Coordination in Planning

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plan of this talk

1. Introduction to Multi-Agent Planning
2. Coordination before Planning
3. Coordination during Planning
4. Coordination after Planning

From single agent problems to multi-agent planning problems

we illustrate the difference between single and multi-agent planning by taking a simple pick-up and delivery planning problem, gradually increasing its difficulty.
Planning in Multi Agent Systems

pick-up and delivery planning

Total cost: 7

easy job: two shortest path calls

Planning for two orders

Total cost: 7

Planning for a lot of orders

Total cost: ?

please send in your solution before Christmas

more than one planner
How to solve these problems with multi-agent planning systems?

the key is: managing dependencies!

Multi-agent planning

A task consisting of interrelated subtasks and specifications of capabilities required.

A set of agents together with a description of their capabilities.
Multi-agent planning

- composite task
- agents
- task refinement
- task allocation
- planning
- coordination

- task refinement attempts at refining the tasks specified such that there is a matching with the set of agent capabilities.
- task allocation refers to the process of assigning tasks to agents such that capabilities offered are sufficient for capabilities required.

Multi-agent planning coordination

- planning is done by the individual agents; the result should be a coordinated plan.
- coordination is provided by (a) coordination mechanism(s).

Multi-agent planning

- composite task
- agents
- task refinement
- task allocation
- planning
- coordination

- joint plan execution

- the joint plan is executed by the agents in a coordinated way.

This is the part we will concentrate on.

joint plan execution
1. pre-planning coordination

- Composite task
- Agents
- Task refinement
- Task allocation
- Pre-planning coordination
- Planning
  - Agent 1
  - Agent 2
  - Agent 3
  - Agent 4

Coordination ends before planning starts; guarantees coordinated individual plans.

Examples: social laws, social conventions, pre-planning protocols.

Ensures autonomous planning.

Combining individual plans is trivial and always successful.

Joint plan execution

2. post-planning coordination

- Composite task
- Agents
- Task refinement
- Task allocation
- Post-planning coordination
- Planning
  - Agent 1
  - Agent 2
  - Agent 3
  - Agent 4

Exploits positive interactions, removes negative interactions (conflicts).

Joint plan execution

3. Coordination during planning

- Composite task
- Agents
- Task refinement
- Task allocation
- Coordination
  - (G)PGP, PEIM, COABS

Coordination and planning as intertwined processes; coordination is applied to partial plans.

Examples: plan integration, plan merging, plan fusion.

Joint plan execution

4. Coordination after Planning

- Introduction to Multi-Agent Planning
- Coordination before Planning
- Coordination during Planning
- Coordination after Planning
Coordinating Self Interested Planning Agents

an example of coordination before planning

Problem specification

Construct a coordinated plan for a set of interrelated tasks distributed over autonomous agents if these agents
• are free in making plans for their set of tasks
• are not willing to revise their plan in composing the joint plan.

Application areas

airport planning: agents for arrival, departure, gate assignment, ground handling and taxi-route planning

interdependent tasks (per plane)
arrive → taxi → dock → taxi → depart

multi-modal logistics
agents for different transportation modalities

interdependent tasks (per package)
loc₁ - modality₁ - loc₂ - . . . - modalityₖ - locₖ

general framework

complex task
agents with different capabilities
task refinements
precedences
• a set $A$ of autonomous (planning) agents
• a set $T$ of interdependent tasks requiring the joint effort of the agents $A$ to complete them

find a method to

• coordinate the activities of the agents such that all tasks can be executed whatever plans will be developed by the individual agents in $A$
• while minimally interfering with the individual tasks given to the agents
Example: multi-modal logistic problems

logistic problem: set-up

logistic problems: tasks assigned
Planning in Multi Agent Systems

**logistic problems: tasks + dependencies**

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**complex task**

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**uncoordinated choice of individual plans**

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Individual plans are ok.

Joint plan is not feasible!

**solving pre-planning coordination problems**

Each individual agent plan is a partially ordering of the tasks assigned to it, respecting the existing constraints.
General idea

add a sufficient number of additional dependency constraints $\Delta_i$ to the dependency constraints between the tasks of agent $i$ such that every combination of individual plans is feasible.

It can be proven that such a family of sets $\Delta_i$ always exists.

( take a total extension of the partial ordered set of tasks and distribute the additional constraints over the agents )

Example: distributed partitioning

$T_A$ is the set of tasks of agent $A$. Dependency information is kept on a common blackboard (trusted party).

begin

for round $i = 1, 2, ..., n$ until $T_A = \emptyset$

each agent $A$ takes a subset $T^i_A$ of tasks from $T_A$

that are not dependent upon tasks of other agents;

the subset $T^i_A$ is stored and removed from $T_A$;

after the last round, the agent $A$ has a sequence of nonempty subsets $(T^1_A, T^2_A, T^3_A, ..., T^n_A)$. Each agent $A$ adds constraints such that $T^j_A < T^{j+1}_A$ for all $j$;

end

Example: application of partitioning

The tasks are divided into subsets based on dependency constraints. Each agent takes a subset of tasks that are not dependent on tasks of other agents. After each round, the agent has a sequence of nonempty subsets of tasks, and constraints are added to ensure feasibility.
Example: application of partitioning

With these dependency constraints added, every set of individual plans leads to a coordinated joint plan.

Check!

Partitioning strategies

distributed task splitting algorithms

A polynomial-time distributed agent-based algorithm to solve the coordination algorithm splitting each agent task into an ordered partition.

Coordination protocols (cf. specialised social laws)

A protocol to be used by the agents to assign to each agent a suitable set of coordination constraints.

A protocol to be used by the agents to assign to each agent a suitable set of coordination constraints.

Local dependency constraints added.
example: protocol for coordination

quality of protocols (analytically)

application to benchmark problems

some experiments
Plan quality (difficult problems track) 
[AIPS2000 special track problems 41.0 - 100.1]

Zooming in plan quality 
[AIPS2000 special track problems 41.0 - 100.1]

CPU-time 
[AIPS2000 special track problems 41.0 - 100.1]

Summary of results

Theoretical
- If agent planning is optimal, allocation, decomposition and scheduling might account for overhead of $\geq 14\%$
- If agent planning is non-optimal, allocation, decomposition and scheduling might account for overhead of $\leq 5\%$

Experimental
- approach allows for
  - high quality
  - fast
- solving of multimodal logistic problems
Summary and comments

- Preplanning Coordination
  - method is suitable for coordinating self-interested autonomous planning agents

- Algorithmic aspects
  - approach suggests a divide and conquer method to multi-agent planning by minimally changing problem instances

- Relevancy for current planning technology
  - approach can be used to reuse existing single agent planning technology for multi-agent planning purposes: coordination mechanisms allow for distributed independent single-agent planning
Coordination during Planning

Why and when to coordinate

- A set of interrelated tasks/goals to achieve a goal affecting performance
- Order at which actions are performed affects performance
- Time at which actions are planned affects performance

(GPGP)’s approach

- Provide coordination module for local planners to handle dependencies
- Uncordinated (abstract) plans are given to the coordination module
- Coordination module applies coordination mechanisms to produce coordinated plans

Example

We use the logistic example to illustrate the coordination during planning approach.
Example logistic problem

Agents $i$ are responsible for local city transportation tasks. Flight agent handles airport to airport transportation.

Transportation tasks consist of interdependent city pre-transportation + flight + city post-transportation tasks.

Problem: create coordinated local plans.

Final representation

Local plan development

Flight agent starts to coordinate with 2 agents. Develop initial schedules:

Flight agent talks to agent 2: conflicts detected.

Agents develop initial schedules:

Flight agent talks to agent 2: conflicts detected.
Flight coordinates with 2 tasks:

flight agent and agent 2 change local constraints;
both update their views: interdependencies known.

flight agent talks to agent 3: they detect a conflict between their plans.

Flight coordinates with 3 tasks:

flight agent and agent 3 change local constraints;
both update their views.

flight agent detects a conflict with agent 2 schedule.
Flight coordinates again with 2

Flight agent detects a conflict with agent 2 schedule: both change plan and starting times.

Flight coordinates with 1

Flight agent talks with agent 1: conflict between starting times.

Flight agent changes plan and schedule.

Conflicts detected with 2 and 3

There are conflicts with both agent 2 and agent 3.
There are conflicts with both agent 2 and agent 3: as a result of coordination changes in plans and schedules occur.

No more conflicts detected; all plans are locally and globally feasible.

Summary and Comments

- Planning and coordination are interleaved processes
- Planning agents are non-autonomous planners (prepared to revise their current local plan)
- Offers possibilities to interleave planning + coordination + execution
- Cooperative properties of agents required? Completeness?
Plan Merging
a post-planning coordination technique

Plan merging: research

- well-known plan merging techniques:
  - Sacerdoti (Noah)
    use critics to handle interactions between parts of a plan (use existing objects, eliminate redundant preconditions)
  - Wilkins (SPE)
    phantoming
  - Foulser, Li and Yang:
    identify subsequences of plans steps that can be achieved by a simpler sequence of less cost. Can also be applied in a single agent version.

Plan merging: research (c’td)

- idea
  - apply merging by identifying free resources (plan products) in (other) plans that can be used to realize goals of an agent
  - as a result, some planning products serving to realize the goals and operators needed to realize them can be removed.
Example plan merging

By cooperating, there exist better plans

Plans: Conceptual representation

Plan representation

Plans developed
Basic idea: use free resources

Plan representation: merging

As a result, we have two new interdependent plans. Agent 1 is now dependent upon agent 2 for achieving the goal of transporting passenger 2 from C to D.
Summary and comments

- plan merging is a suitable technique for both competitive and cooperative planners to improve their own plans by removing incompatibilities and exploiting positive interactions.

- the quality of the resulting plan is dependent upon the cooperativeness of the participating agents and the quality of the original plans produced.

- plan merging algorithms differ in:
  - the choice of the plan objects to be merged,
  - the amount of detail required about the plans to be merged and
  - the any-time character of the merging algorithm applied.