Massachusetts Institute of Technology

Robust Execution of Contingent, Temporally Flexible Plans

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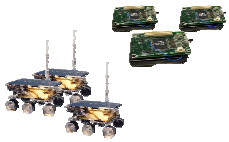
Model-based Embedded & Robotic Systems

CSAIL

Real World Autonomous Agents

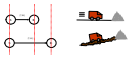
- Coordinate multiple agents
- Provide robustness

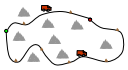


Robustness to Disturbances

Robustness to ...

- Temporal uncertainty : Temporally flexible mission plan
- Execution uncertainty : Dispatchable execution
- Communication latency : Distributed architecture
- Plan failure : Contingent mission plan





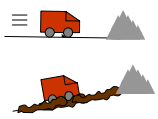
Robustness to Temporal Uncertainty

Robustness to ...

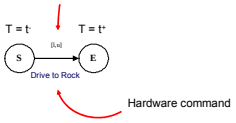
- Temporal uncertainty : Temporally flexible mission plan

Temporally flexible plans allow activities with *uncertain duration*

"Drive to rock"



Simple temporal constraint : $l \le t^+ - t^- \le u$



Hardware command

Robustness to Execution Uncertainty

Robustness to ...

- Temporal uncertainty : Temporally flexible mission plan
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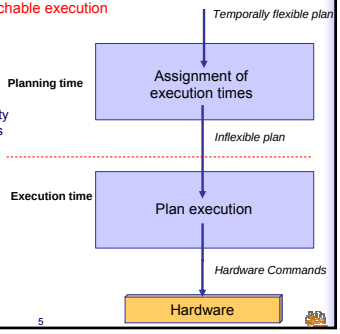
Problem : Plan is either …

- Brittle to temporal execution uncertainty
- Overly conservative to ensure success



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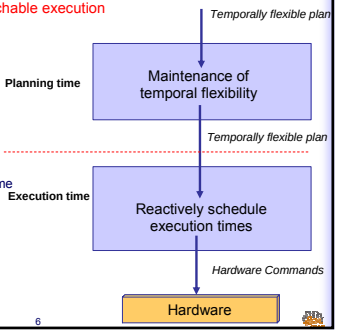
- Postpone scheduling until execution time



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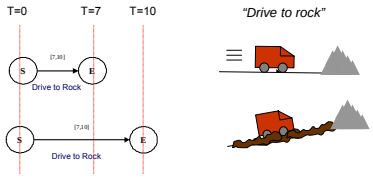

Least commitment planning allows the executive to use temporal flexibility to respond to uncertainties at run time

Robustness to Execution Uncertainty

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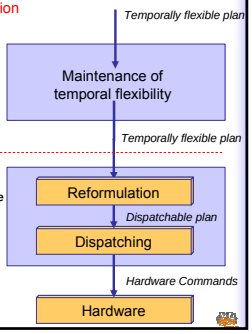
Requires two-stage execution …
- Plan reformulation to compile the plan to a form for easy dispatching
- Dispatching to schedule and execute activities



Robustness to Communication Latency

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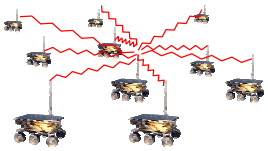

Problem : Centralized architecture introduces communication bottleneck at master agent

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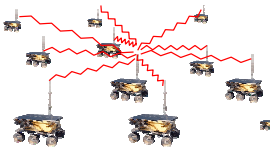
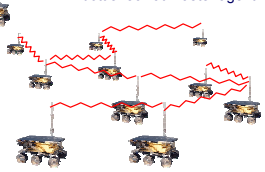
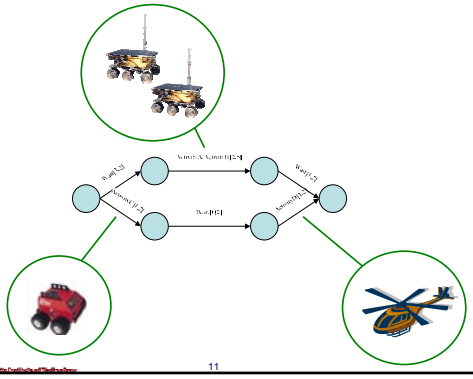


Problem : Centralized architecture introduces communication bottleneck at master agent

Solution : A distributed architecture evens out the communication requirements



Distributed Architecture



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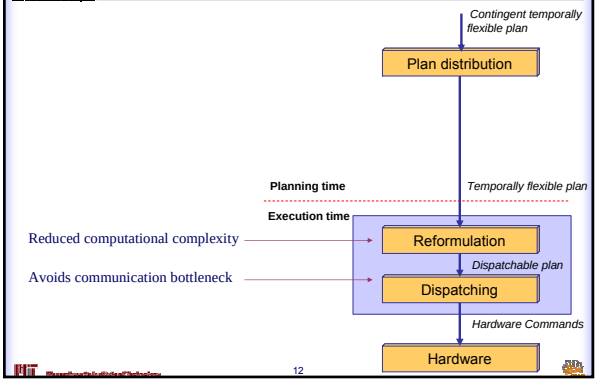
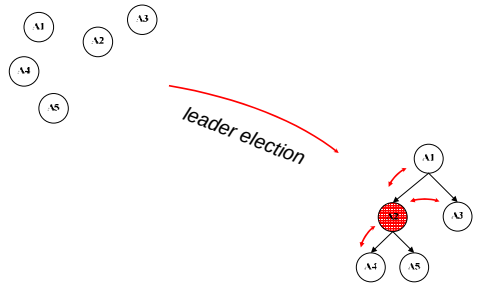


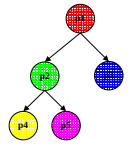
Plan Distribution

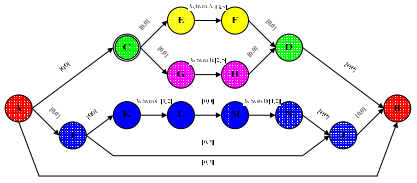


Plan Distribution

Exploit common hierarchical structure

```
if network is a single activity
  processor takes activity
else if processor has followers
 distribute subnetworks to followers and self
else if processor has co-leaders
 distribute subnetworks to coleaders and self
else
  processor takes entire network
```





Robustness to Plan Failure

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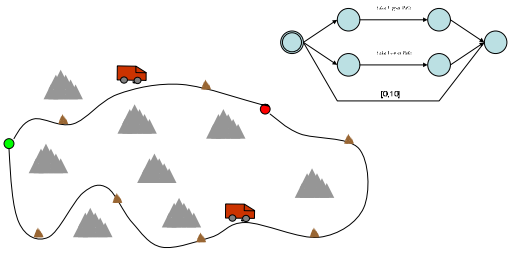

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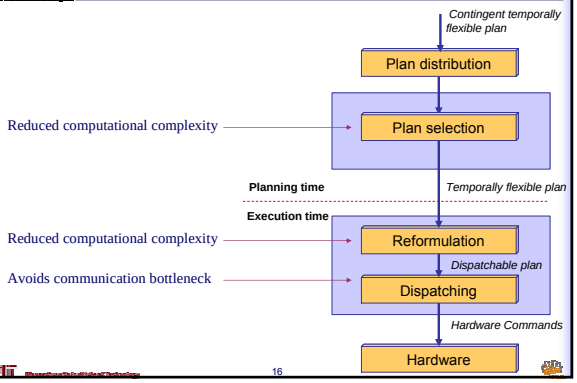

Interleaved Candidate Generation and Consistency Checking

1. Generate candidate plans through distributed search on the TPN
2. Test the generated plans for temporal consistency

} *Interleaved* and *concurrent*

Implemented using a message passing scheme …

findfirst	Initial search for a consistent set of choice variable assignments
findnext	Search for a new consistent assignment, to achieve global consistency
fail	No consistent set of choice variable assignments was found
ack	A consistent set of choice variable assignments was found

Candidate Generation

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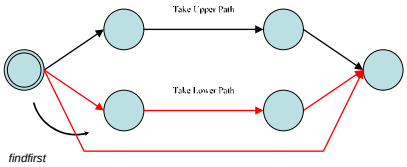
Candidate Generation

Nodes send *findfirst* messages to their children

Search progresses at increasing depth



Consistency Checking

1. Generate candidate plans through distributed search on the TPN
2. Test the generated plans for temporal consistency

Interleaved and *concurrent*

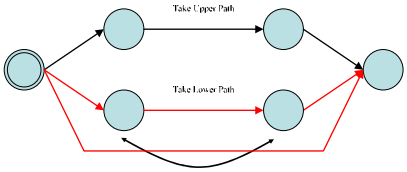
Implemented with synchronized distributed Bellman Ford Single Source Shortest Path algorithm

- Requires only local knowledge
- Uses a message passing scheme
- Runs on distance graph corresponding to active portions of the TPN
- Processor synchronization at every update cycle gives linear run time

Consistency Checking

Nodes perform consistency checking and report to their parent

Checking progresses at decreasing depth



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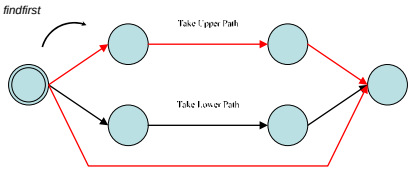

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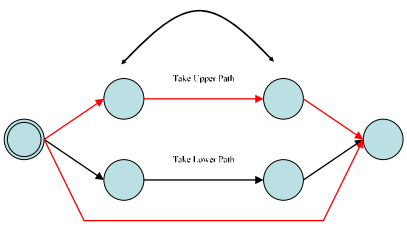

Time Complexity Analysis

	Centralized Planner	DTP
Candidate Generation	N^e	N^e
Temporal Consistency Checking	$N^2 \log N + NM$	N
Overall Time Complexity	Exponential	Exponential

N Number of nodes
M Number of edges
e Size of domain of choice variables

- Worst case complexity of candidate generation corresponds to a plan entirely composed of choice nodes
- DTP uses parallel processing for parallel and sequence networks
- Time complexity much lower in realistic examples
- In practice, complexity of DTP is near-linear

Questions ?