Multi-Agent Goal Reasoning with the CLIPS Executive in the RoboCup Logistics League

ICAART'21

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Planning and Execution on Mobile Robots

Challenges when reasoning on mobile robots:

- Offline planning is not sufficient
- Robots need to react to a changing environment and adapt their goals
- Action execution is unreliable:
  - Actions may fail
  - Plans may execute faster/slower than expected
- Robots need to coordinate effectively

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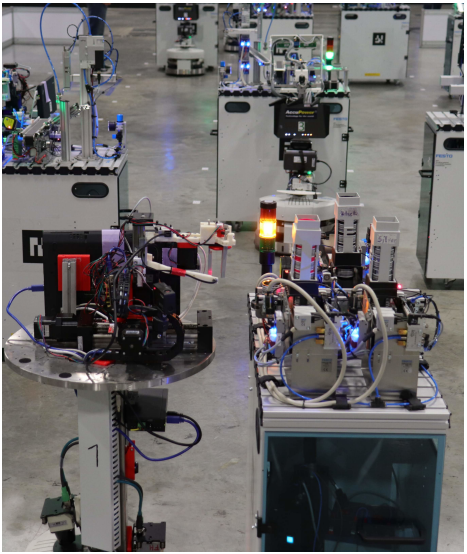
The RoboCup Logistics League (RCLL)

- Replication of a smart factory
- In-factory production logistics
- Robots operate machines to manufacture products
- Machines are static, robots are mobile
- Each machine performs one manufacturing step
- Each team consists of three robots



RoboCup Logistics League – Production

Product Composition:

- Products of four complexities (number of rings)
- Base (3 colors) + 0–3 rings (4 colors) + cap (2 colors)
- Machines:

  Base Station: retrieve base workpiece
  Ring Station: mount ring
  Cap Station: mount cap
  Delivery Station: deliver product

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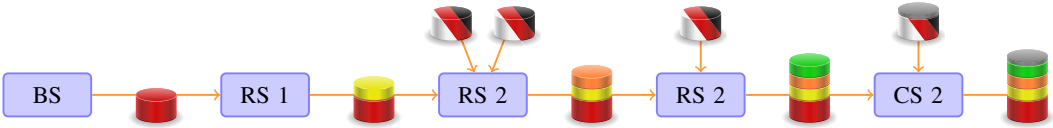

Goal Reasoning with the CLIPS Executive [Niemueller et al., 2019]

Goal reasoning:

- No fixed goal
- Explicitly represent goals
- Continually reason about goals
- Dynamically adjust and prioritize goals

→ Reason about *what* to accomplish,
only then *how* to accomplish it

- Goal lifecycle: goal progress during execution

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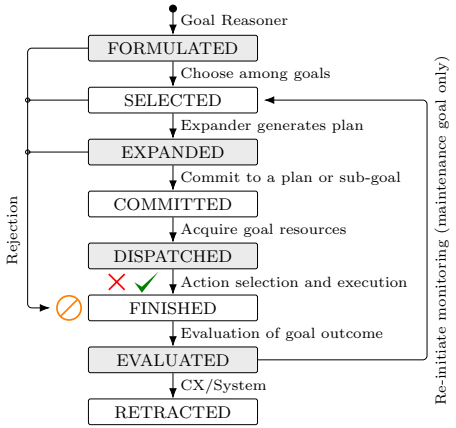

Goal Reasoning in the RCLL

Main questions:

1. How to represent the RCLL as a goal reasoning problem?
2. How to achieve one specific goal?
3. How to coordinate the three robots?

Splitting the RCLL productions into goals

- Observation: tasks can be split up to start and stop at a machine

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Purpose	Goal Class	Source	Destination
Assembly	`MOUNT-RING`	$BS_{I/O}$, RS_O	RS_I
Assembly	`MOUNT-CAP`	RS_O	CS_I
Assembly	`PRODUCE-C0`	$BS_{I/O}$	CS_I
Preparation	`FILL-CAP`	CS_{Shelf}	CS_I
Preparation	`FILL-RS`	$BS_{I/O}$, CS_O	RS_{Slide}
Preparation	`CLEAR-MPS`	Any MPS_O	-
Completion	`DELIVER`	CS_O	DS_I

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- *Machine instructions* can be handled separately
  $\rightarrow$ separate `PREPARE` goal that can be executed concurrently

Goal Trees

- *Simple* goals can be structured in a goal tree
- Goal types:
  - `RUN-ALL` Run all sub-goals successively, succeed if all sub-goals succeed
  - `TRY-ALL` Subsequently run all sub-goals until first succeeds
  - `RUN-ONE` Run one of the sub-goals, outcome is the child's outcome

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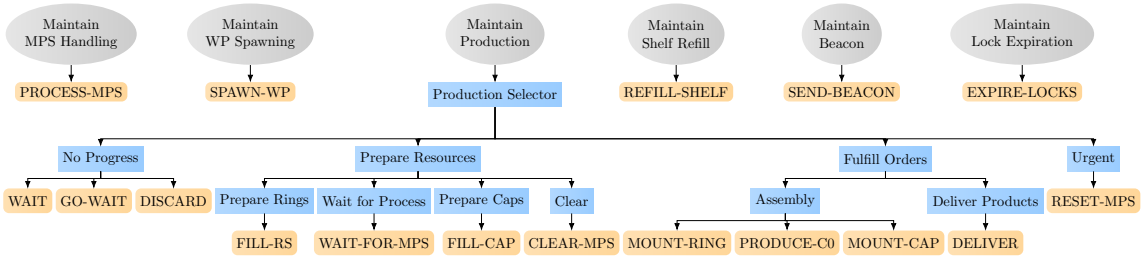

Goal Expansion and Execution using PDDL

- Each goal is expanded into a PDDL plan
- PDDL preconditions are used to verify the expected world state
- PDDL effects update the agent's world model
- Execution monitoring may intervene if
  - an action is not executable
  - an action did not have the expected effects
  - the current plan or goal is no longer feasible

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```
(move (wait-pos ?ds INPUT) ?ds INPUT)
(wp-put ?wp ?ds)
(prepare-ds ?ds ?order)
(fulfill-order ?complexity)
(go-wait ?ds INPUT (wait-pos ?ds INPUT))
```

The plan for a `DELIVER` goal

Multi-Agent Coordination

- Distributed agent: one agent per robot

→ Each robot acts on its own

→ Need to coordinate

- Three coordination mechanisms:
  1. Shared world model
  2. Locking actions
  3. Goal resource allocation

Shared world model

- Objective: share (some) world model facts among the agents
- Fact-based world model with key-value pairs
- PDDL domain facts are translated into a key-value pair:

```
; PDDL representation
(wp-at WP1 C-CS1 INPUT)
; CLIPS representation
(domain-fact (name wp-at) (param-values WP1 C-CS1 INPUT))
; Translation into key-value pair
(wm-fact (id "/wp-at?wp=WP1&m=C-CS1&side=INPUT")
         (value TRUE))
```

- Each agent runs a MongoDB database instance
- Key-value pairs are stored in the database
- Database instances are managed as replica set
- Replica set is automatically synchronized in the background

Mutual Exclusion Mechanism

Mutual exclusion using a database:

- Separate database for *mutex documents*
- Updates using *majority acknowledgement*

→ No two agents can acquire a mutex simultaneously

Mutex expiration to avoid a crashed robot holding a mutex:

- A mutex expires after 30 s

→ After a crash, another robot can take over after the mutex expired

- Periodic refresh to avoid expiration

Locking Actions

```
(:action lock
 :parameters (?name - object)
 :precondition
  (not (locked ?name))
 :effect (locked ?name))
```

```
(:action unlock
 :parameters (?name - object)
 :precondition
  (locked ?name)
 :effect (not (locked ?name)))
```

- Locking actions based on mutexes
- Principle: lock any physical object for any interaction
- Agent waits for a certain time if it cannot acquire the lock immediately
- Specialized action `location-lock`
  - unlocking is only done after reaching a certain distance to the location

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```
(go-wait ?start ?side (wait-pos ?ds INPUT))
(location-lock ?ds INPUT)
(move (wait-pos ?ds INPUT) ?ds INPUT)
(lock ?ds)
(wp-put ?wp ?ds)
(prepare-ds ?ds ?order)
(fulfill-order ?complexity)
(unlock ?ds)
(location-unlock ?ds INPUT)
(go-wait ?ds INPUT (wait-pos ?ds INPUT))
```

Goal Resource Allocation

- Locking actions are scoped locally, i.e., to guard parts of a plan
- Expectation: The state of the resource is not altered

→ Can perform the same actions on the resource

- Not suitable for deciding *what to do*,
  e.g., buffering a cap changes the state of the CS

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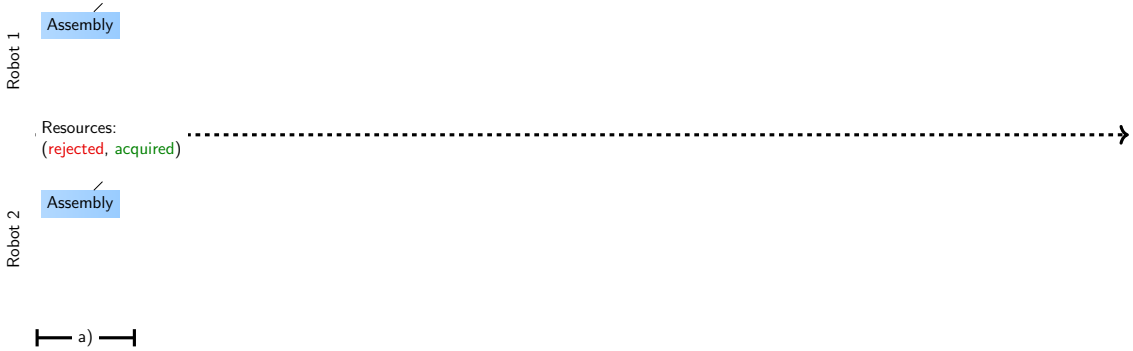
⇒ *Goal resource allocation*:
Additional coordination mechanism on goal level

- Each goal has a set of *required resources*
- Agent needs to acquire those resources before dispatching the goal

Coordination by Means of Goal Resource Allocation



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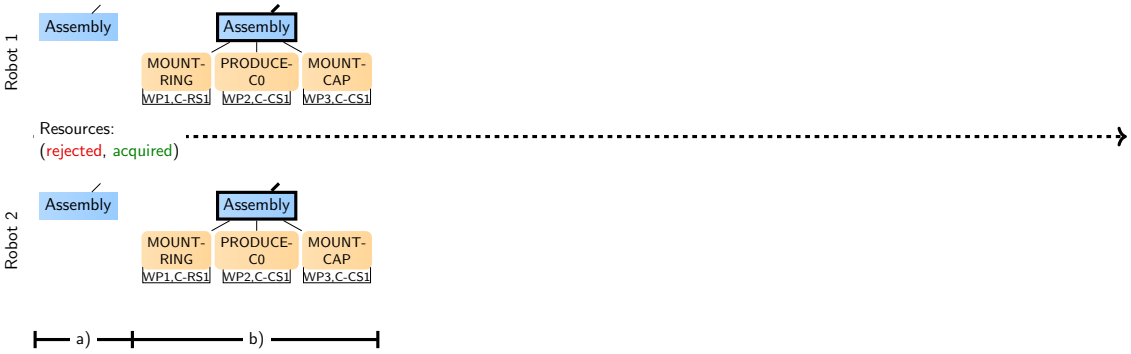

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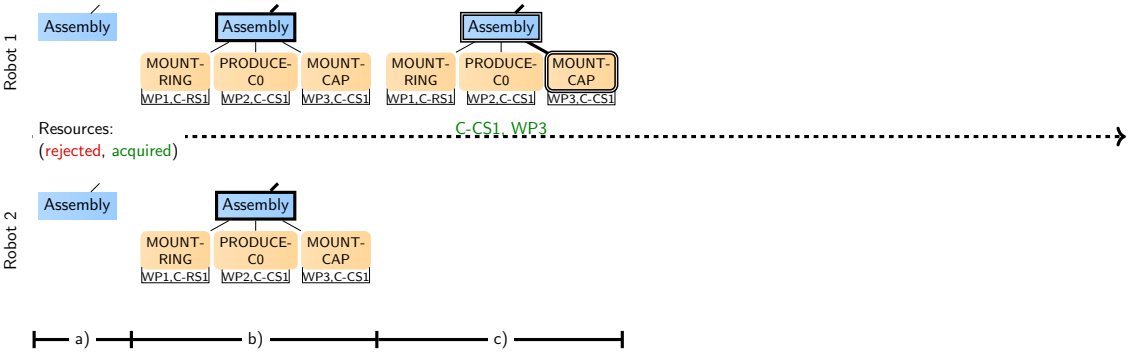

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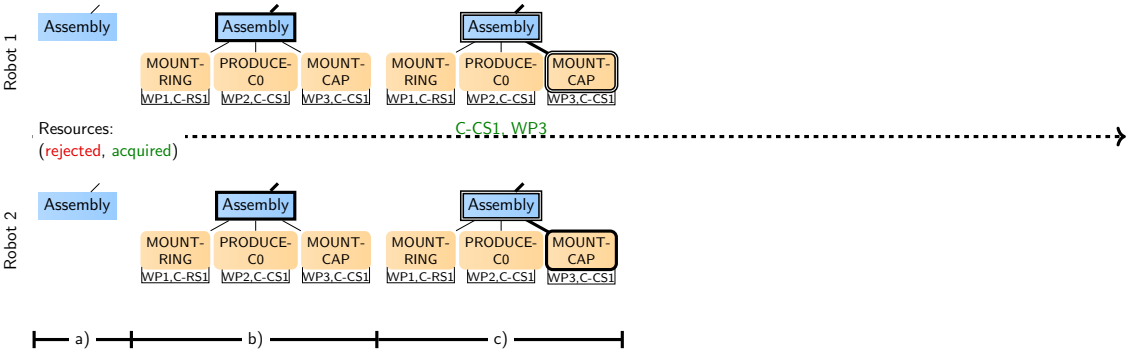

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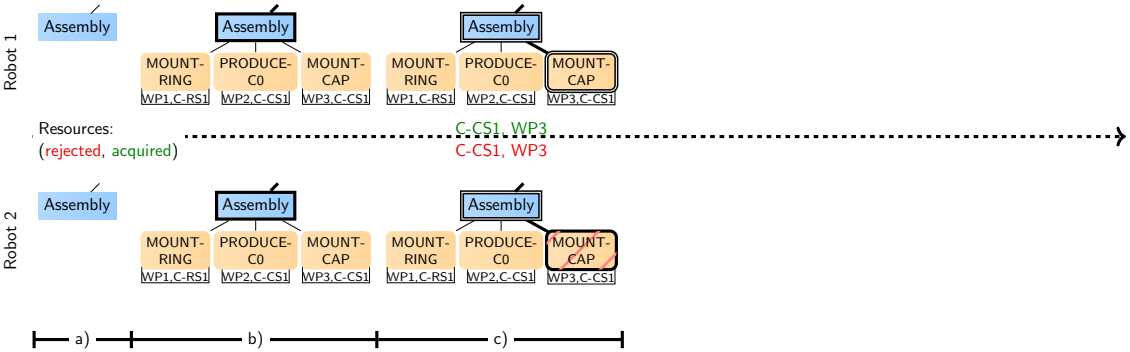

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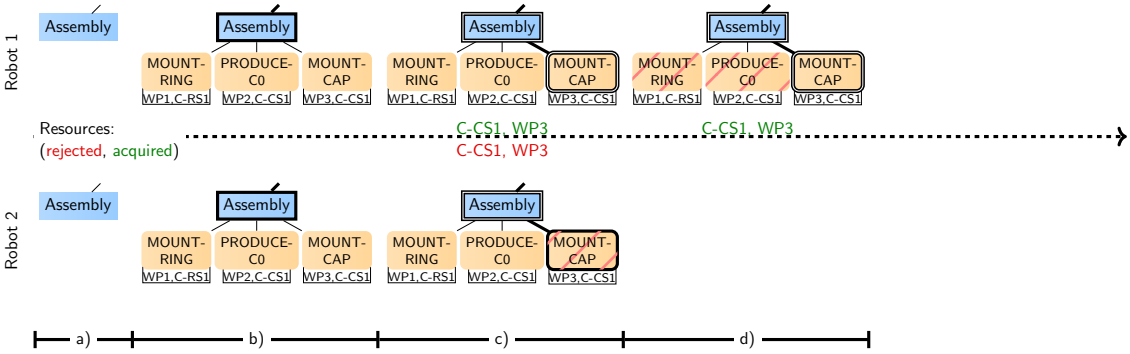

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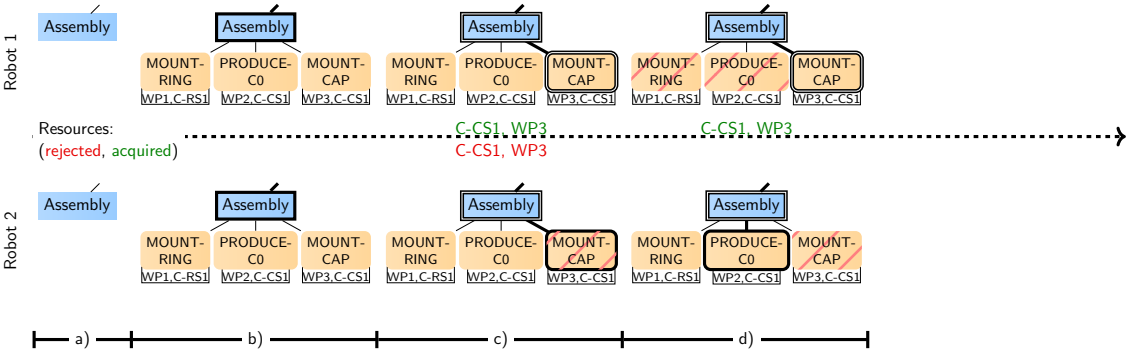

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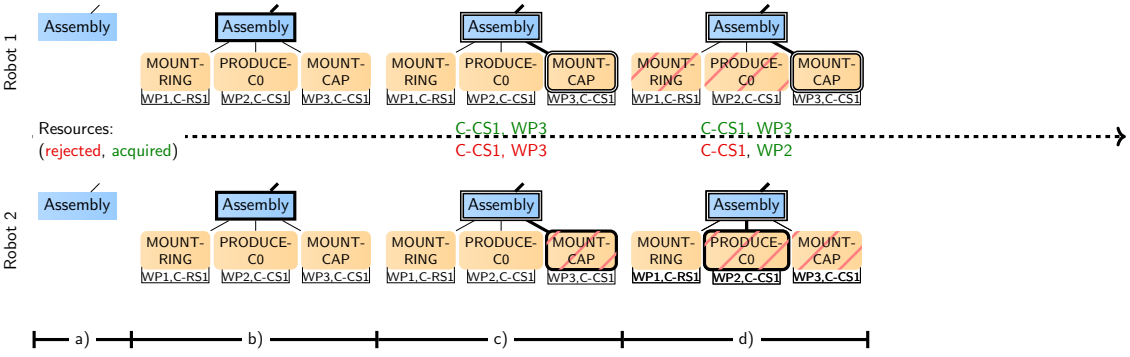

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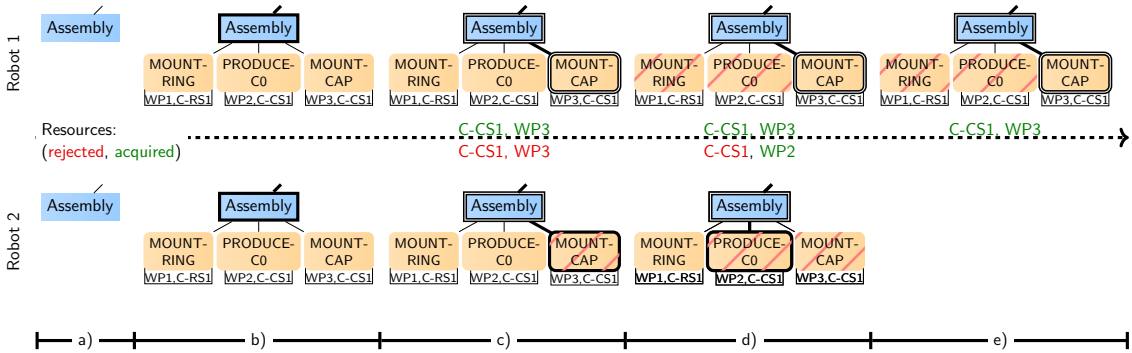

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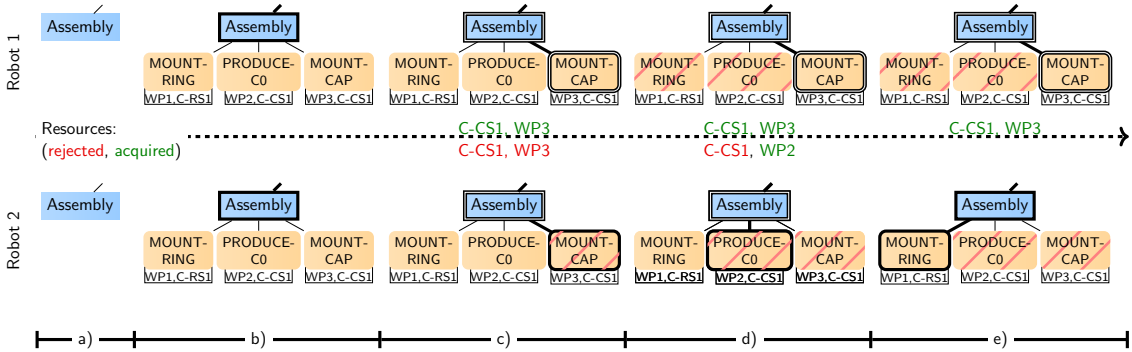

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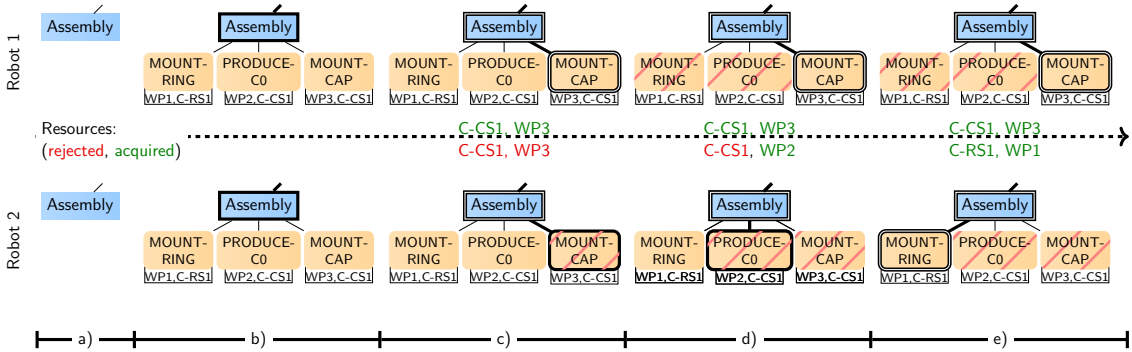
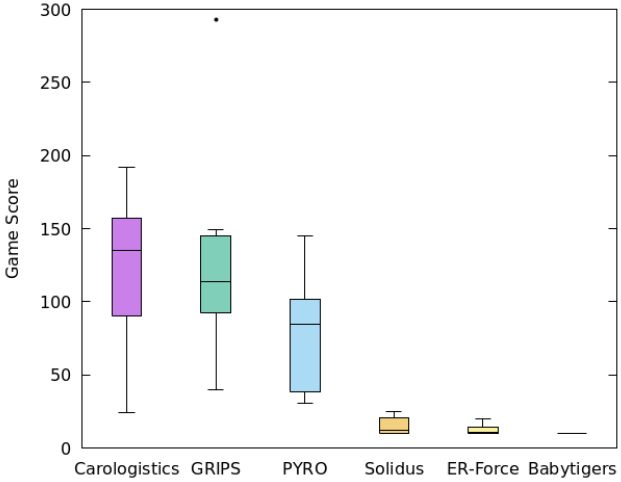


Evaluation: Game Scores at RoboCup 2019

- Setting: RoboCup World Cup 2019
- Scores from all official games
- Final result: 1st place



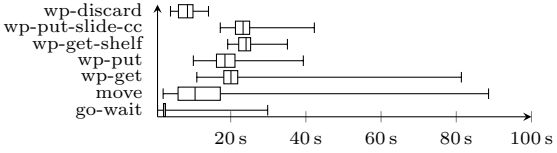
Evaluation: Execution

- High variation in execution time

→ Distributed and incremental reasoning can react dynamically

- 28 % of the goals eventually failed
- 22 % of the failed goals could be recovered
- Robots can react by retrying and taking over

⇒ Good performance despite high failure rates



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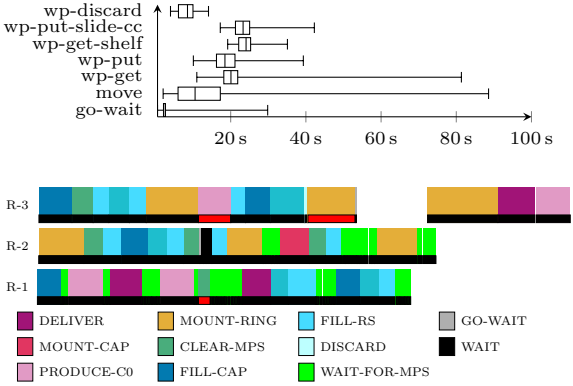

Conclusion

- Distributed multi-agent goal reasoning system
- Each agent decides on its own goals
- Decide what to do next without creating a plan for the complete problem

→ Quickly react to changes during execution

- Multi-agent coordination based on:
  1. A shared world model
  2. Locking actions
  3. Goal resource allocation

→ Effective coordination of a team of three robots

References I

T. Niemueller, T. Hofmann, G. Lakemeyer.

Goal reasoning in the CLIPS Executive for integrated planning and execution.

Proceedings of the 29th International Conference on Automated Planning and Scheduling (ICAPS), 2019.