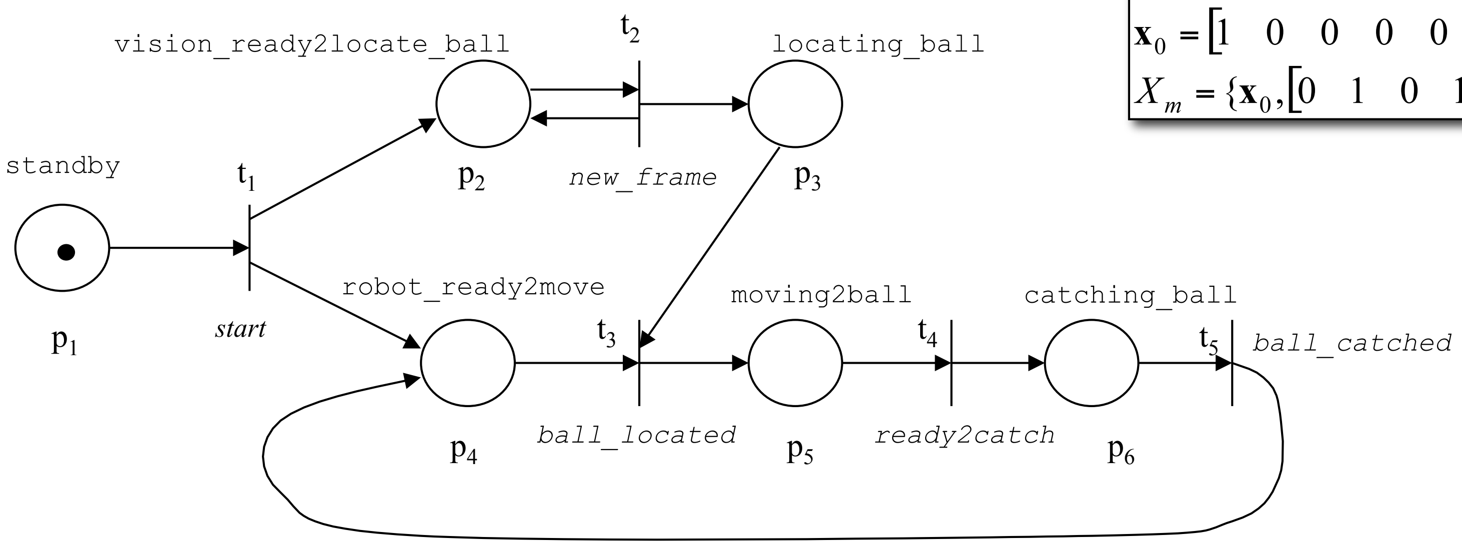
Petri Net N

$E = \{s, nf, bl, r2c, bc\}$

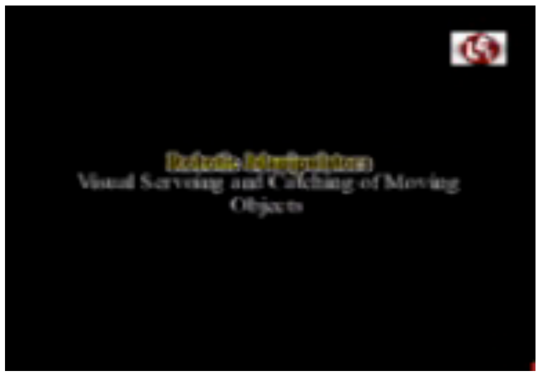
$l(t_1) = s, l(t_2) = nf, l(t_3) = bl, \ldots$

$\mathbf{x}_0 = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]$

$X_m = \{\mathbf{x}_0, [0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 0]\}$



$\mathbf{x} = [1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$ marking or state



Generated and Marked Languages

$$L(N) = \{\varepsilon, s, s\ nf, s\ nf\ \ bl\ nf, \ldots\}$$

$$L_m(G) = \{\varepsilon, s, s\ nf\ \ bl\ r2c\ bc\} \subseteq L(G)$$

MODELS FOR COOPERATIVE ROBOTS

RELATIONAL BEHAVIORS

temporary behaviors involving 2 or more team members
e.g., group of friends moving to a location to meet there

Messages between teammates create new controllable events and predicates

Communication is used for *commitments* and *synchronization*

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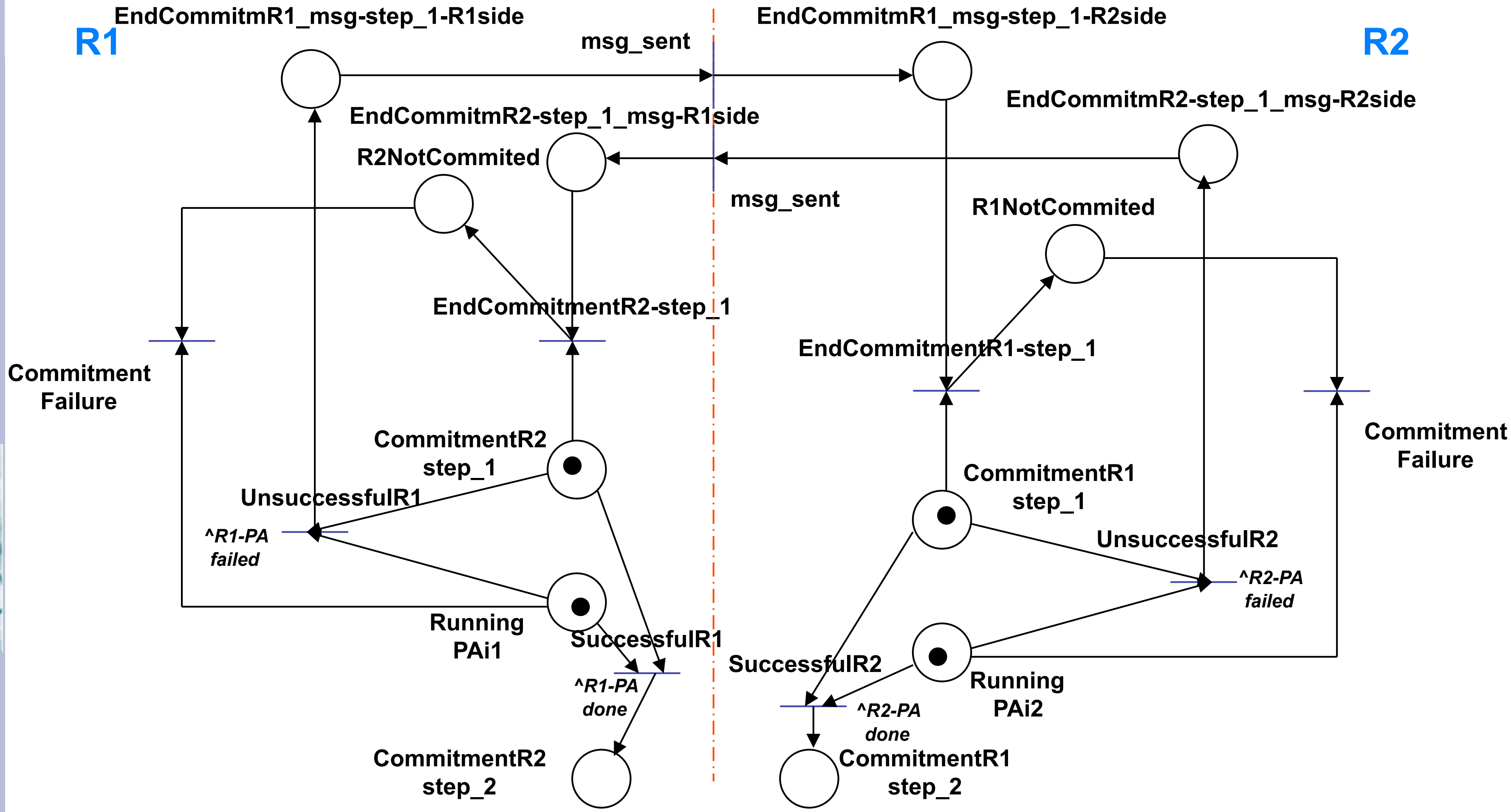
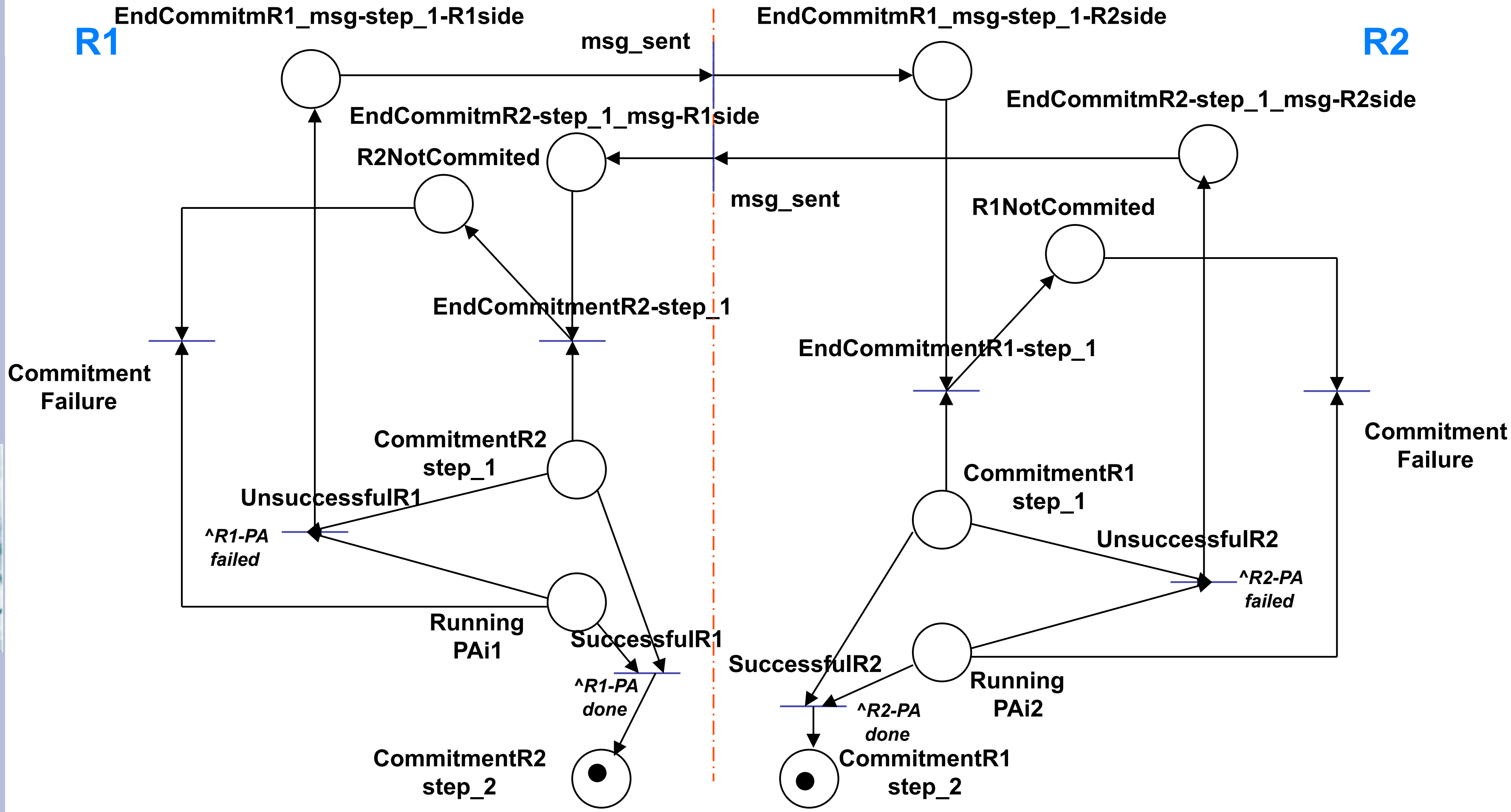
MODELS FOR COOPERATIVE ROBOTS

Commitments



MODELS FOR COOPERATIVE ROBOTS

Commitments



MODELS FOR COOPERATIVE ROBOTS

Synchronization

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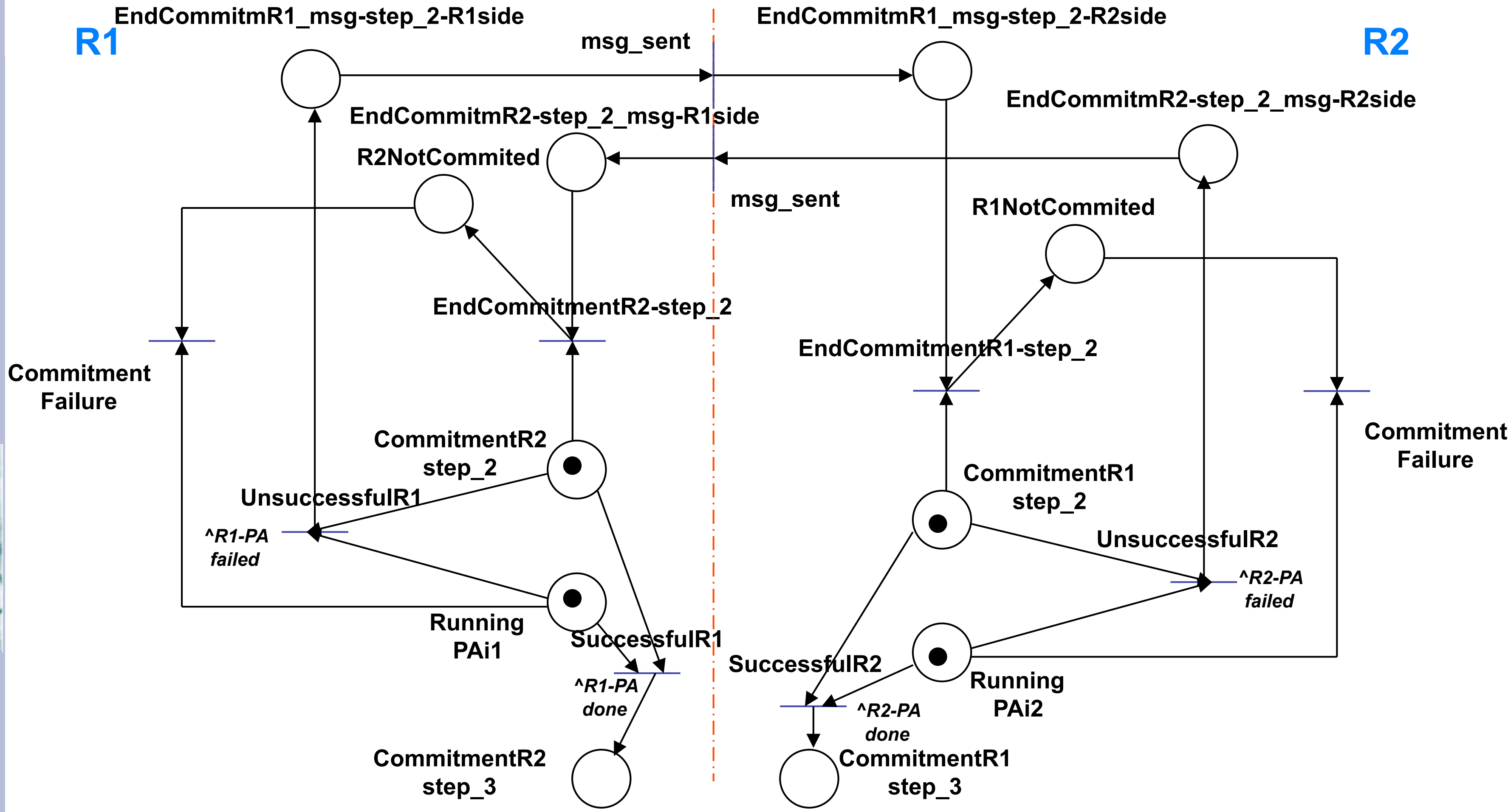
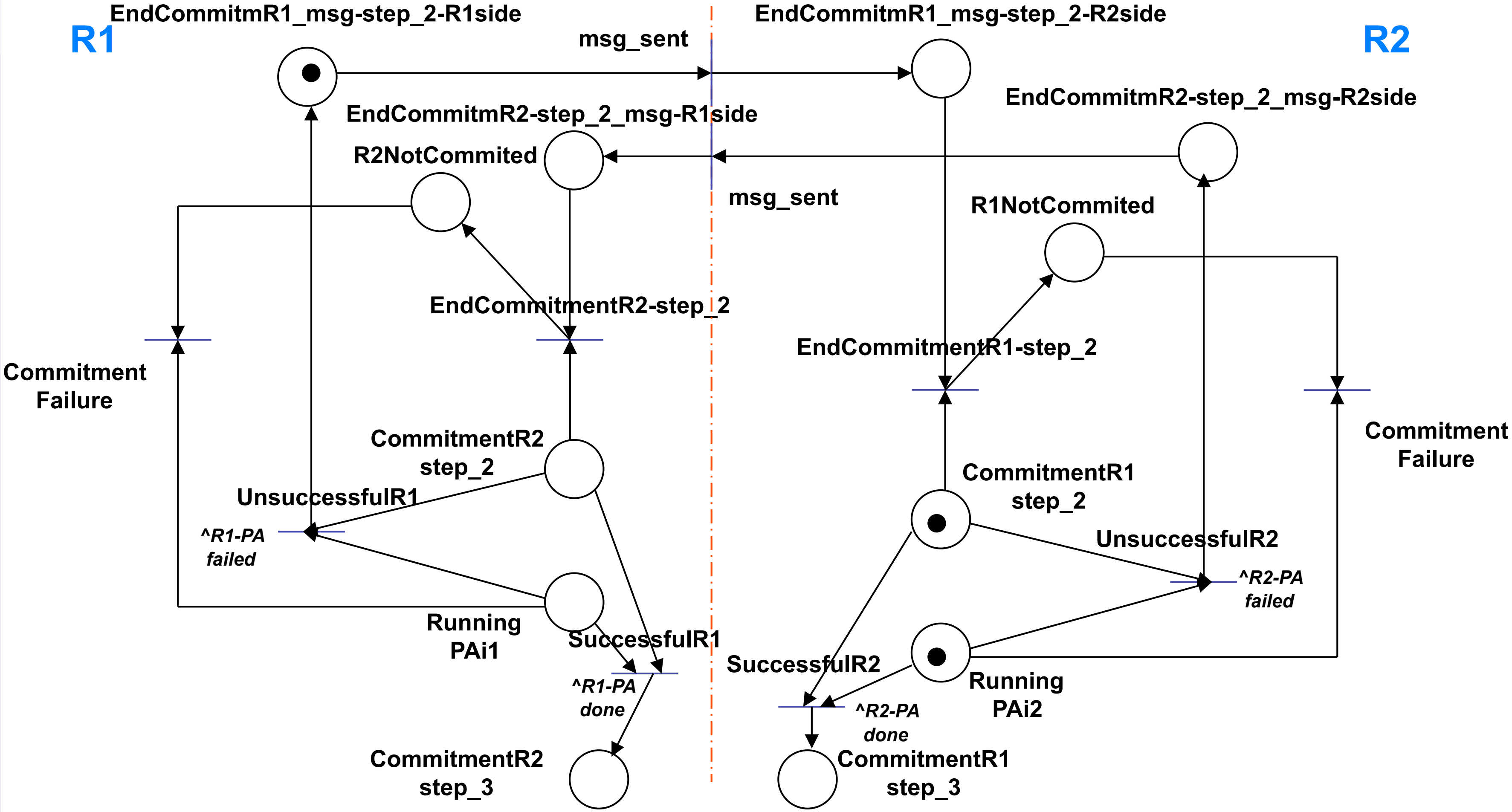
MODELS FOR COOPERATIVE ROBOTS

Breaking a Commitment



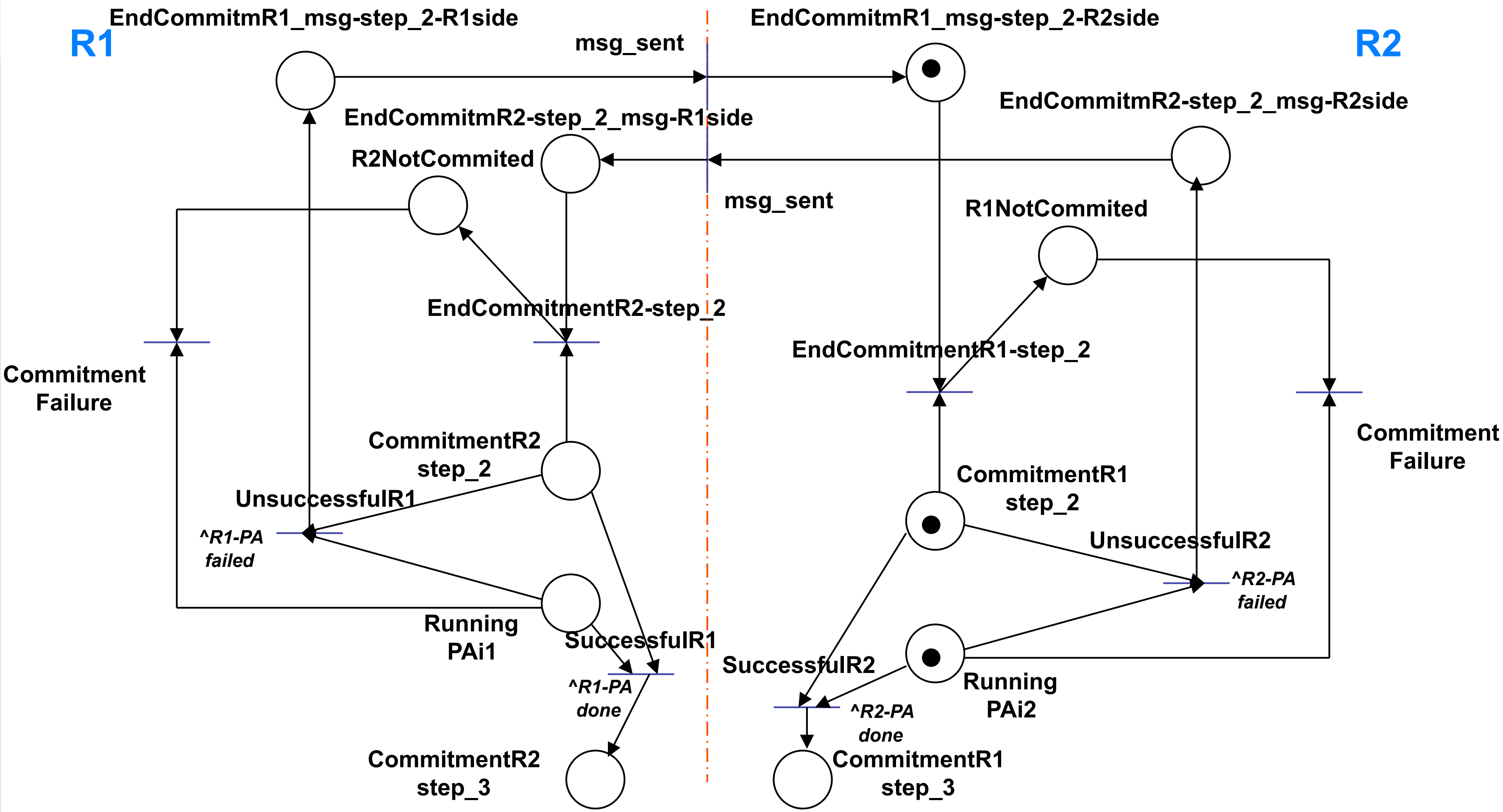
MODELS FOR COOPERATIVE ROBOTS

Breaking a Commitment



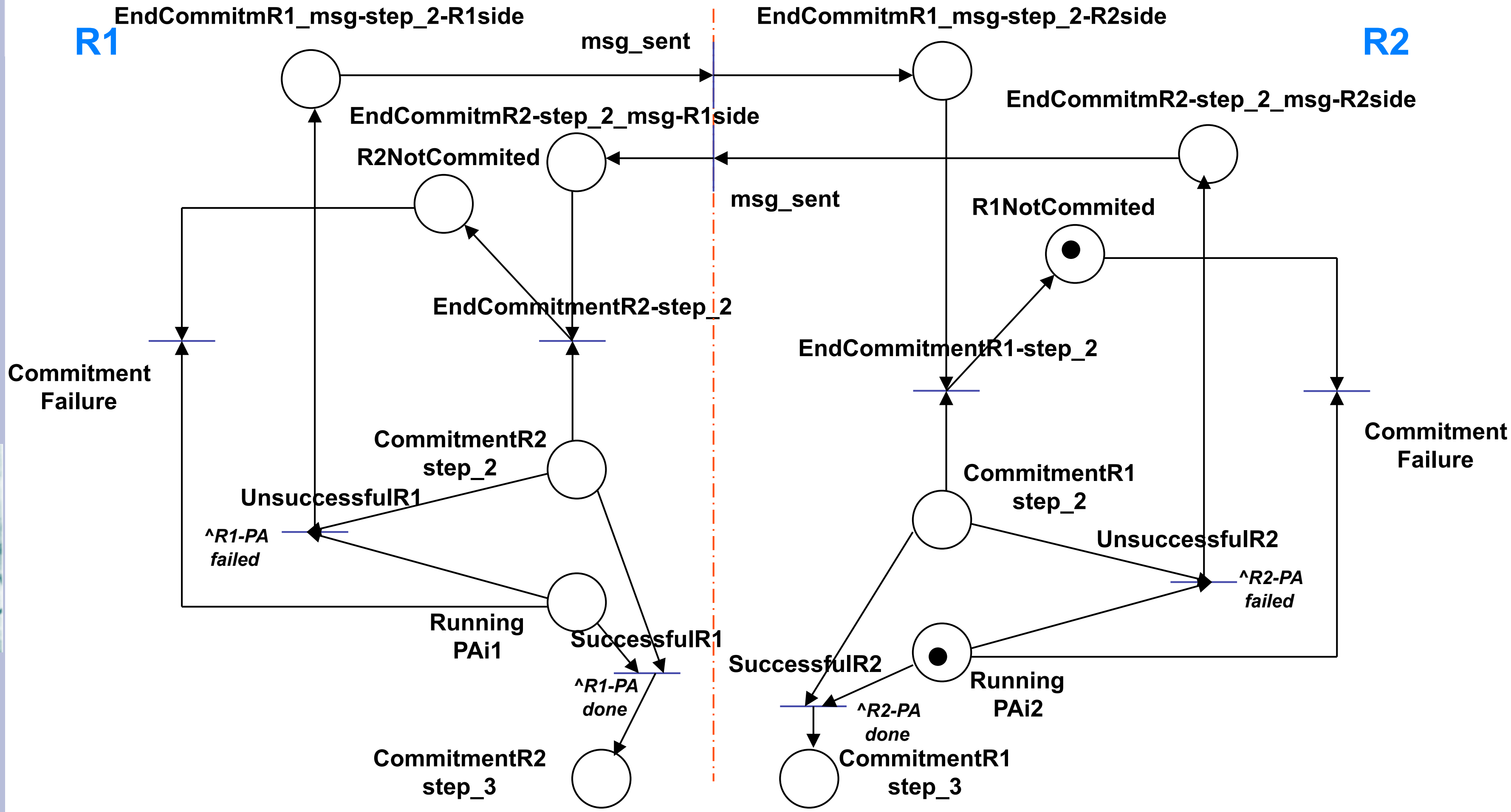
MODELS FOR COOPERATIVE ROBOTS

Breaking a Commitment



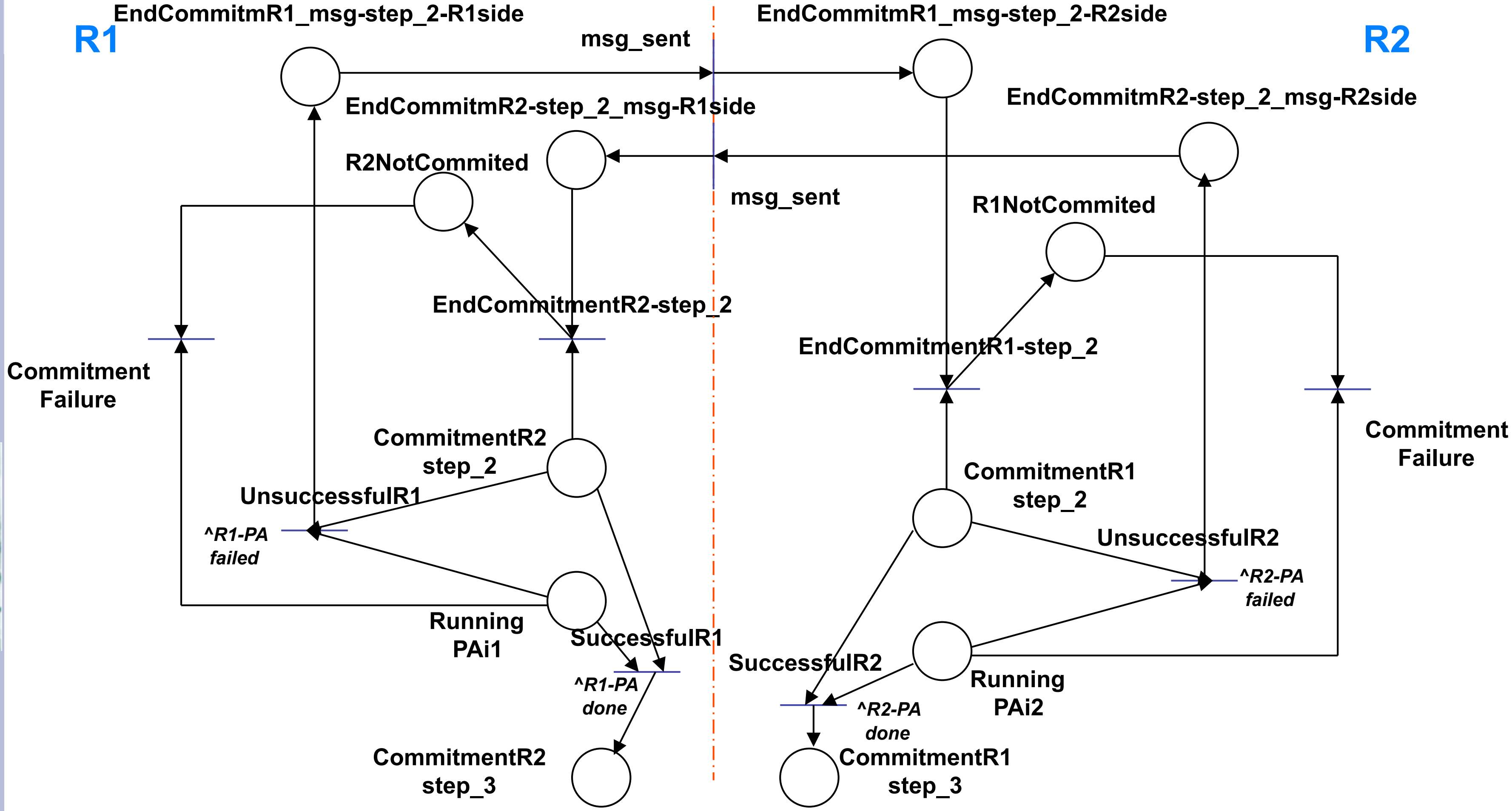
MODELS FOR COOPERATIVE ROBOTS

Breaking a Commitment



MODELS FOR COOPERATIVE ROBOTS

Breaking a Commitment



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EXAMPLE IN SOCCER ROBOTS

Programmed using Petri nets

SYNCHRONIZATION

Free Kick (simulated *vs* real)

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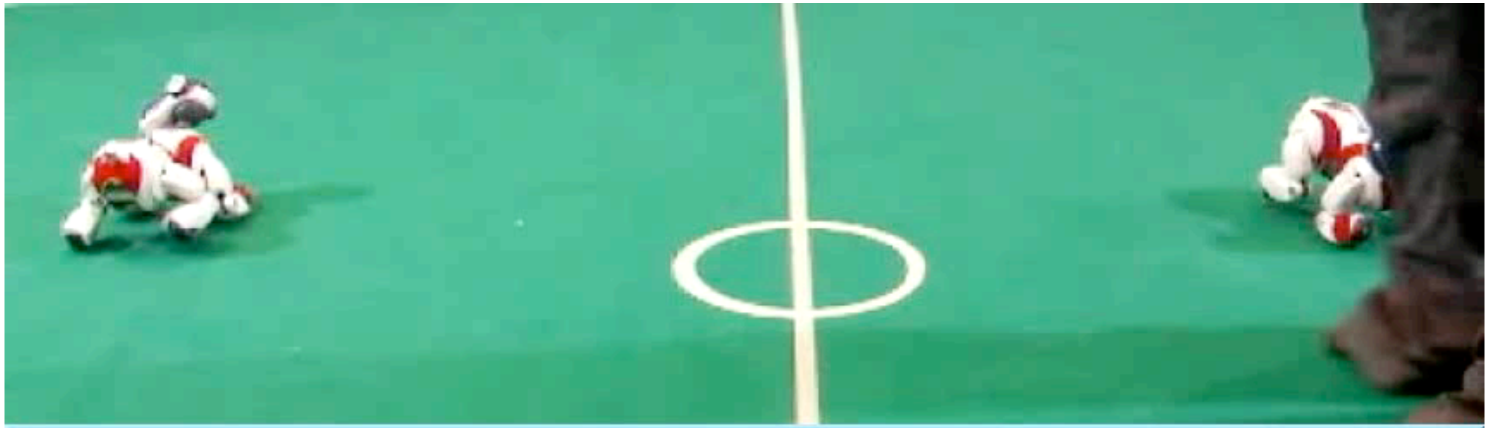
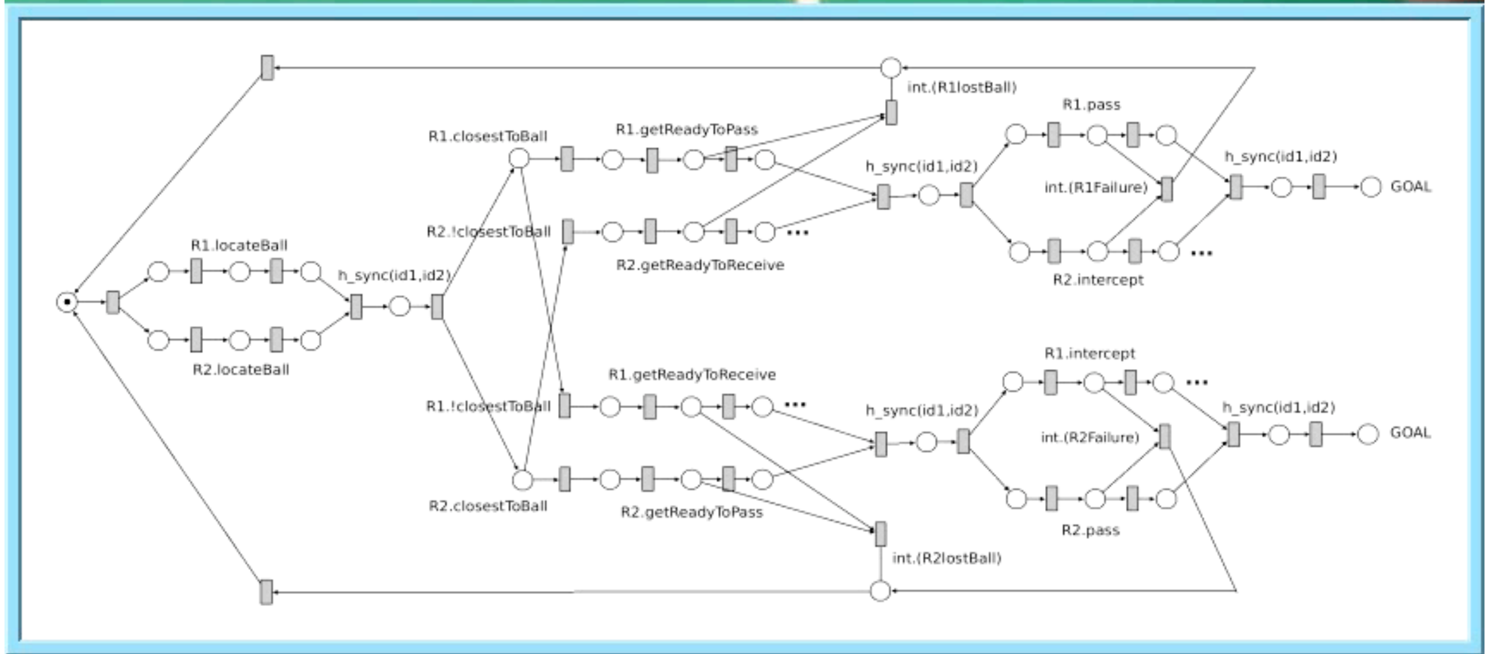
EXAMPLE IN SOCCER ROBOTS

Programmed using Petri nets

(Palamara *et al*, 2008)

SYNCHRONIZATION





RELATIONAL BEHAVIOR - PASS

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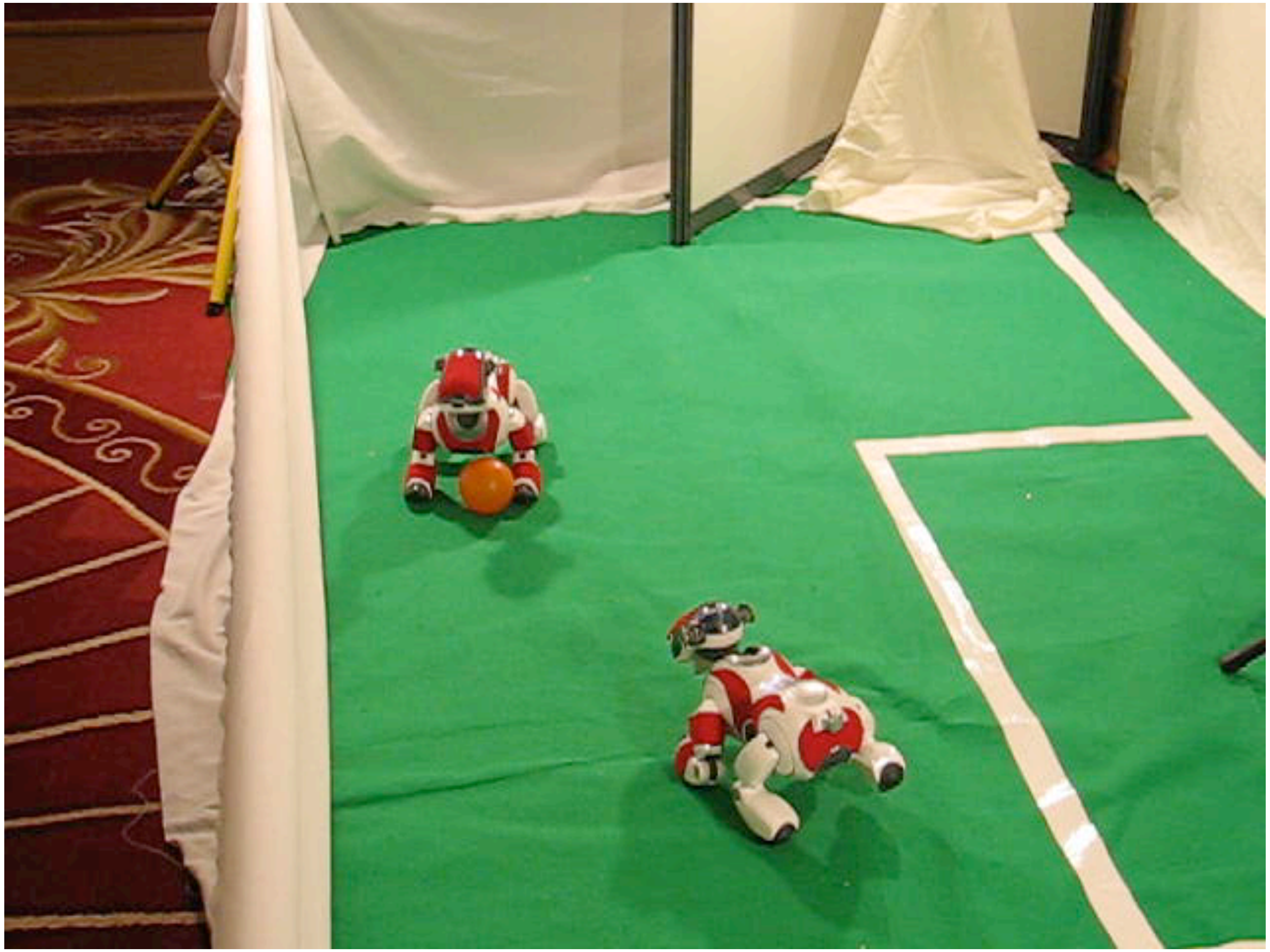
EXAMPLE IN SOCCER ROBOTS

Programmed using Petri nets

(Palamara *et al*, 2008)

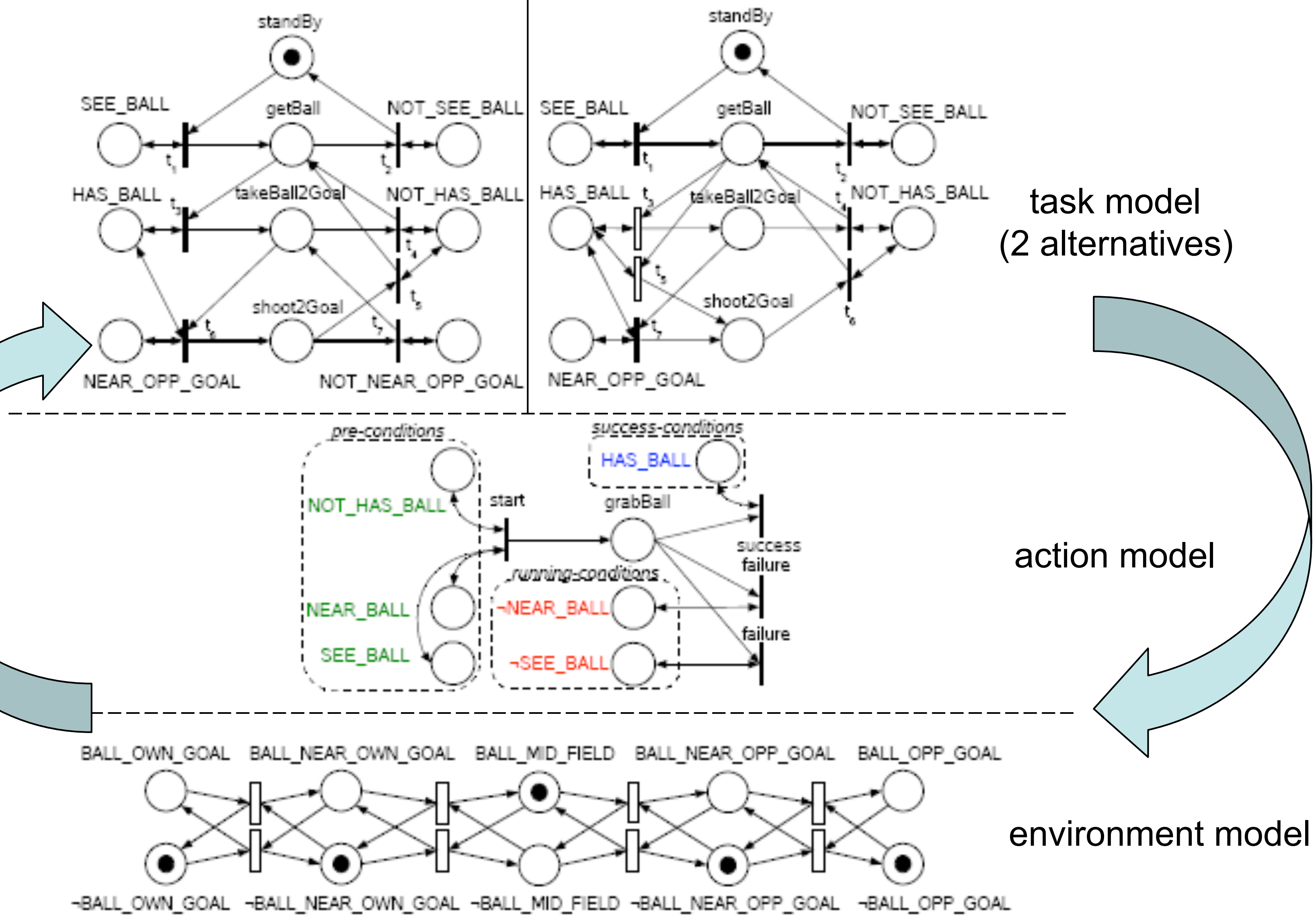
SYNCHRONIZATION + COMMITMENT



RELATIONAL BEHAVIOR - PASS

TASK + ENVIRONMENT MODEL

(Costelha, Lima, IROS 2007, AAMAS 2008)



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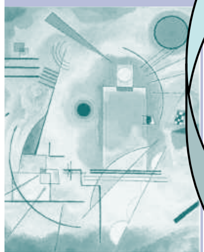

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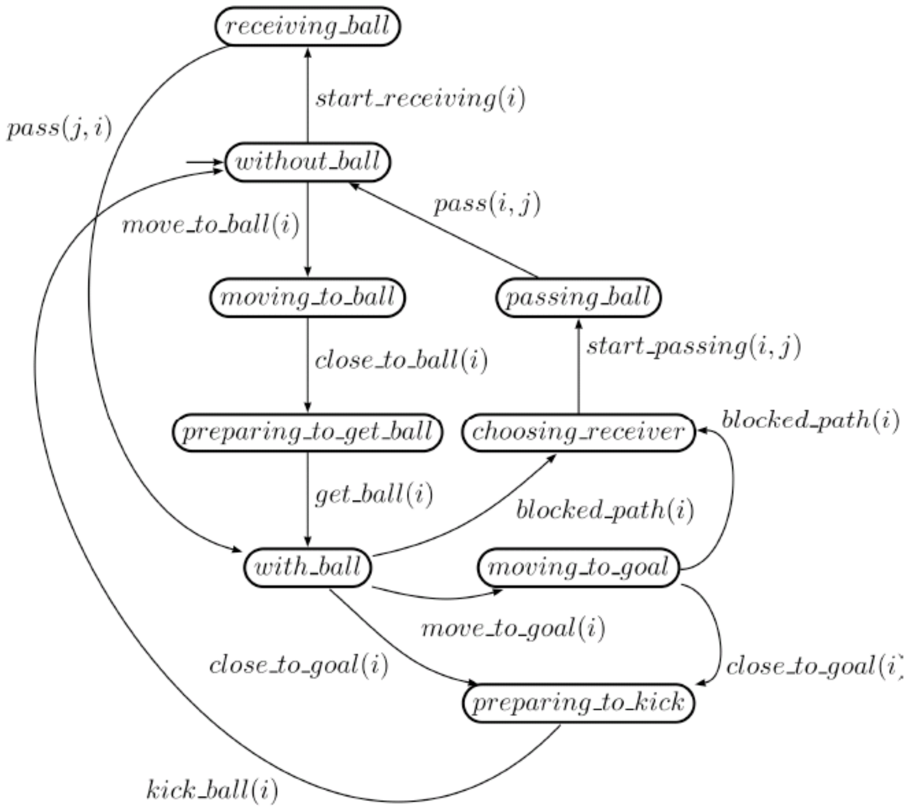
DES SUPERVISION USING LOGIC SPECIFICATIONS

(Lacerda, Lima, 2008)



- model for 1 robot + environment
- several models can be composed
- controllable events are
  - *start_receiving*
  - *move_to_ball*
  - *pass*
  - *start_passing*
  - *move_to_goal*
  - *kick_ball*
- unsupervised behavior enables several robots going to the ball or a robot start receiving a pass without a pass being made

temporal logic specifications disable those undesired behaviors

$$\varphi_1 = (G(\bigvee_i moving2ball(i) \vee \bigvee_i hasball(i)) \Rightarrow (X(\neg(\bigvee_i move\_to\_ball(i)))))$$

$$\varphi_{2,i} = ((\neg start\_receiving(i)) \wedge (G[(\bigvee_{j \neq i} start\_passing(j,i)) \Leftrightarrow (X start\_receiving(i))]))$$

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ROBOTIC TASK MODELS WITH UNCERTAINTY

Untimed	Stochastic Timed
$e_1, e_2, \ldots, e_k, \ldots$ → FSA → $x_0, x_1, \ldots, x_k, \ldots$	stochastic time associated to events → STA → $x(t)$ $p(x(t))$
$e_1, e_2, \ldots, e_k, \ldots$ → PN → $\mathbf{x}_0, \mathbf{x}_1, \ldots, \mathbf{x}_k, \ldots$	stochastic time associated to transitions/events duration + random switches → SPN → $\mathbf{x}(t)$ $p(\mathbf{x}(t))$

⇒ **EQUIVALENT MARKOV CHAINS**

exponential stochastic time

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ANALYSIS AND DESIGN

Stochastic models enable answering *analysis* questions such as:

- what is the probability of success of a task plan?
- given a desired probability of success for the plan, what is the accumulated action cost (e.g., time, energy) to accomplish the task?
- what is the sensitivity of a plan to over- or under-estimation of the probability of success of one of its composing actions?

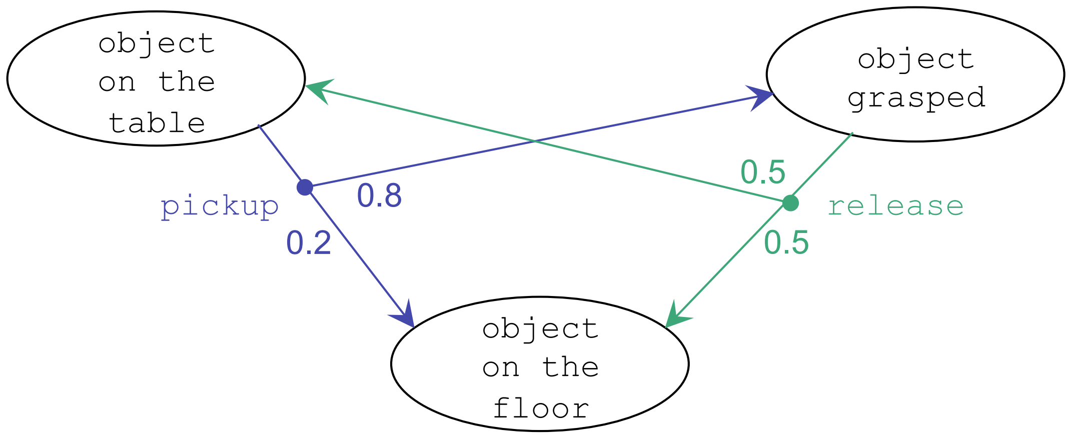
Stochastic models enable *designing* plans from specifications:

- given some desired probability of success, determine the plan that minimizes the accumulated action cost
- design a robust plan, in the sense of keeping its reliability above some threshold, in the presence of over-estimation of the probability of success of one of its composing actions?

ANALYSIS AND DESIGN

- environment + controller composition
- stochastic model - equivalent Markov Chain
- some of the events are controllable and represent decisions on starting actions – controllable Markov Chain

MARKOV DECISION PROCESSES (MDP)



- effects of robot actions are uncertain but environment states are fully observable
- can be solved by **Reinforcement Learning** algorithms

DECENTRALIZED PLANNING UNDER UNCERTAINTY

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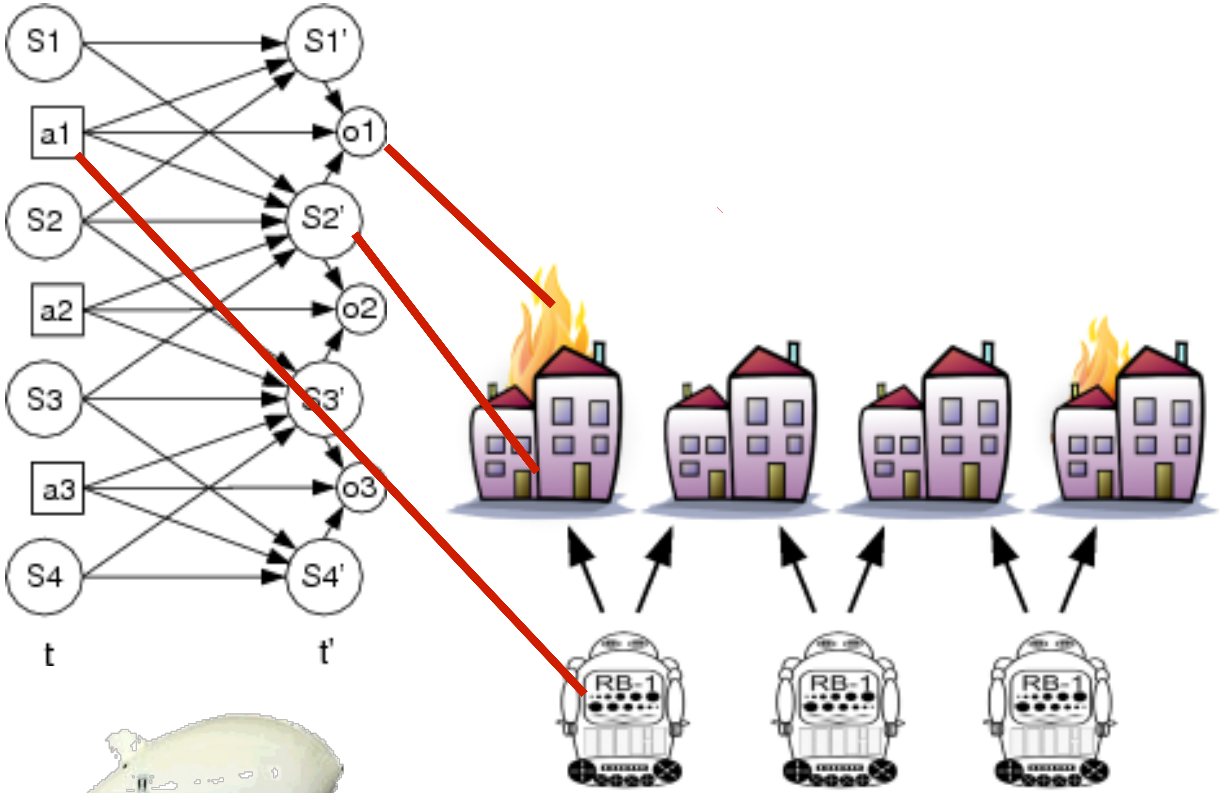
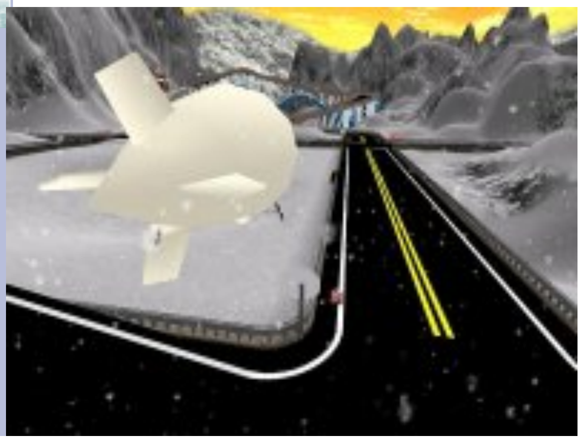
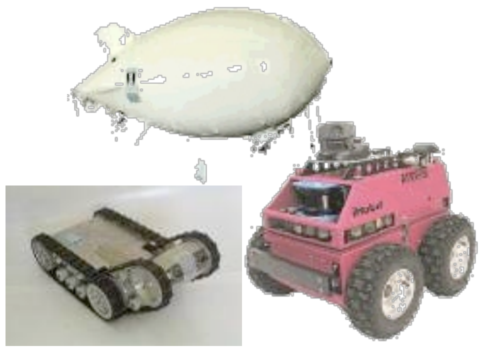
APPLICATION TO COOPERATIVE PLAN EXECUTION IN SEARCH AND RESCUE

(Spaan, 2008)







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DECENTRALIZED PLANNING UNDER UNCERTAINTY

APPLICATION TO ACTIVE COOPERATIVE PERCEPTION

EC FP7 URUS Project

Cooperative perception using:

- embedded and own sensors
- fusion techniques and technologies

Cooperative environment perception

INSTITUTIONAL ROBOTICS

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- Decisions are not always necessarily based on **rational** principles, e.g., like with (PO)DMPs
- Inspiration from social sciences (namely Institutional Economics) to handle robotic collectives
- Robots are situated, embodied and social agents
- Their behavior is neither pre-programmed nor does it simply emerge
- Emergence is regulated by existing institutional norms
- By using institutional norms similar to those of humans, we expect this approach to simplify human-robot interaction, e.g., in search and rescue teams

INSTITUTIONAL ROBOTICS

physical properties → drivers must slow down and go left or right

BUT...

How to choose the appropriate direction not to crash one with the other?

INSTITUTIONAL ROBOTICS

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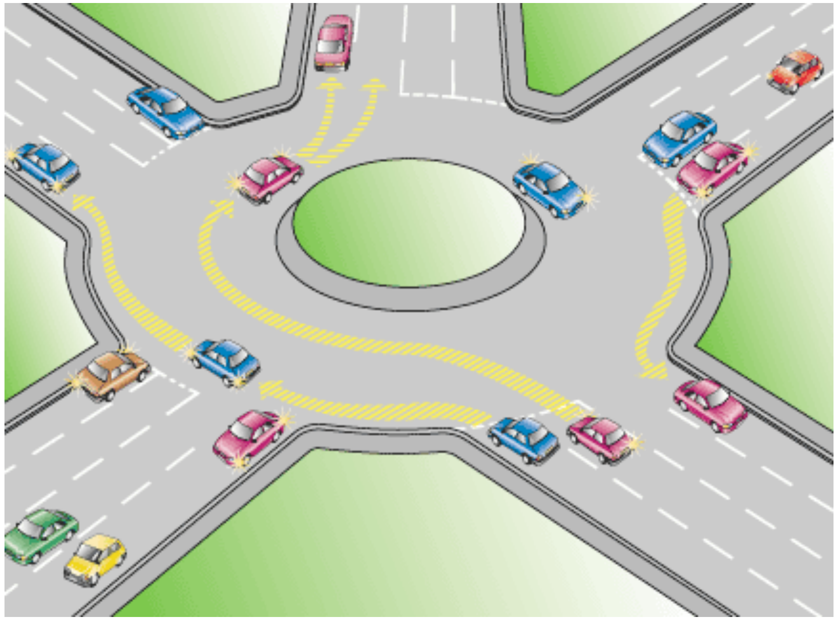
Portugal, Spain, Germany, ...

Convention (road code): go right

UK, South Africa, New Zealand, ...



Convention (road code): go left

CONCLUSIONS

Systems-theory-based task design methods for general robotic tasks are promising concerning

- systematic approach to modeling, analysis and design
- analysis of formal properties and performance

To Be Proven

- *scaling up to realistic applications*
- *design from specifications*