Multi-robot exploration under communication constraint: a disCSP approach

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Outline

Multi-robots exploration

DisCSP for multi-robot coordination

Simulation

Conclusion

Context

Multi-robot systems (MRS) :

- set of autonomous mobile robots (usually with ***communication abilities***)
- collaboration between robots to perform a mission

In MRS, MANET are frequently employed. Each robot :

- is a node of the network
- is able to send, receive and relay data to other robots

Multi-robots exploration issue

In this work, we consider the problem of multi-robots exploration with communication constraints :

- a fleet of robots has to navigate in an unknown environment and construct a map of this environment
- robots have to collaborate to spread out on the ground and consequently speed up the exploration
- robots have to keep in touch with each other and/or with a control center to exchange data (partial maps, videos, ...)

Major difficulty : ***conciliate the two last point***

Related works

Most of algorithms use the concept of ***frontier-based exploration*** [Yamauchi98] :

- to speed up the exploration, robots have to gain new information about the environment,
- robots try to move towards the boundary between open space and unexplored area

In [Yamauchi98], no cooperation between robots. Most of improvements consist in introducing ***multi-robots coordination***.

Related works

Multi-robots coordination for the frontier-based exploration

- ***Centralized coordination :***
  - bids mechanism [Simmons *and al*00] (no maintenance of connectivity)
  - generate and test approach + use of utility function to choose the best joint move [Rooker and Birk07] (connectivity of the network ensured)

- ***Distributed coordination :***
  - selection of different behaviors based on analysis of the network topology [Vazquez and Malcolm04]
  - distributed bidding algorithms [Sheng and al06] (connectivity of the network taken into account but not guaranted)

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What is a disCSP ?

A disCSP (X, D, C, A) is an extension of classical CSP :

- A is a set of agents $\{A_1, A_2, \ldots, A_p\}$
- X is a set of variables, each A_k owns a subset of X : X_{A_k} with $\bigcap_{A_k \in A} X_{A_k} = \emptyset$
- D a set of domains : each variable $x_i \in X$ is associated to $dom(x_i) \in D$
- C a set of constraints applied to variables (a constraint of C can be intern to a agent or can link different agents)

Many distributed and asynchronous backtracking algorithms for solving disCSP : ABT [Yokoo90], AWCS [Yokoo], disDB [Bessiere and al05], ...

How to model multi-robots exploration as a disCSP ?

Basic ideas :

- each agent have one variable that expresses its next action (move)
- the space of possible actions can be modelled as domain
- the assignation of variables has to fulfill the following constraints :
  - the future location of each robot does not break the connectivity of the network,
  - the future location of each robot does not create overlaps between the sensor ranges of robots,

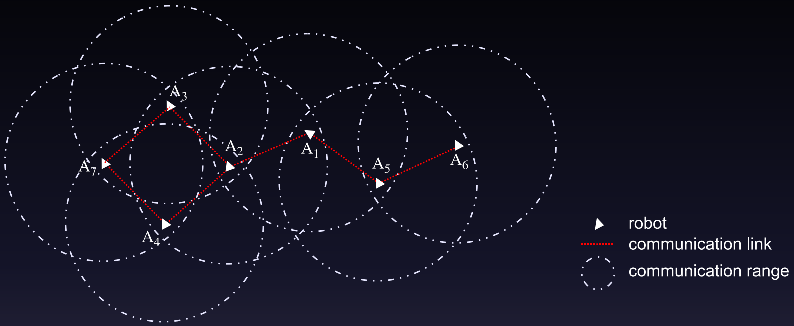
Requirement : each robot has to be aware about the network connectivity

Connectivity awareness

We use an algorithm proposed in [Le *and al*09] :

- each MRS has a reference node
- when all robots maintain a communication path towards the reference node, then the connectivity of the network is ensured
- based on exchanged messages, each robot maintains a table containing the id of access robots with which it has to maintain a direct connection in order to stay in touch with the reference node

Connectivity awareness : example



If A_1 is the reference node :

- table of A_3 :

Access Robots	Access Paths
A_2	(A_2, A_1)

- table of A_7 :

Access Robots	Access Paths
A_3	(A_3, A_2, A_1)
A_4	(A_4, A_2, A_1)

Multi-robots exploration as a disCSP

- $A = \{A_1, A_2, \ldots, A_p\}$ a fleet of p robots,
- $X = \{x_1, x_2, \ldots, x_p\}$, each x_i the next heading of A_i,
- $D = \{dom(x_1), \ldots, dom(x_p)\}$ with $dom(x_i)$ the set of all 8 cardinal directions that a robot A_i can choose to plan its next movement.
- $C = C_1 \cup C_2$ where :

$$\begin{aligned} C_1 = \ & \{\forall A_i \in A, \ \ \exists A_j \in AR_{A_i}, \\ & \qquad dist\,(fp(A_i, x_i), fp(A_j, x_j)) < cr\} \\ C_2 = \ & \{\forall A_i \in A, \ \ \forall A_j \in A \setminus A_i, \\ & \qquad 2sr < dist\,(fp(A_i, x_i), fp(A_j, x_j))\} \end{aligned}$$

with :

- AR_{A_i} the set of access robots for A_i,
- sr the sensor range of a robot,
- $fp(A_i, x_i)$ the future position of A_i
- cr the communication range of a robot.

How to express the frontier-based principle in our model ?

The fact that each robot has to move towards the frontier can be expressed by ordering the domain of each robot :

$$v_1 \preccurlyeq v_2 \equiv dist(fp(A_i, v_1), frontier) < dist(fp(A_i, v_2), frontier)$$

with $(v_1, v_2) \in dom(x_i)^2$.

Considering a particular direction, if an obstacle exists between the current position of a robot A_i and the frontier then this direction is put at the end of $dom(x_i)$.

Exploration algorithm

While a frontier exists do :

- update maps and connectivity tables for each robot
- construct the disCSP based on connectivity tables and current positions of robots
- order the value of each domain taking the distance to the frontier and to obstacles into account
- solve the disCSP to obtain future directions of each robot
- operate the movement of each agent during a fixed time period

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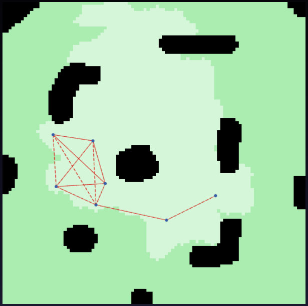
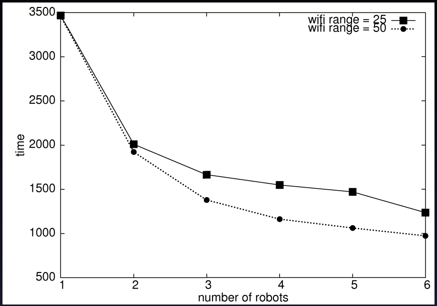
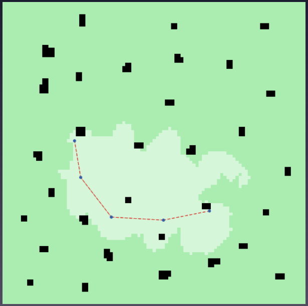
Simulation details

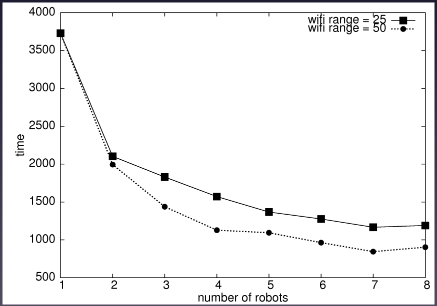
- simulation using NetLogo
- environment as a 100 x 100 grid
- robots tuned with different parameters : sensor range, communication range, ...
- data recorded at each simulation : exploration duration, travelled distance by each robot, number of exchanged messages, ...
- ABT as disCSP solving algorithm

Simulation results









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- disCSP is a good formalism to model coordination in multi-robot exploration
- exploration consist in solving a disCSP
- interesting results in simulation :
    - reasonable number of exchanged messages
    - exploration duration is reduced when robots are added
    - robust connectivity maintenance

Future works

- simulation with more complicated environments (with rooms, corridors, ...)
- tests with different disCSP solving algorithms
- implementation on real robots