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Master in Artificial Intelligence

Introduction to Multi-Agent Systems

Analysis of Cooperation Mechanisms

Deliverable 2

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1 Introduction

In this report we analyze the cooperation mechanisms of the multi agent system (MAS) described in the previous report with the task of recycling the garbage in a virtual city. Section 1.1 defines the common goal and performance measure of the MAS on which the choice of different possible actions of the agents will be based. Section 1.2 gives an overview of the different coordination tasks in this specific problem.

Section 2 analyzes the different possible cooperation mechanisms that could be chosen to solve the problem: Contract Net, Auctions, Coalitions, GPGP, and Voting. For all mechanisms a general description is given, followed by possible applications to the specific problem of garbage collection, and advantages and disadvantages.

In section 3, the chosen mechanisms are presented together with a justification of why they were chosen.

1.1 Goal Definition

All the agents in our MAS are contributing to the goal of recycling the garbage in the city in an efficient manner (except for the SystemAgent, which is solely taking care of the state of the virtual city and not further interacting with it). In order for several agents to contribute towards solving a distributed problem, they need to be coherent (working towards the same goal) and competent (knowledge how to work together). While we define the competence of the agents in the following sections by specifying their coordination mechanisms, we start with defining the common goal of the MAS, that ensures coherent behavior.

All agents should aim to maximize a common global performance measure. According to the project description, the MAS ought to maximize the benefits (points received by recycling centers) while minimizing the time to recycle garbage. The agents' decisions will be based on evaluating different possible plans for the next t time steps using these goal measures and often there will be a trade off between achieving maximum points or minimal waiting time.

For all possible plans of actions $p \in \mathbb{P}$ we want to maximize the benefits of the plan:

$$\max_{p \in \mathbb{P}} b(p)$$

with $b(p)$ being the sum of benefit points achieved with the plan p, while, at the same time, we want to minimize some measure of waiting time:

$$\min_{p \in \mathbb{P}} t(p)$$

with $t(p)$ being an evaluation of the waiting time corresponding to p. Looking at the specific domain of garbage recycling, it makes sense to punish long waiting times over-proportionately. Hence we choose $t(p)$ to be the sum of squared waiting times of all garbages between being put on the map and being picked up by a HarvesterAgent.

Combining our two subgoals, we get the combined performance measure:

$$\max_{p \in \mathbb{P}} \theta_1 \cdot b(p) - \theta_2 \cdot t(p)$$

with θ_1 and θ_2 weighting the relative importance of benefits and weighting time. Since there are no further indications as to which of the subgoals should be considered more important, we set $\theta_1 = \theta_2$.

1.2 Analysis of necessary cooperation

The MAS is cooperative-benevolent, i.e. all agents work towards the same goal, which we defined in the previous subsection. The following coordination tasks are necessary to achieve the common goal:

- **Scouting Coordination**: The task of coordinating the Scout Agents (SA) in a way that maximizes the probability of detecting new garbage. SAs should obviously be well distributed over the map and primarily scout areas with high probabilities of detecting garbage (i.e. areas that haven't been scouted for a long time).
- **Harvesting Coordination**: The task of coordinating the Harvester Agents (HA) in a way to most efficiently recycle the detected garbage with respect to the performance measure defined in section 1.1.
- **Vehicle Coordination**: The task of combining the plans of scouting and harvesting, detecting collisions of vehicles, and resolving these collisions in a way that leads to the smallest loss of performance measure.

2 Analysis of Cooperation Mechanisms

2.1 Contract Net

2.1.1 General Description

The Contract Net protocol was developed by R.G.Smith in 1980 [Smi80] and is based on the way in which companies put contracts out to tender. There are five phases the protocol runs through to resolve a certain task:

- **Recognition**: An agent (called the "manager") recognizes a task that has to be done and that it cannot solve or does not want to solve.
- **Announcement**: The manager announces the task to all agents (general broadcast), a group of agents (limited broadcast), or specific agents (point-to-point announcement). The specification of the task includes a description of the task, constraints, and meta-information.
- **Bidding**: When an agent receives a task evaluate the task with respect to their specific properties and, if they are able and willing to solve the task, they submit a tender to the manager, indicating the relevant capabilities of the agent to solve the task.

- **Awarding**: A manager may receive several tenders for a task. Based on the information provided in the tenders, it chooses the best fitting agent or agents to execute the task. Chosen agents are called contractors for this task.
- **Expediting**: The chosen contractor or contractors then execute the task. If there is more than one contractor, further cooperation mechanisms might be necessary.

The Contract Net is based on a mutual selection process: Managers can select the best fitting tender and contractors can decide, for which announced tasks they want to create a tender.

2.1.2 Application to Practical Work

Harvesting Coordination: The coordination of harvesting garbage can be solved by using a Contract Net protocol. Newly detected occurrences of garbage are recognized by the Harvester Coordinator and then announced to Harvester Agents. This announcement can either be a limited broadcast to all Harvester Agents or even a point-to-point announcement to specific Harvesters of the right type that are currently idle. The Harvesters can individually evaluate which of the announced tasks fit well enough to their current situation (based on garbage types, current location, free capacity, planned route, etc.) and then submit tenders for these tasks. The HarvesterCoordinator can then choose the most suitable candidate(s) to take care of the garbage. If several HarvesterAgents are selected to solve a single task (e.g. because their individual capacity does not allow one HarvesterAgent to take the entire trash), they can use further coordination mechanisms to split up the task among them, or the Harvester Coordinator assigns the exact distribution of splitting up the task. Since the bidding process is based on several attributes (distance, capacity, targeted recycling center, etc.), we are facing a multi-attribute negotiation.

Scouting Coordination: The Scout Coordinator could use a Contract Net to announce the tasks of visiting cells that have been idle for a long time (and thus have a high probability of neighboring a building with garbage). Scout Agents can then submit tenders, e.g. containing how many steps they need to reach the idle cell and a numeric evaluation of the "idleness" of the path to this cell. This would be a multi-attribute-negotiation.

Vehicle Coordination: Potentially, when an upcoming collision of two vehicles is detected, the CoordinatorAgent can announce a task to the involved Agents (or their Coordinators) to resolve this collision in the best way they can come up with. The Coordinator Agent then chooses the best plan of avoiding the collision, based on a metric such as the number of extra steps required.

2.1.3 Advantages and Disadvantages

The Contract Net is well applicable for this problem, because:

- The goal of collecting all garbage is dividable into several subgoals: one for each occurrence of garbage in the city

- The subtasks of collecting individual garbage are sufficiently complex and it is worthwhile to spend effort into distributing them efficiently.

The disadvantages are the computational effort due to the exchange of messages, and the time delay for deliberation and waiting for responses

2.2 Auctions

2.2.1 General Description

A class of negotiation protocols, which provide us with methods for allocating goods/resources, based upon competition among self-interested parties. There are different types of auctions like the simple ones: English, Dutch, FPSB-First price sealed bid, Vickrey and then Multi-unit, Multi-attribute, Combinatorial and Others ...

2.2.2 Application to Practical Work

In case the Scouts would compete to get different or specialized routes they could bid to get different routes and then the ScoutCoordinator will choose to whom assign the specific route.

If this was the case we would choose a FPSB- First price sealed bid in which all of the scouts will bid of a specific route/position and then the one with the less cost/max performance will be the winner for that specific position/route, all of the scouts bids without knowing the others bids.

The harvester coordinator could make an auction for each group of garbage units to determine which harvester(s) should go there. The bids of the harvesters could depend on their current position, the position of the garbage, its current state (idle, on its way to another garbage collection, going to the recycling centre, pending garbages, ...)

This could be for example a FPSB where each of the Harvesters will bid (communicate its positions in regards to the garbage they want to collect and how much it will cost them to get there) without knowing each of the other harvesters.

There could be multi-unit auctions, if several garbage points are located close to one another and they are auctioned together. There could be a combinatoric auction of all the garbage at a certain point in time. Collected garbage could also be auctioned between recycling centers, if they were autonomous agents in this case the recycling centers will bid on which are closer to a specific harvester and its type of garbage.

2.2.3 Advantages and Disadvantages

The advantage of an auction is that it creates competition; it enhances the seller's bargaining power, this means that the harvester will really compete for getting a job as collecting a garbage and the coordinator (seller) will get to choose which is the best bid.

Flexibility, as protocols can be tailor-made

Advantages of multi-attribute auctions: They allow more degrees of freedom for bidders: price may not be the only attribute of interest and more efficient information exchange among the market participants

Disadvantages: The direally doesn't apply to our problem.. most are related to real bidding problems, like lying, shills, that doesn't apply to these agents

2.3 Coalitions

2.3.1 General Description

Coalition formation involves several agents creating a possibly temporary group to help achieve tasks that could either not be achieved individually, or in order to complete the task more efficiently by working together.

2.3.2 Application to Practical Work

Coalitions are definitely applicable to our garbage collection problem as the MAS has agents that are cooperative, communicate, and deliberative.

The different agents in our garbage collection problem have different and complementary abilities to achieve the common goal of collecting garbage as efficiently as possible. We have five different agents, as well as clones of scouts and harvesters. A coalition would bring together different agents (not clones) to help achieve the common goal more efficiently.

Joint action is possible regardless of whether the agents are cooperative or selfish, as long as a coalition is beneficial for the agents involved (Coalition structure generation: A survey). For instance, the scouting coordination and harvesting coordination are selfish in the sense that the agents involved act selfishly with regard to their tasks, acting in its own best interest with its own goal. In our case however, how the agents are structured, despite their own 'selfish' goals, they already contribute to the overall goal of the system to collect and recycle trash as efficiently as possible.

"When the task is completed, the payoff is distributed, the coalition is disbanded and agents continue to pursue their own agendas"

Scouting Coordination: The scouts are told where to go by the scout coordinator. They are purely reactive, as all they do is respond to find trash and communicate this information. A coalition between the scout agents only would not be useful as they do not have a common goal other than walking around as efficiently as possible. This efficiency has to be determined by the scout coordinator.

Harvesting Coordination: As suggested in the slides, the harvester agents could form a coalition given a list of detected garbage. This would include their current position, the position and quantify of garbage remaining to be collected, the agent's capacity (in case they are already loaded with garbage), and their state (whether their waiting or in the process of picking up or recycling garbage). A coalition is dismantled once the task is completed.

Vehicle Coordination: The vehicle coordination could work using a coalition between scouts and harvesters. When scouts and harvesters are working on fulfilling their own tasks, if they encounter one another, there is a conflict has to be resolved in order to continue. Forming a coalition could help avoid these conflicts, in order for each to complete their tasks more efficiently. This could work for instance by forming a coalition when agents are within a certain distance of one another. If an agent notes other agents within its personal radius, it can form a coalition to ensure that they efficiently get past each other without colliding and/or waiting longer than necessary. Additionally, the scouts and harvesters do not communicate with each other. However, it could be possible for instance if a scout and harvester are close to each other, and the scout spots some garbage along its path, that this information is immediately passed to the harvester.

2.3.3 Advantages and Disadvantages

The evident advantage of coalitions is that they allow agents to work together to increase efficiency; theoretically they are only formed if a better outcome can be achieved by working together.

A core issue of working with coalitions is to identify which coalitions should be formed in order to achieve a goal (Algorithms paper). "This usually requires calculating a value for every possible coalition, known as the coalition value, which indicates how beneficial that coalition would be if it was formed." It always requires a lot of communication between the agents who have to decide which coalitions to form, and they have to decide which mechanisms to use for the formation.

2.4 PGP

2.4.1 General Description

1. Each agent creates a local plan: its own goals and most important actions to solve problem (abstract plan), and steps to achieve next step in abstract plan. This is updated as plan is executed.

2. Agents exchange local plans and generate PGP by combining local partial plans. Each agent knows organisation structure and knows which agents to send plans to.

3. Optimise PGP: analyse received information e.g. detect if several agents working on same activity. Alter local plans to better coordinate activities.

2.4.2 Application to Practical Work

Scouting Coordination: The scout agents (SA) could be responsible for deciding their paths to discover garbage. They will put their proposed route information into their local plans and then send this onto the scout coordinator (SC). The SC then builds a PGP with the local plans from all agents. The SC detects if SAs plans are conflicting e.g. they plan to search the same area of map, they modify the PGP to avoid this and send this back to the scouts.

Harvesting Coordination: Similarly, when harvester agents (HA) find out about garbage location they can generate their own plan (route) to harvest this located garbage.

They add their suggested route to the garbage and onto appropriate recycling centre to their local plan, and send this onto the harvester coordinator (HC). The HC builds a PGP with the local plans from all HAs, and decides which HA route is the most beneficial for collecting which garbage. The HC modifies the PGP with its decision for each garbage collection and sends this back to the HAs so they have their updated individual plans.

Vehicle Coordination: The SC decides the routes that the SAs will take and this information goes into its local plan (it knows the current location and planned future location of all agents). Similarly, the HC is aware at all times of the location of all HAs, which are idle and which are en route to harvest garbage. This information is put into their local plan. The SC and HC send their local plans to the coordinator agent (CA). The CA builds a PGP and is able to see the locations and planned routes of all SAs and HAs. Using this information it can resolve conflicts e.g.two agents on one cell at one time, by deciding (based on a predetermined hierarchy) which agent must allow for another to pass by before continuing on its path. It will update the PGP with these decisions and send back to the SC and HC to update the SAs and HAs of any path modifications.

2.4.3 Advantages and Disadvantages

Advantages:

Flexible - so beneficial for changing environment i.e. new garbage added, plan can be updated to make optimal.

Efficiency - no two agents will work on same subproblem e.g. collecting same garbage

Disadvantages: Complexity

2.5 GPGP

2.5.1 General Description

GPGP is a domain-independent extension of PGP. Furthermore, GPGP mechanisms communicate scheduling for "particular tasks" [Decker & Lesser, 1995] rather than a complete schedule as in PGP. In this way agents can detect and coordinate task interactions.

(i) Agents update non-local viewpoints by sending information about a particular task to all other agents that can also solve it.

(ii) Deals with 'Hard' coordination relationships e.g. by committing prerequisites of certain tasks to be completed by a certain deadline and rescheduling agent actions.

(iii) Deals with 'Soft' coordination relationships e.g. where possible, committing for certain tasks to be completed as soon as possible if they benefit other tasks.

(iv) Avoiding redundancy: when it appears that more than one agent will be completing the same task, one agent is chosen either by random choice or by other means e.g. calculating the best solution. All other agents are updated with this information denoting another agent is completing the task.

2.5.2 Application to Practical Work

If two harvesters commit to collect the same garbage, this information will be shared in their non-local viewpoints. The harvester coordinator would detect the redundancy in this task and will choose the agent that offers the best solution e.g. closest to garbage. This agent will be notified to collect the garbage and the other will be updated with instructions that another agent is completing the task.

2.6 Voting

3 Chosen Cooperation Mechanisms

3.1 Scouting Coordination

As part of the global goal definition of the MAS (see section 1.1), one important subtask is to efficiently detect new garbage on the map. New garbage should be quickly detected in order to allow its harvesting. As rational agents, Scout Agents and the Scout Coordinator want to maximize the expected performance of this task.

We have chosen to employ a combination of cooperation mechanisms in order to best fit the scouting coordination task. This task is a special case of the multi agent patrolling problem, a problem that has been thoroughly investigated by the research community. [Alm+04] have investigated a variety of different approaches for this problem and conclude that the best approach on most classes of map topologies is a TSP[1]-based Single Cycle Approach. A cyclical path based on TSP-algorithms is computed for all cells of the map and Scout Agents patrol on this path in the same direction with more or less equal distances between them on the path. In order to achieve and uphold this equidistance, e.g. after collisions, we combine this approach with GPGP.

A near optimal TSP path through the map will be calculated based on some common heuristic-based algorithm (calculating optimal solutions is unfeasible since the TSP problem belongs to the class of NP-complete problems).

The SAs keep their local viewpoints updated with their current goals and actions - this will always be to follow their given path and to find garbage. If a situation arises in which a SA has to change its path to avoid a collision, (this coordination is described in Vehicle Coordination Mechanism), then this change of path will be updated to the SA's local viewpoint and then passed to the scout coordinator (SC) who will keep a partial plan of all SA local plans. The SC will calculate how best to keep the SAs equidistant following this change of path, e.g. by keeping all SAs stationary until the collision-avoiding SA is back to its original given path, and then it will pass these instructions back to the individual SAs. The SAs will now have updated local plans and will follow these new actions. In this way the SAs will continue, ensuring they are at equidistant points on their path to maintain our optimal map search. The same mechanism will be used to

[1]Traveling Salesman Problem

3.2 Harvesting Coordination

For the harvesting coordination we have chosen to implement three different cooperation mechanisms: voting for the garbage ordering, contract nets to assign the harvester to the garbage, and coalition for idle harvesters.

For the ordering of pending garbage, not yet picked up and unassigned, a voting mechanism will be implemented. The harvest coordinator will announce which garbage is pending, and each harvester agent will respond with an ordered list of the pending garbage that they could pick up most efficiently. Only the available harvesters will vote for the garbage.

In order to assign a harvester to a specific garbage collection task, we have chosen to use contract nets. In the order determined by the voting, the harvester agents bid if they are willing and able to pick-up the garbage in question. The coordinator then chooses the best fitting agent for this task and assigns it to the garbage.

In order for the idle harvesters to be more purposeful, they will form a coalition with the scouts. As the idle scout has no task to complete in the current state, it will follow a scout around in order to be closer to potential garbage to be discovered.

3.3 Vehicle Coordination

We will use GPGP for vehicle coordination. Each SA and HA includes their current goals and actions in their local plan. These are passed to their respective coordinators and from there passed to the coordinator agent (CA) who has a partial plan of all SA and HA current paths/actions. If a situation arises in which the paths of 2 vehicles are going to collide in n steps, the CA detects this and sets out to resolve it using the following solution:

We define a hierarchy of vehicle priorities, P, as follows:

1. Vehicle already moving to avoid collision
2. Harvester Agent moving to recycling centre (to recycle garbage)
3. Harvester Agent moving to garbage location (to harvest garbage)
4. Scout Agent
5. Harvester Agent idle

Avoiding collision solution:

`Max P (Vehicle 1, Vehicle 2) =>` Continue moving on current path.

`not Max P (Vehicle 1, Vehicle 2) =>` Go back on previous path taken until no longer in current path of prioritised vehicle. Remain stationary until prioritised vehicle is out of path. Move again on original path. (Note: whilst moving back on path and waiting stationary to avoid collision, this vehicle has higher priority than any other vehicle).

Using the above solution the CA sends these updated paths for the vehicles involved to the SC and HC, who in turn pass these to each vehicle. Their paths are updated in their local plans to avoid the collision.

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