Coordination despite constrained communications: a satellite constellation case

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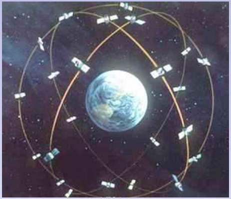
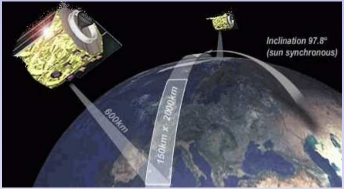
Introduction





Satellite constellation

- team of observation satellites ;
- communicate when they meet ;
- new tasks may arrive anytime ;

Observation tasks

- asynchronous tasks
- various priorities ;
- constrained by :
  - mutual exclusions ;
  - composition of sub-tasks.

Introduction

What is our problem ?

- Satellites (agents) must build a collective plan such as :
  - the number of realized tasks is maximal ;
  - the number of realized observations is minimal ;
  - observations are realized as soon as possible.
- Centralized planning is not considered because :
  - operating ground stations is costly ;
  - users desire to implement on-board autonomy ;
  - asynchronous requests prevent a reactive centralized planning.

What is our approach ?

- agents plan individually ;
- agents communicate in order to build a common knowledge ;
- agents build coalitions that influence their individual plans.

Outline

- A multi-agent system
- How to communicate ?
- Coordination via coalition formation
- Experiments and results

A multi-agent system

Constellation

Public knowledge

A constellation $\mathcal{S}$ is a triplet $\langle \mathcal{A}, \mathbb{T}, \text{Vicinity} \rangle$ with :

- $\mathcal{A} = \{a_1 \dots a_n\}$ the set of n agents representing the n satellites ;
- $\mathbb{T} \subset \mathbb{N}^+$ a set of dates defining a common clock ;
- $\text{Vicinity} : \mathcal{A} \times \mathbb{T} \mapsto 2^{\mathcal{A}}$ a symmetric non transitive relation specifying for a given agent and a given date the set of agents with which it can communicate at that date (*acquaintance* model).

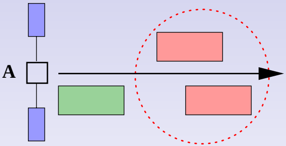
Each agent has a private knowledge :

1. knows some tasks to realize ;
2. plans tasks through intentions.

Tasks

A task t is defined by :

- a priority $prio(t)$;
- b_t a boolean specifying if t has been realized ;
- contraints : mutual exclusion and composition in sub-tasks.



What is a redundancy ? Two agents that realize the same task.

What is a composition ? A task compound of many subtasks.

Intentions

Intentions $I_t^{a_i}$ of agent a_i towards task t

- proposal ($\Diamond$) : a_i proposes to realize t ;
- weak withdrawal ($\neg\Diamond$) : a_i does not propose to realize t ;
- commitment ($\Box$) : a_i will realize t ;
- strong withdrawal ($\neg\Box$) : a_i will not realize t.

Each intention is associated with :

- a realization date $rea(I_t^{a_i}) \in \mathbb{T} \cup \{\emptyset\}$;
- a download date $tel(I_t^{a_i}) \in \mathbb{T} \cup \{\emptyset\}$.

How to generate intentions ?

- planned tasks generate proposals ($\Diamond$) ;
- unplanned tasks generate weak withdrawals ($\neg\Diamond$) ;
- others ($\Box$ and $\neg\Box$) are generated through coordination.

Knowledge

Tasks and intentions are captured through knowledge

A piece of knowledge $K^{\tau}_{a_i}$ of agent a_i at time τ is :

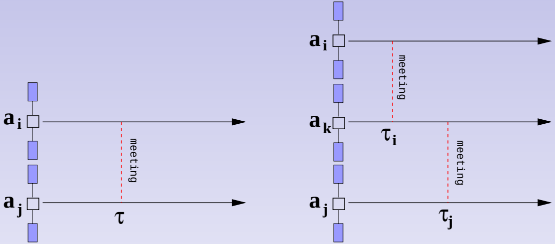
- a task t or an intention $I^{a_k}_t$ of a_k about t ;
- $A_{K^{\tau}_{a_i}} \subseteq \mathcal{A}$ is the subset of agents knowing $K^{\tau}_{a_i}$;
- $\tau_{K^{\tau}_{a_i}} \in \mathbb{T}$ is a temporal timestamp indicating the last update.

Knowledge is the information communicated by agents

How to communicate ?

How to communicate ?

There are two kinds of communications from a_i to a_j



direct communication **indirect communication**

Each communication is associated with $(\tau_i, \tau_j) \in \mathbb{T}^2$:

- τ_i is the emitting date of a_i ;
- τ_j is the receipt date of a_j

Communication

An epidemic protocol

1. each agent a_i considers its own knowledge changes ;
2. a_i communicates the changes to $a_j \in \mathrm{Vicinity}(a_i, \tau)$;
3. a_j updates its own knowledge thanks to the timestamp $\tau_{K^{\tau}_{\mathbf{a_i}}}$.

Aim

- build a common knowledge ;
- define a trust notion about proposals.

Common knowledge

Common knowledge on an intention $I_t^{a_i}$ captured by $K_{a_i}^{\tau}$

- incremental building ;
- based on $A_{K_{a_i}^{\tau}} \subseteq \mathcal{A}$ (agents knowing $K_{a_i}^{\tau}$) ;

At time τ, agent a_i knows that agent a_j knows $I_t^{a_i}$ iff :

- $a_j \in A_{K_{a_i}^{\tau}}$ **or**
- a_i communicated with a_j at (τ_i, τ_j) such as $\tau_{K_{a_i}^{\tau}} \leq \tau_i$, $\tau_j \leq \tau$.

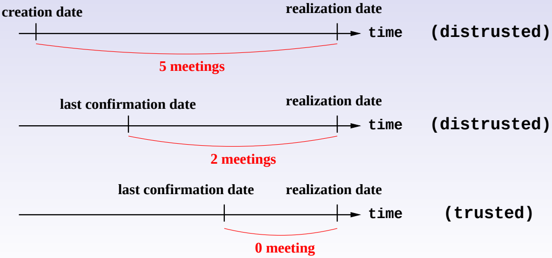
Trusting a proposal

Why trusting ?

- agents may revise their plans when new tasks arrive ;
- as communications are delayed, a proposal may become obsolete ;
- we propose dynamic and local trust computing.

How a_i computes trust about a proposal $I_t^{a_j}$? a_i computes :

1. the last confirmation date of the proposal ;
2. the number of meetings between this date and the realization date ;
3. if the proposal can be trusted or not.



Coordination via coalition formation

The collaboration model

What is our approach ?

- building a common knowledge ;
- generating coalitions tacitly and locally ;
- refining proposals ($\Diamond$) in commitments ($\Box$).

What are coalitions ?

- a set of goals (a task and its sub-tasks) ;
- a set of members ;
- a power : the set of goal tasks it members intend to realize.

Each agent :

1. generates the potential coalition structure ;
2. checks if it is incited to join a coalition ;
3. checks if it can withraw from a coalition to minimize it.

Generating the coalition structure

Coalition structure

- generated individually by each agent ;
- based on current knowledge of agents ;
- the potential coalition structure is not the same for each agent ;
- agents communicate to fix some part of the structure.

Each agent :

1. partitionates the set of tasks $\mathcal{T}_{a_i}^{\mathcal{T}}$ in $\{\mathcal{T}_1 \ldots \mathcal{T}_h\}$ according to the composition constraint ;
2. the coalition members for subset $\mathcal{T}_i$ are the agents that intend to realize a subset of $\mathcal{T}_i$;
3. the power of each coalition is this subset of $\mathcal{T}_i$.

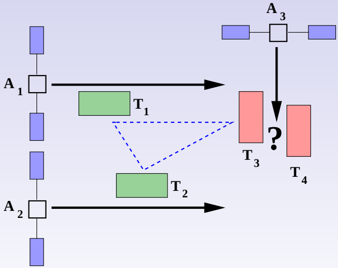
Incentive

The mechanism is based on :

- the aim is to angle the planning process towards collective goals ;
- these goals are the sub-tasks of a coalition goal ;
- task priorities are modified in the individual planning process.

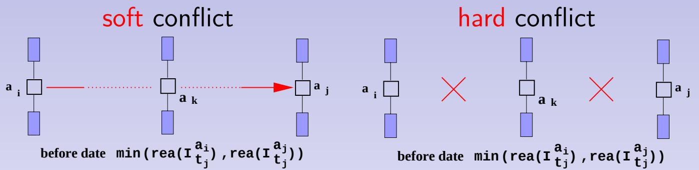
Exemple :

- O : goals ;
- P : planned tasks ;
- **Incentive :**
  $\forall\ t \in O,\ \text{prio'}(t) \leftarrow \frac{prio(t)}{1+|P|}$

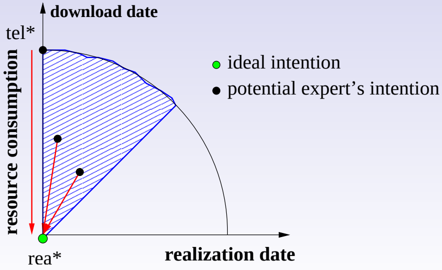


Minimization (1)

Conflict : agents that intend to realize the same task (redundancy)



Conflict resolution : optimization criterion



Minimization (2)

Soft conflict

1. expert agent commits ($\Box$) ;
2. non expert agents :
   - keep their proposal ($\Diamond$) if they don't trust the expert ;
   - else they withdraw strongly ($\Box\neg$).

Hard conflict

1. agents unaware of the conflict keep their proposal ($\Diamond$) ;
2. aware agents :
   - keep their proposal ($\Diamond$) if they don't trust unaware agents ;
   - else they withdraw strongly ($\Box\neg$).

Experiments and results

Experiments

Scenario 1 : performance

- 54-hours of simulated time ;
- every 6th-hours 40 new tasks (with sub-tasks) are generated ;
- 3 satellites ;
- metrics : realized tasks with and without redundancy.

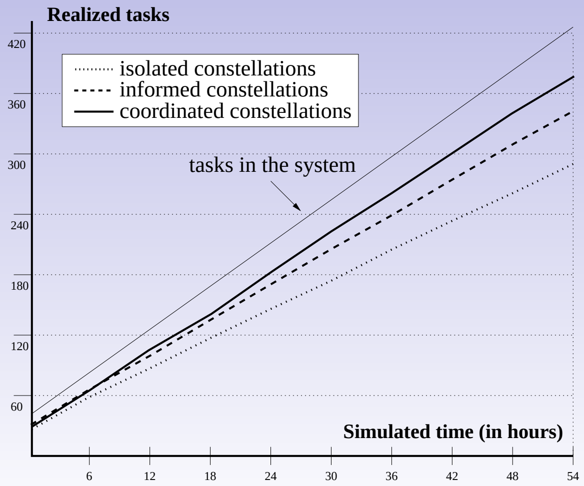
Scenario 2 : scalability

- 500 initial tasks to be realized (no time bound) ;
- 1 to 16 satellites ;
- metrics : swiftness and efficiency.

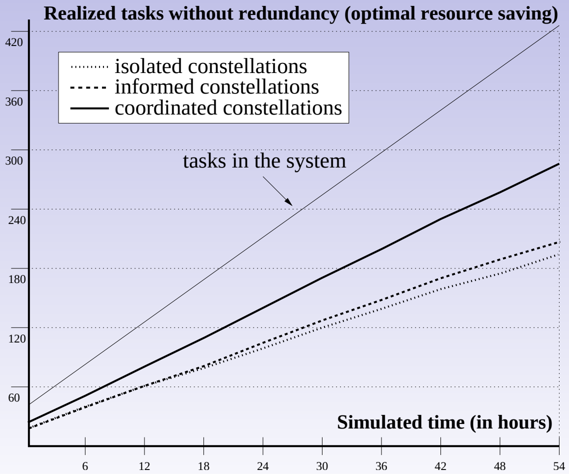
Three kinds of constellations

- isolated constellations ;
- informed constellations ;
- coordinated constellations.

Scenario 1

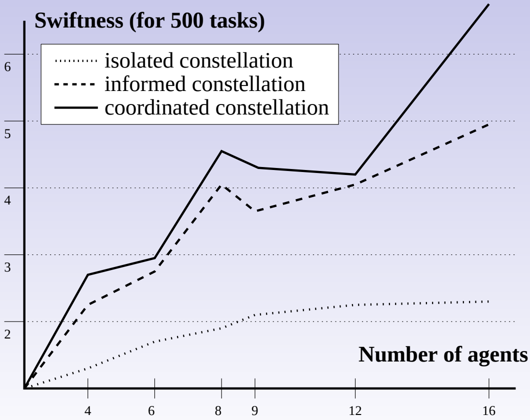

Realized tasks
420
360
300
240
180
120
60
isolated constellations
informed constellations
coordinated constellations
tasks in the system
Simulated time (in hours)
6
12
18
24
30
36
42
48
54

Scenario 1


Realized tasks without redundancy (optimal resource saving)
420
360
300
240
180
120
60
isolated constellations
informed constellations
coordinated constellations
tasks in the system
Simulated time (in hours)
6
12
18
24
30
36
42
48
54

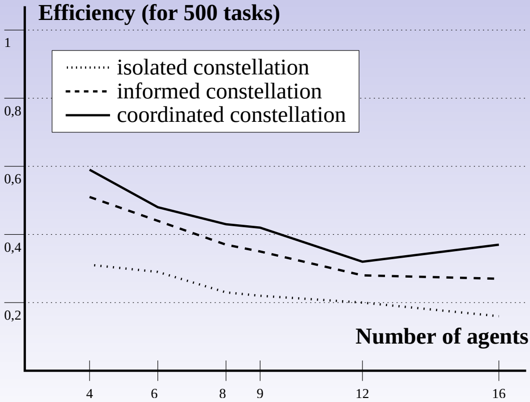
Scenario 2

$$\text{Swiftness} = \frac{\text{Time needed by a single agent}}{\text{Time needed by the whole constellation}}$$



Scenario 2

$$\text{Efficiency} = \frac{\text{Number of tasks}}{\text{Number of observations}}$$



Conclusion

Application

- constellation of communicating satellites ;
- new tasks arrive as time passes.

Coordination model

- agents build individual plans through intentions ;
- they share their knowledge and build a common knowledge ;
- from its knowledge, each agent builds the potential coalition structure ;
- coalitions are refined through incentive and minimization ;
- the coalition structure is adapted as new knowledge arrives.

Experiments

- the incremental process allows to realize more tasks ;
- efficient reduction of the resource consumption ;
- coordination allows important reduction of the number of satellites.

Thank you for your attention