Challenges raised by the deployment of fleets of drones

Decisional issues in multi-UAV systems

simon.lacroix@laas.fr
Laboratory for Analysis and Architecture of Systems
CNRS, Toulouse

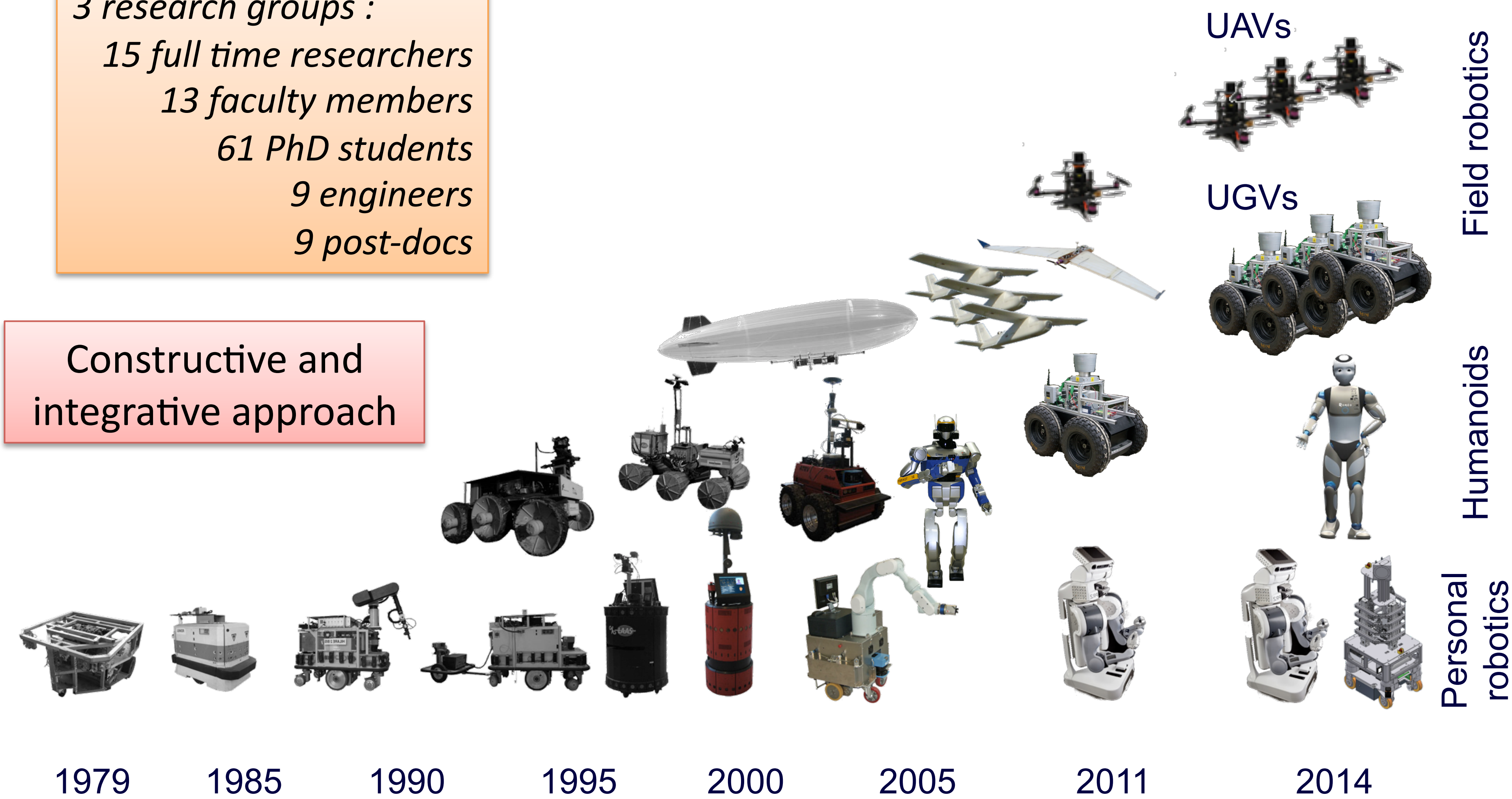
LAAS-CNRS

1st French-Danish Workshop on Unmanned Systems, DTU SkyLab, Feb 26-27 / 2015

(Where do I come from?) Robotics @ LAAS

3 research groups :
15 full time researchers
13 faculty members
61 PhD students
9 engineers
9 post-docs

Constructive and integrative approach



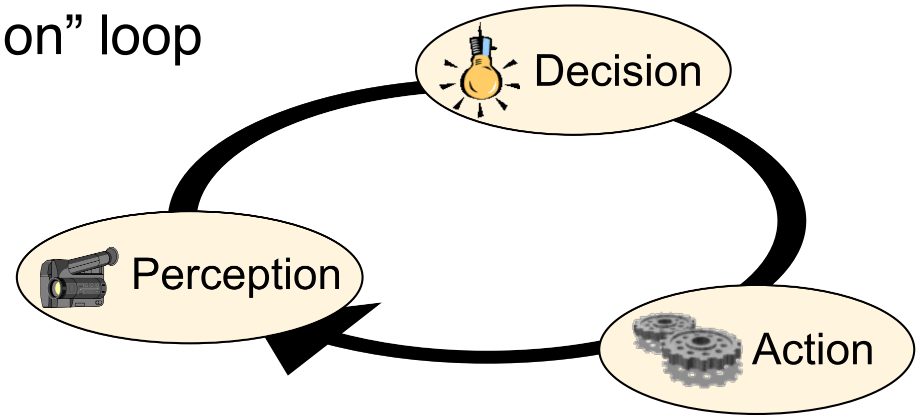
Open source software tools: www.openrobots.org

Our view of Robotics

"From automatic control to autonomous control"

- Automatic control :
  - Well defined task *("regulate variable", "follow trajectory"…)*
  - "Direct" link between (simple) perception and action
- Autonomous control :
  - More general task *("reach position", "monitor area "…)*
  - Calls for *decisional processes*

⇒ "Perception / Decision / Action" loop



Plus :
- Processes *integration*
- Learning
- Interaction with humans
- Interactions with other robots
- …

On multi-robot teams

- Advantages brought by robot teams
  - Increase of the achievable task and operation spaces
  - Higher robustness wrt. failures
  - Complementarities
    ➙ Operational synergies
    ➙ Robotic synergies

On the importance of *models* for autonomy

Planning = Simulation + Search

- Simulation of the effects of an action with a predictive model
- Search over possible organizations of possible actions to meet a goal or to optimize a criteria

Illustration: autonomous rover navigation

Simple instance of a perception / decision / action loop:

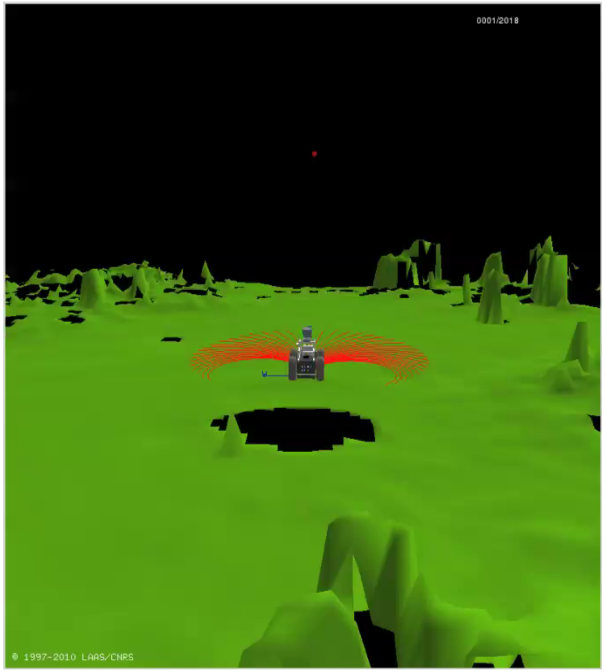
- Gather data on the environment, structure it into a model
- Plan the trajectory to find the “optimal” one
- Execute the trajectory

On the importance of *models* for autonomy

Planning = Simulation + Search

- Simulation of the effects of an action with a predictive model
- Search over possible organizations of possible actions to meet a goal or to optimize a criteria

Illustration: autonomous rover navigation



Simulation = convolution of action and environment models ➡ Environment models:

- at the heart of autonomy
- at the heart of cooperation

Multiple robots call for more autonomy

Main drivers for autonomy

- Dirty, Dull, Dangerous tasks
- Operations in remote areas
- Allows the deployment of complex systems
- Money savings !

Multiple robotics systems

- Are inherently more complex
- Call for new specific processes :
    - Cooperation
    - Task allocation
    - Task coordination
- Implies new decisional architectures

Outline

- Introduction: autonomy, models
- Illustrations:
  - Observing a set of locations
  - Multiple UAV/UGV systems
  - Exploring clouds

Observing a set of locations

Environment model ?   an empty space !

(possibly with a non uniform atmospheric flow field)

➡ Allows for "easy" development at the core of decision

"Monitoring a set of locations" mission

➡ For a fleet of UAVs, mainly a *task allocation* problem: which UAV will observe which location?

The task allocation problem

The “canonical” task allocation problem:

- Given:
  - A set of robots $\{R\}$
  - A set of tasks $\{T\}$
  - A cost function $c : \{R \times T\} \rightarrow \Re^{+} \cup \{+\infty\}$
- Find the allocation A^{*} that minimizes the cost sum (or the max. of individual costs, or the individual cost repartition, or…)

A well-known and well-posed problem (also named “optimal allocation problem) – but highly combinatorial

Main approaches:

- Centralized : optimization (MILP), genetic algorithm, simulated annealing
- Distributed :
  - DCOP, distributed protocols
  - Negotiation-based approaches: market-based approaches

Market based task allocation

Auctions (tasks) are published, robots bid, the "best" bidder gets the task

Basic functions required

- Ability to bid: task insertion cost evaluation
- Auctioning strategies: who places auctions ?
- Overall objective function to minimize

Many possibilities for each function, *e.g.*:

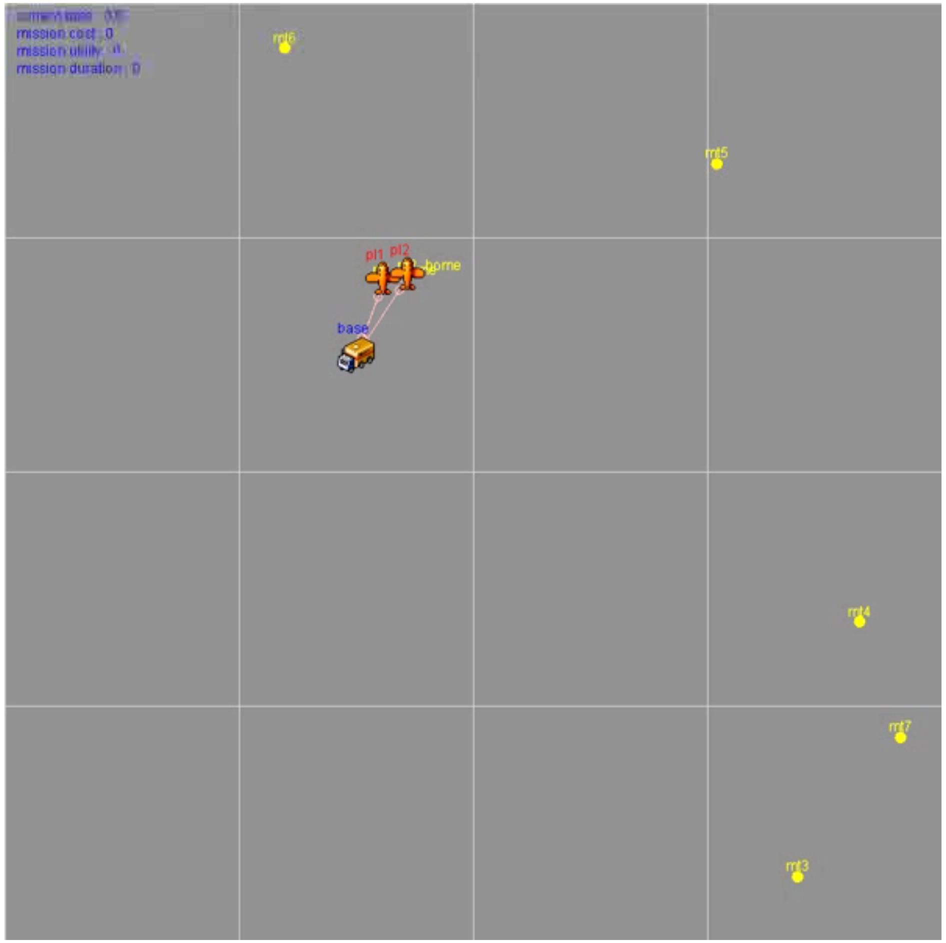
- Task insertion
  - From a simple cost addition…
  - … to a (complex) plan update
  - Mix costs, risks, utilities…
- Auctioning strategies
  - Centralized vs. bidders can emit auctions
  - When to close the market ?
  - Auctions can concern a set of tasks…
- Objective function
  - Sum of individual costs, dispersion of individual costs, max of individual costs…

B. Dias "Market-Based Multirobot Coordination: A Survey and Analysis" 2006

Market based task allocation

Illustration 1: the Multiple travelling salesman problem

- White dot = auction token
- Simple task insertion
- The cost includes an “equity” constraint
- All tasks are allocated before moving
- All robots must fly back home



Market based task allocation

Main features of market-based approaches

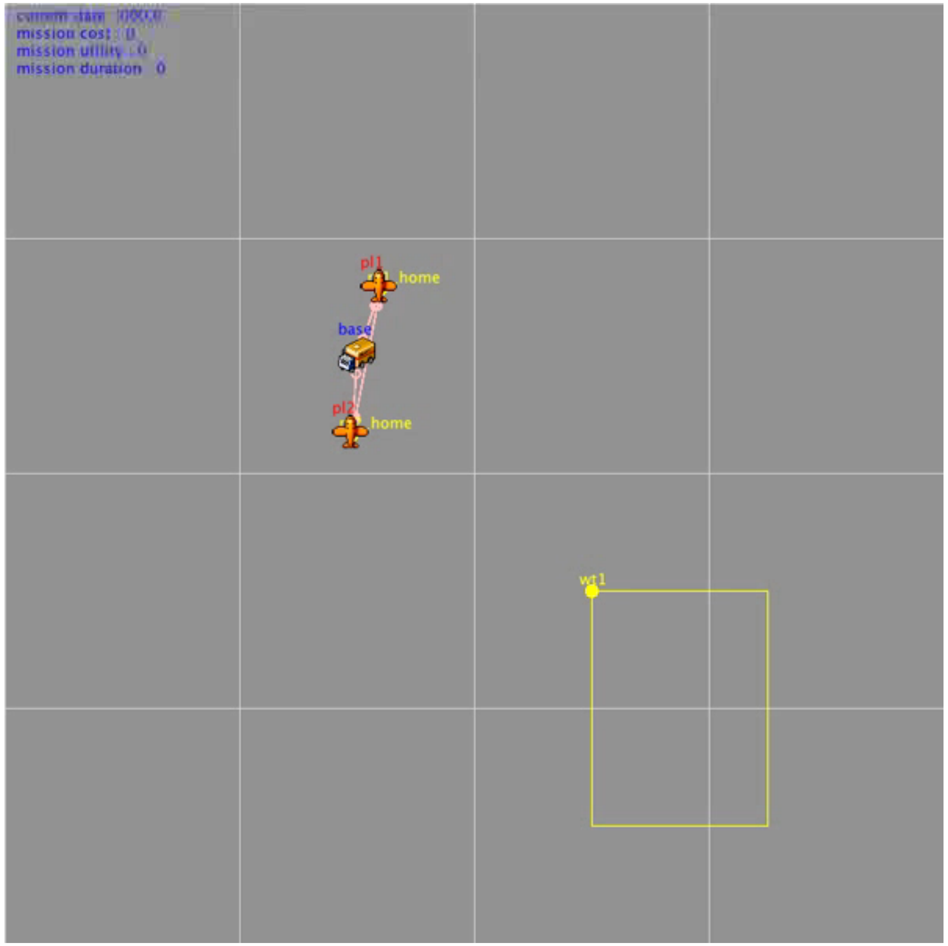
- A simple protocol, applicable to a wide variety of complex problems
- Can be distributed (can bear with communication constraints)
- Can handle dynamic events:
    - Robot failures
    - Unexpected events
    - New tasks

- No guarantee on any optimality

Satisfying communication constraints

- One single “survey” task (= square pattern)

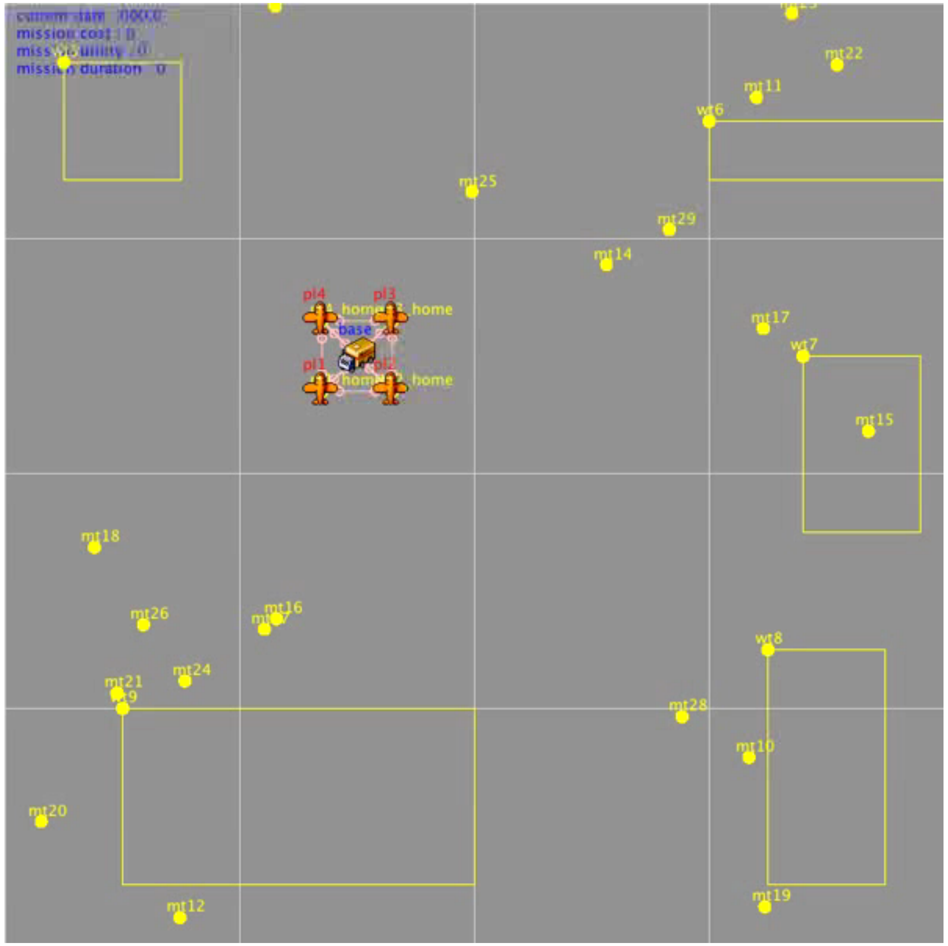
- The constraint satisfaction yields new tasks (“com relay”)



Satisfying communication constraints

Illustration: multi TSP + several constrained "survey" tasks

- 4 robots
- 5 survey tasks
- 18 places to visit



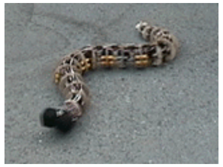
Outline

- Introduction: autonomy, models
- Illustrations:
  - Observing a set of locations
  - Multiple UAV/UGV systems
  - Exploring clouds

Fleets of robots

- *E.g.* Air / Ground fleets of robots
  - Ground robots





Good at:

- ✓ Precise information gathering
- ✓ Physical intervention
- ✓ Long duration missions
- ✓ Heavy load carrying

Not so good at:

- ✓ Global information gathering
- ✓ Self localization
- ✓ High speed mobility
- ✓ Avoiding hazards

  - Aerial robots


Good at:

- ✓ Global information gathering
- ✓ High speed mobility
- ✓ Avoiding hazards
- ✓ Communication relaying

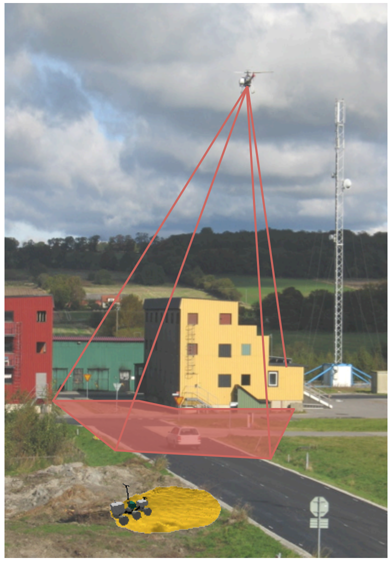
Not so good at:

- ✓ Long duration missions
- ✓ Physical intervention
- ✓ Heavy load carrying

Fleets of robots

- *E.g.* Air / Ground fleets of robots

  A variety of possible cooperation schemes:
  - UAVs assist UGVs
    - Localization
    - Communication relay
    - Environment modeling
  - UGVs assist UAVs
    - Detect clear landing areas
    - Carry on UAVs
    - Provide energy support



  - UAVs and UGVs cooperate to achieve a task / mission
    - Exploration
    - Monitoring
    - Intervention
    - …

Illustration: planning a patrolling mission

What action models have been used?

- Robot motion model

$$nav\_time(R_i, C_j, C_k) \in [0, +\infty]$$

$$nav\_cost(R_i, C_j, C_k) \in [0, +\infty]$$

- Observation model

$$obs1(R_i, C_j) = \{C_1, ..., C_n\} \subset M_{R_i}, C_j \in M_{R_i}$$

$$obs\_utility(C_j) \in [0, 1], C_j \in M_{R_1} \cup ... \cup M_{R_n}$$

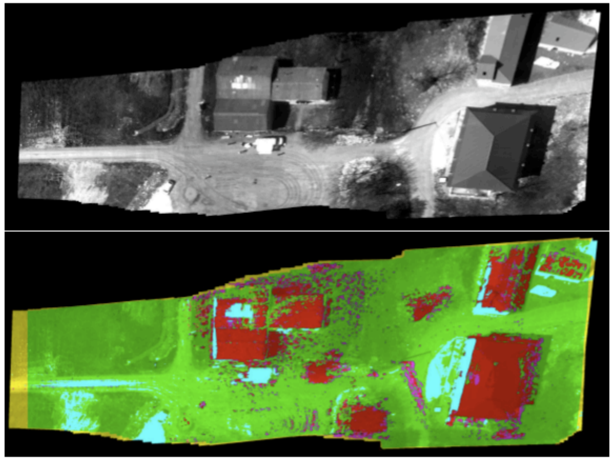
- Communication model

$$com(R_i, C_j) = \{C_1, ..., C_n\} \subset M_{R_i}, C_j \in M_{R_i}$$

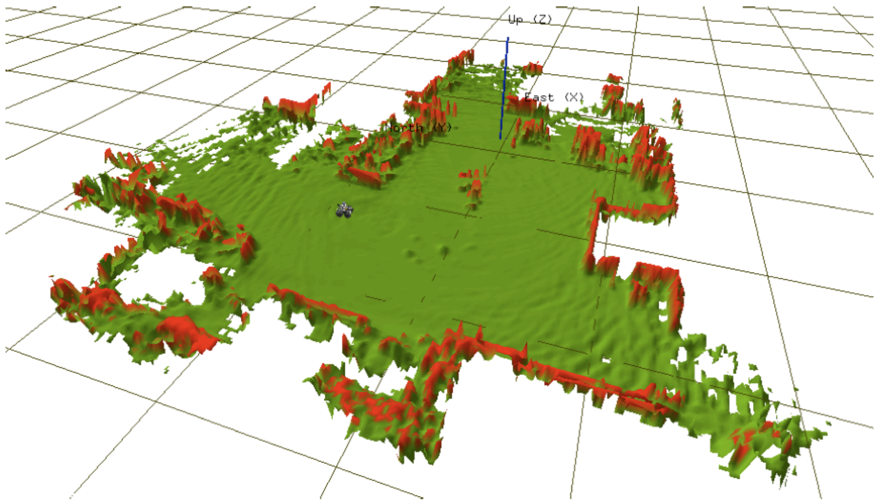
$$com2D(R_i, C_i, R_j, C_j) \in \{0, 1\}$$

What environment models have been used?

- To plan motions: express traversability / accessibility



- To plan observations: line of sight visibility



- To plan communications: line of sight visibility

Illustration: autonomous navigation revisited

Illustration : a cooperative patrolling mission

Outline

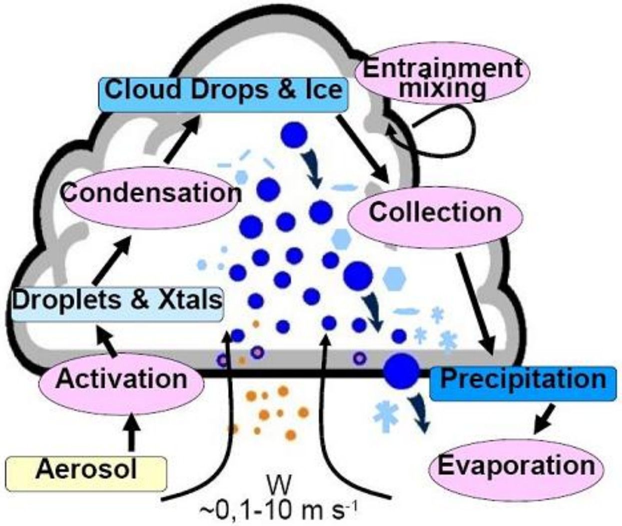
- Introduction: autonomy, models

- Illustrations:
    - Observing a set of locations
    - Multiple UAV/UGV systems
    - Exploring clouds

SkyScanner

"Deploying fleets of enduring drones to probe atmospheric phenomena"

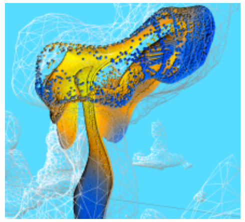
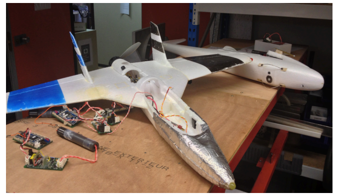
- Overall target: follow the evolution of a cloud with multiple drones to study entrainment and the onset of precipitation



  - Characterize state of boundary layer below and surrounding a cloud
    - atmospheric stability
    - lifting condensation level
    - cloud updraft
  - Follow 4D evolution of the cloud
    - entrainment at edges
    - inner winds
    - amount of liquid water
    - cloud microphysical properties

➡ Impacts the drone conception and the fleet control

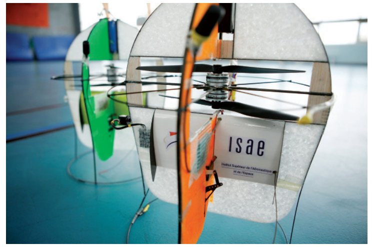
SkyScanner: involved partners

CNRM

“Centre National de Recherches Météorologiques”

Experts in atmospheric sciences, fly drones

ISAE

“Institut Supérieur de l’Aéronautique et de l’Espace”

Experts in fluid dynamics, flight mechanics & drones

ONERA

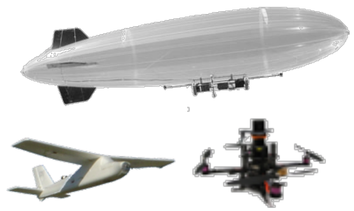
“The french aerospace lab”

Experts in flight control


ENAC

“École Nationale de l’Aviation Civile”

Experts in drones (cf Paparazzi autopilot)



LAAS

Laboratory for Analysis and Architecture of Systems

Roboticists

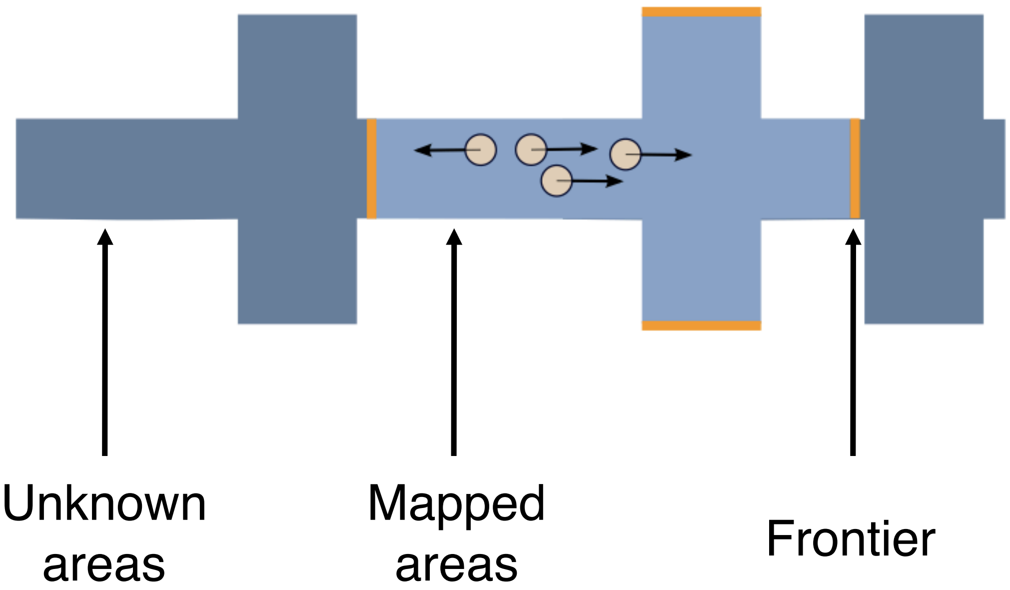
Fleet control

- An adaptive sampling problem
  - Servo on the gathered information to gain more information
  - Optimize the drones trajectories (trade-off: explore vs. sustain)

- Inputs
  - Models of the drones
  - Model of the cloud (initiated by LES, continuously updated on-flight)

Analogy with multi-robot exploration

- A well studied problem

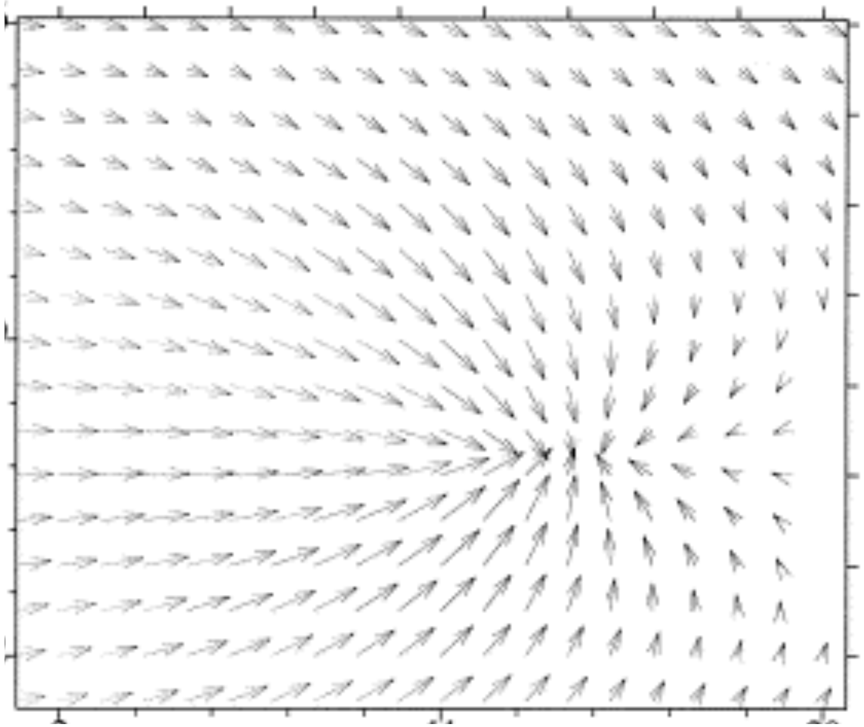


Frontier-based exploration:

- Who goes where?
- How?

Limits of the analogy…

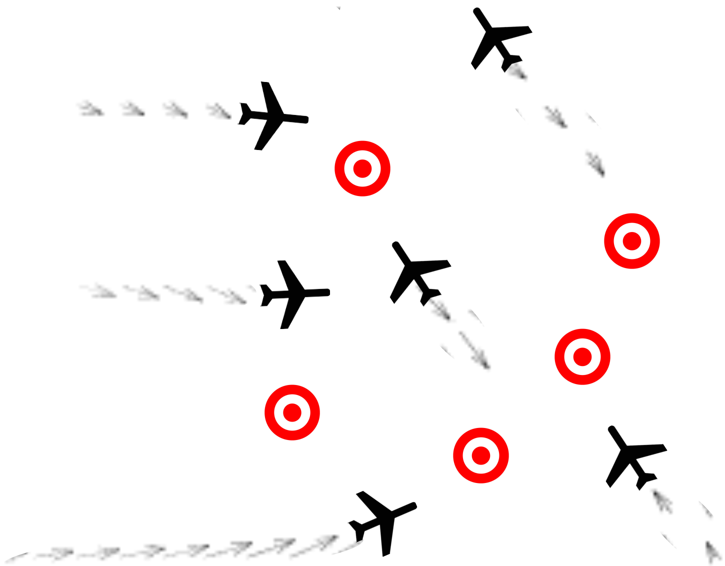
- A *dynamic* phenomenon…
- … observed *locally*



"Air truth"

Limits of the analogy…

- A *dynamic* phenomenon…
- … observed *locally*



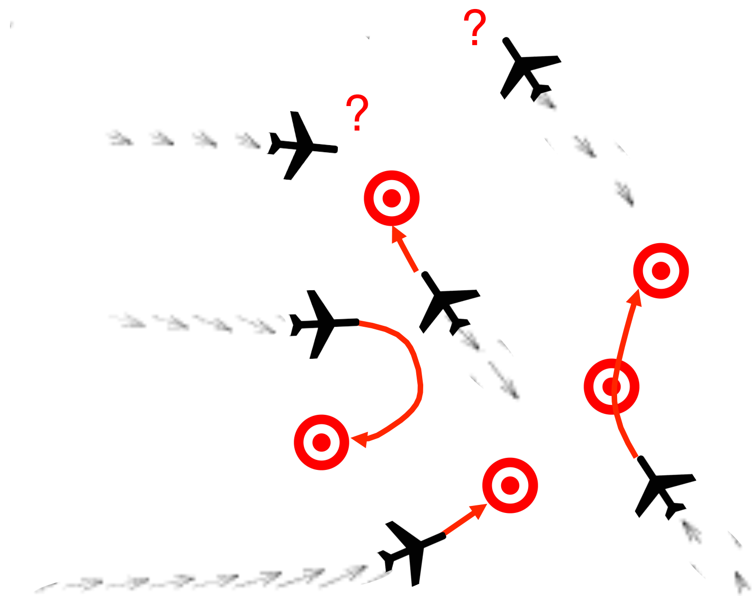
Known information at time t

1. Where to gather new information?

2. Who is flying where?

Limits of the analogy…

- A *dynamic* phenomenon…
- … observed *locally*



Known information at time *t*

1. Where to gather new information?

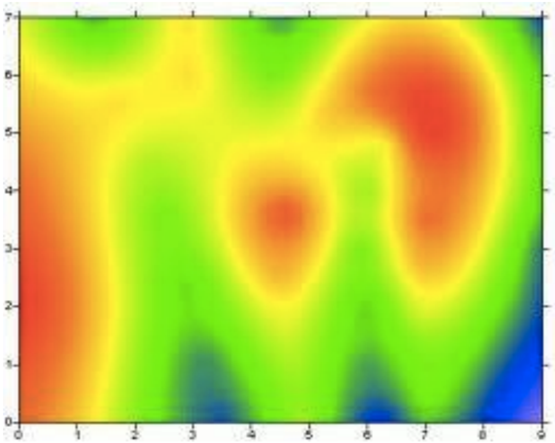
2. Who is flying where? And how?

➡ Numerous questions to answer

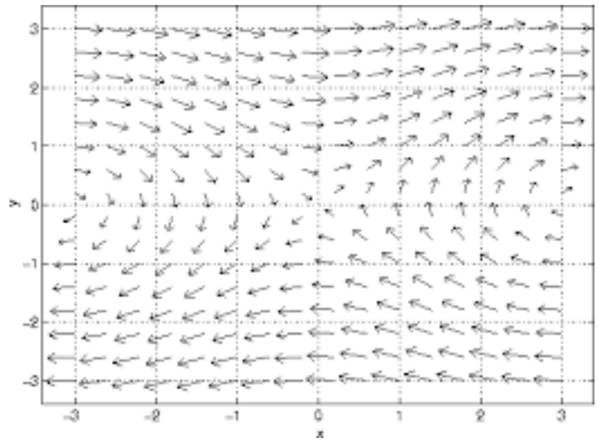
- Predefined patterns vs. pure adaptive solutions?
- Distributed vs. centralized solutions?
- Waypoint nav. vs. trajectory following?
- Heterogeneous fleet?
- …

Models

- Which environment model?
  - For the planning purposes



Scalar “utility” field



Wind vector field

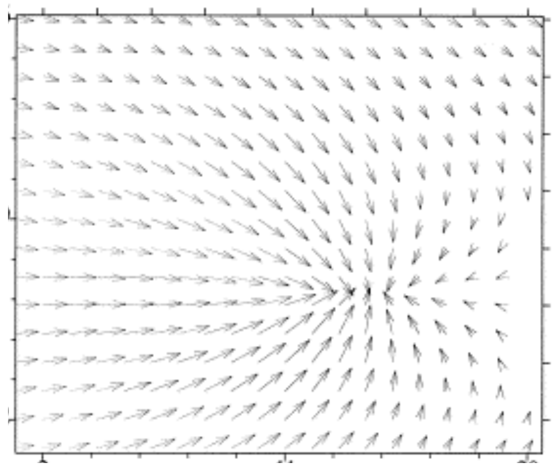
(both information are 3D, time varying and uncertain)

1. How to define the utility?
   - Atmospheric parameters (P,T,U,winds, …)
   - Uncertainties
   - “Scientist knowledge” (~ coarse cloud model)

} ¿ utility ?

Models

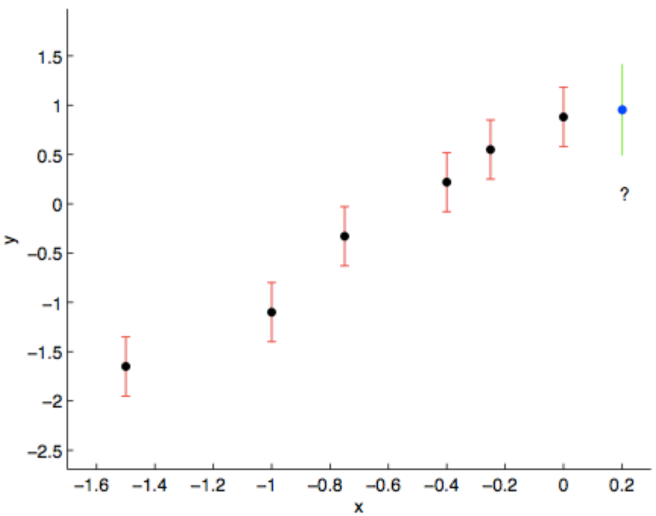
2. How to build the environment models?

From  to 

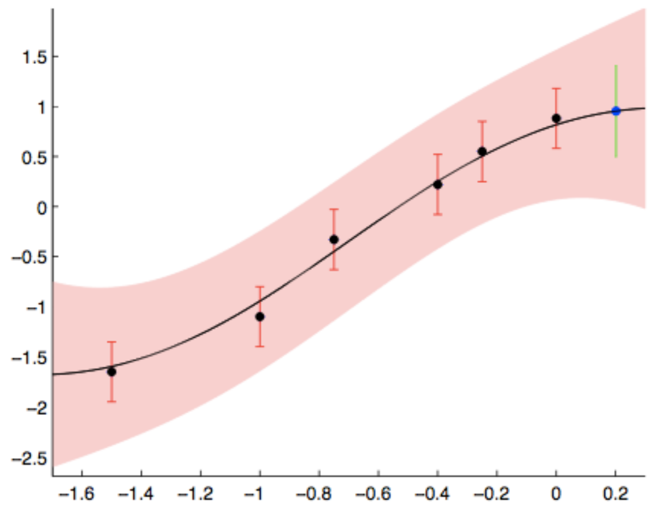
Models

2. How to build the environment models?
   - Gaussian Process Regression ? (*aka* “kriging”, originally exploited in geosciences, spatial analysis – used in [Lawrance 2011])

From



to

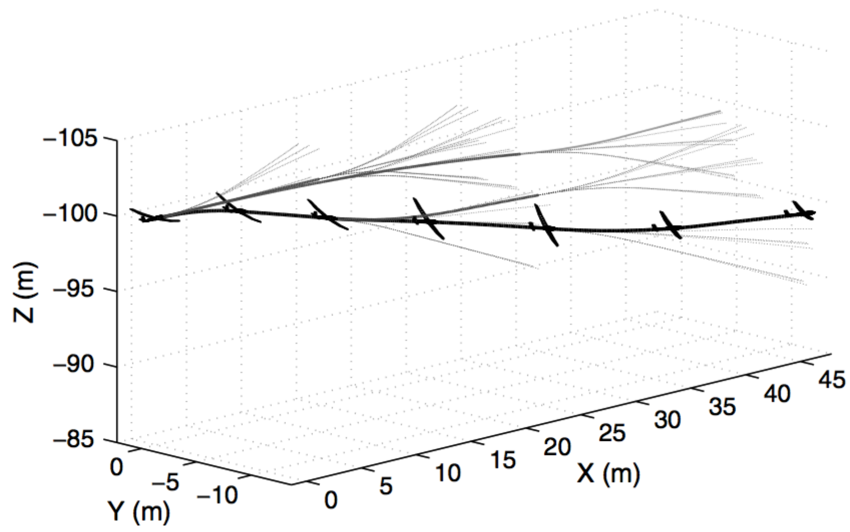


Estimate y^* from any x^* using *only* a kernel function $k(x_1,x_2)$ that encodes the spatial dependence between the data

(still possible to introduce priors on the model – *cf* coarse cloud model)

Models

- Which drone model?
  - Kinematic constraints



  - Express energy variations
    - Kinetic (airspeed)
    - Potential
    - Stored (battery)

Outline

- Introduction: autonomy, models
- Illustrations:
    - Observing a set of locations
    - Multiple UAV/UGV systems
    - Exploring clouds
- Wrap up

Conclusions

- Models are at the core of autonomy
  - Action models
  - Environment models

➡ Models are at the core of cooperation

- Most often, having the required information is having solved the problem

  ➙ Numerous tasks / missions can be turned into of information gathering approaches

- Autonomous robots (robot teams) are info-centric systems

  ➙ Key-role of environment representations