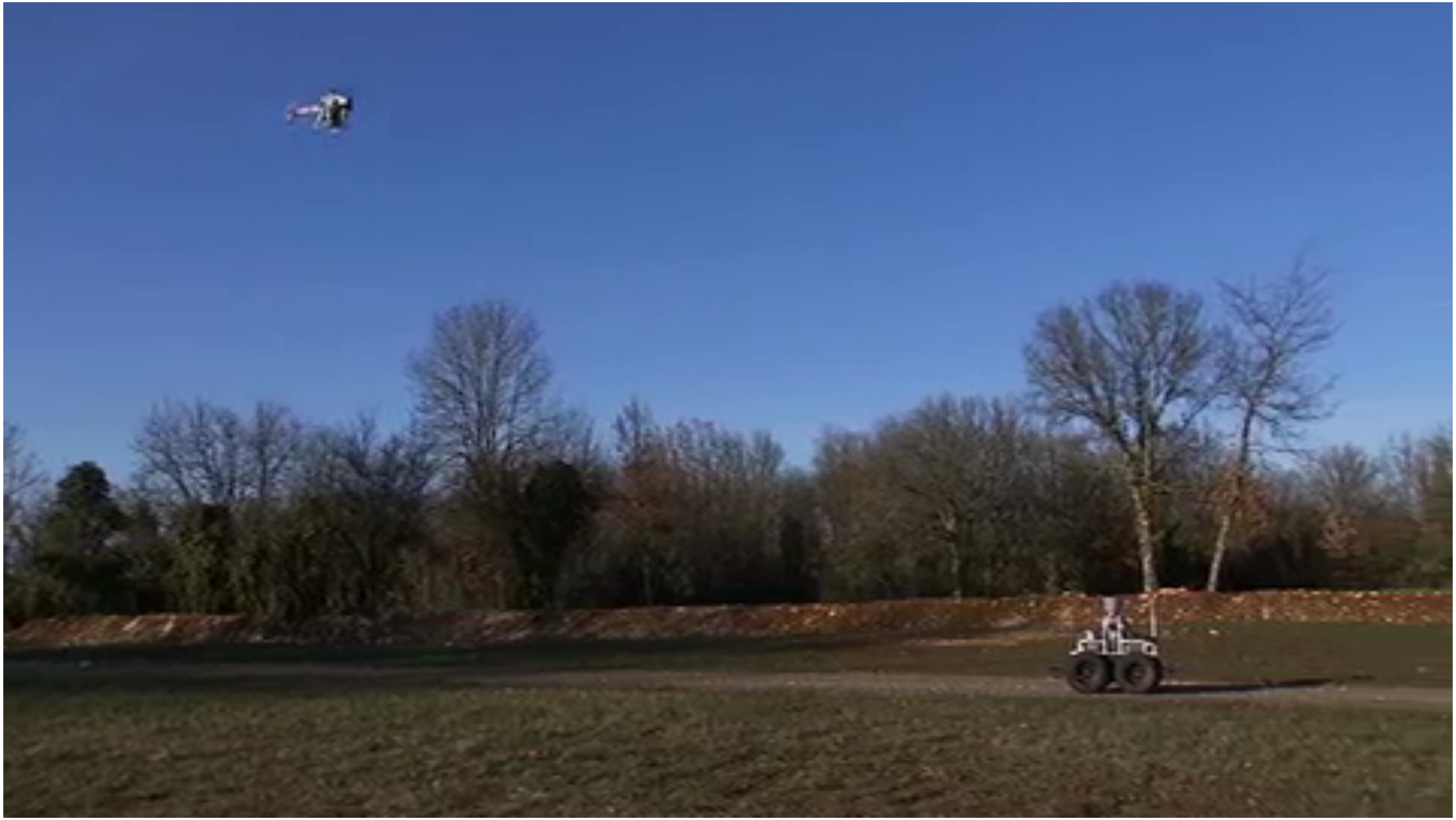
Autonomous teams of aerial and ground robots in search and rescue missions

Simon Lacroix
Laboratory for Analysis and Architecture of Systems
CNRS, Toulouse

LAAS-CNRS

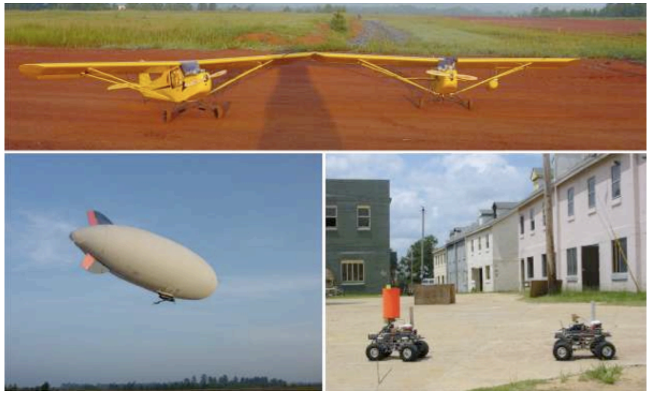
Context: teams of field robots



Air/ground robot teams

"Remote eye" @ CMU

On going work @ ACFR



Mars2020 @ UPenn

Usual advantages brought by robot teams

- Increase of the operation space
- Higher robustness wrt. Failures
- Complementarities
  - ➞ Operational synergies
  - ➞ Robotic synergies

UAVs assist UGVs

- Localization
- Communication relay
- Environment modeling
- …

UGVs assist UAVs

- Detect clear landing areas
- Carry UAVs
- Provide energy support
- …

Where and what for?

Dozens of *heterogeneous* robots *cooperate* to achieve *long-lasting* missions in *large* environments

Considered missions:

- exploration, search
- coverage / patrolling: observations, scene analyses, situation assessments
- *interventions* in the environment

In various application contexts:

- Environment monitoring (pollutions, science, …)
- Search and rescue
- Civil security, defense applications

Where and what for?

Dozens of *heterogeneous* robots *cooperate* to achieve
long-lasting missions in *large* environments

Large scale (km^3) implies:

- Faster robots, longer missions (“lifelong autonomy”)
- Communication constraints
- Large (multi-scale) environment models

Robot teams must not imply teams of operators !
➞ A *high level* of autonomy is required

(operators are not considered throughout this talk)

Outline

“On the importance of environment models”

Outline

Autonomous decision making in air/ground systems

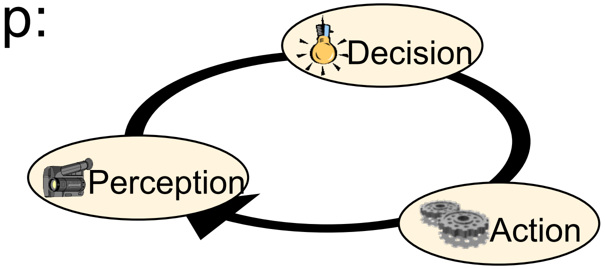
Environment models

And yes, localization

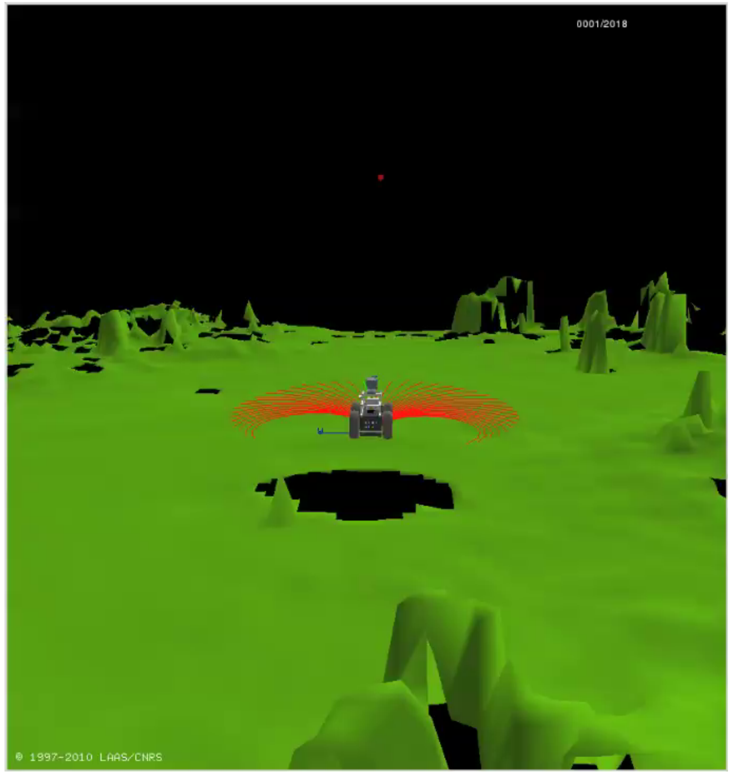
(Mostly on-going work, with some unstable choices / ideas)

An elementary decision: AGV obstacle avoidance

Simple instance of a perception / decision / action loop:

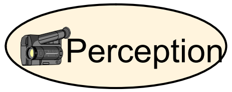


- Gathering data on the environment
- Structuring the data into a *model*
- *Planning* the trajectory to find the "optimal" one
- Executing the trajectory

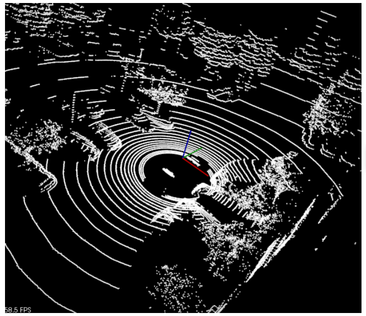


An elementary decision: AGV obstacle avoidance

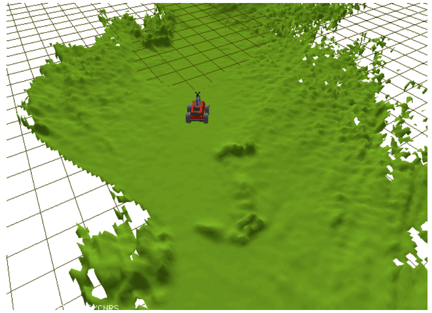
Simple instance of a perception / decision / action loop:



- Gathering data on the environment
- Structuring the data into a *model*



Depth image



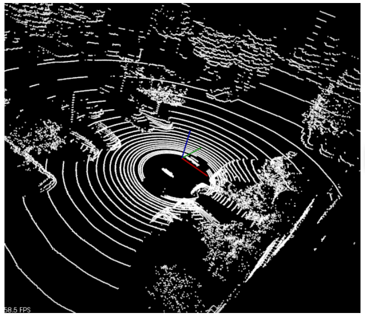
Digital terrain map

An elementary decision: AGV obstacle avoidance

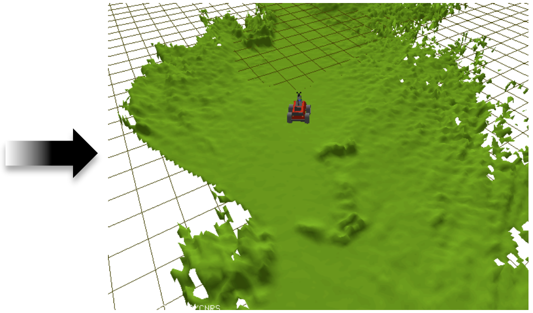
Simple instance of a perception / decision / action loop:

Perception

- Gathering data on the environment
- Structuring the data into a *model*



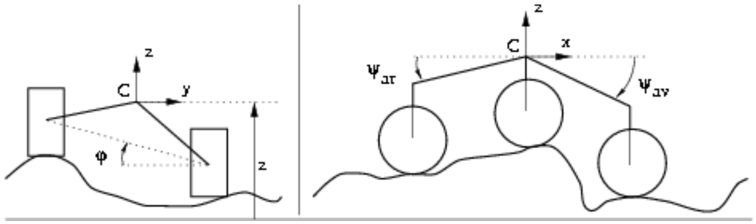
Depth image

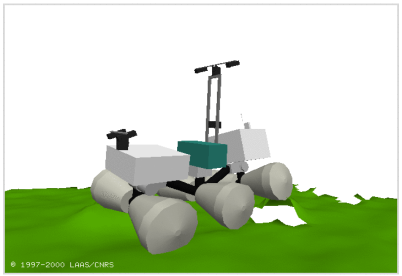


Digital terrain map

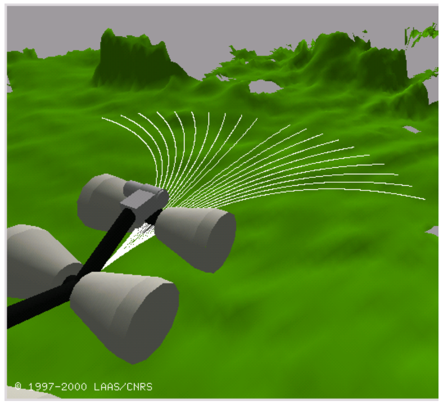
Decision

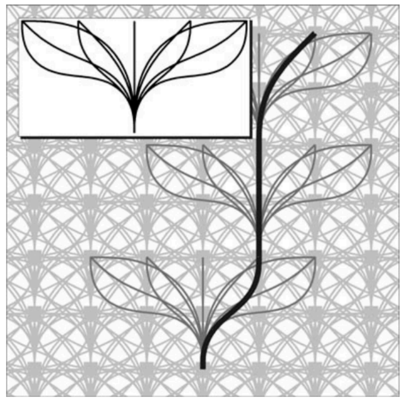
- *Planning* the trajectory to find the “optimal” one





Convolution of the robot model with the terrain model





Search

Action

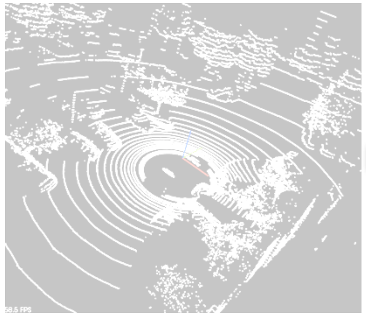
- Executing the trajectory

An elementary decision: AGV obstacle avoidance

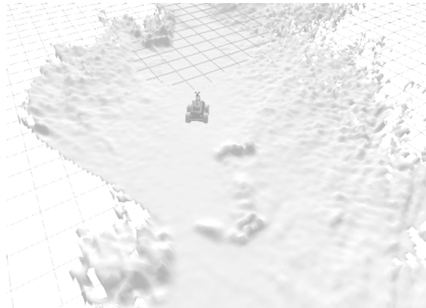
Simple instance of a perception / decision / action loop:

Perception

- Gathering data on the environment
- Structuring the data into a *model*



Depth image



Digital terrain map

Decision

- *Planning* the trajectory to find the “optimal” one

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

Action

- Executing the trajectory

1. Planning a surveillance mission

Given:

- A team of robots
- An environment to monitor
- A set of constraints to satisfy (*e.g.* communications)

➡ Find the (optimal) trajectories to observe the whole environment

1. Planning a surveillance mission

Given:

- A team of robots
- An environment to monitor
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Observation tasks (hence motion tasks)
- Communications

Approach:

- A task allocation process (distributed market-based approach)
- Large scale: interleaving allocation and decomposition processes

1. Planning a surveillance mission

1. Planning a surveillance mission

Given:

- A team of robots
- An environment to monitor
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Observation tasks (hence motion tasks)
- Communications

Required models:

- Of the observation tasks
- Of the robots motions
- Of the communications

2. Navigating a rover in an unknown environment

Given:

- A team of robots
- An unknown environment
- A set of constraints to satisfy (*e.g.* communications)

➡ Find the (optimal) trajectory for the rover to reach a given goal

2. Navigating a rover in an unknown environment

Given:

- A team of robots
- An unknown environment
- A set of constraints to satisfy (*e.g.* communications)

Approach:

- The UAV serves the UGV, by providing *traversability maps*
- Find the areas to perceive by the UAV relevant for the mission

Actions to plan:

- Environment modelling tasks
- AGV and UAV Motions
- Communications

2. Navigating a rover in an unknown environment

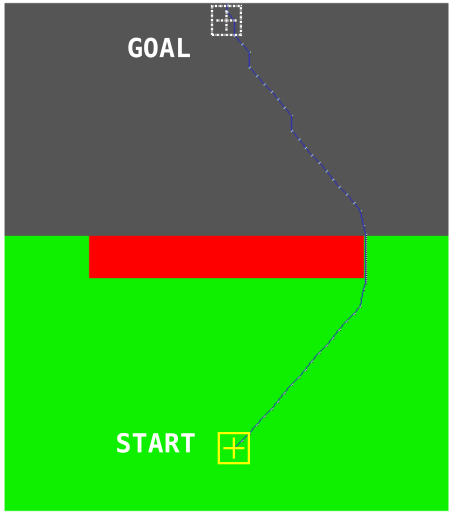
Given:

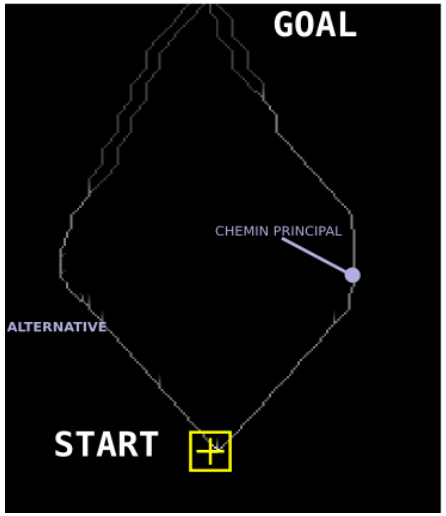
- A team of robots
- An unknown environment
- A set of constraints to satisfy (*e.g.* communications)

Approach:

- The UAV serves the UGV, by providing *traversability maps*
- Find the areas to perceive by the UAV relevant for the mission

1. Run a A* search for theUGV
2. Integrate developed node costs
3. Evaluate the alternate paths, considering the UAV perception capacities





2. Navigating a rover in an unknown environment

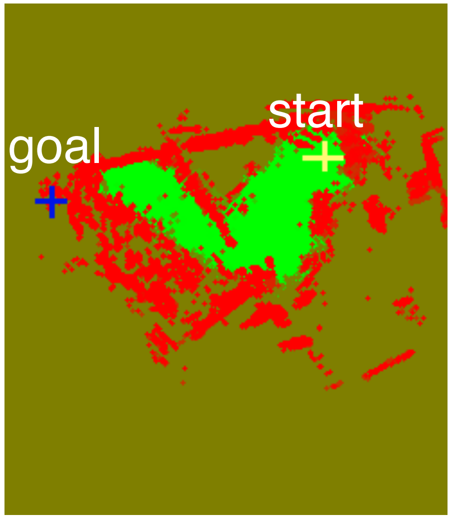
Given:

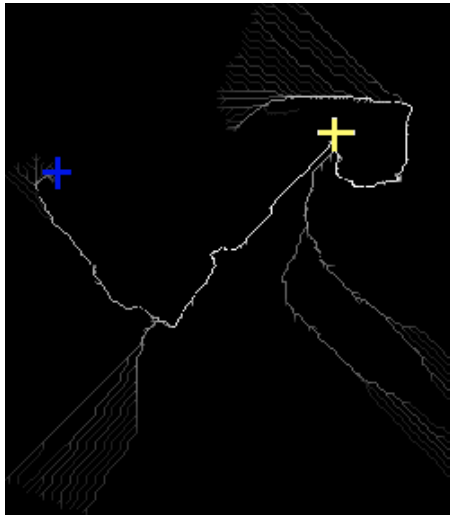
- A team of robots
- An unknown environment
- A set of constraints to satisfy (*e.g.* communications)

Approach:

- The UAV serves the UGV, by providing *traversability maps*
- Find the areas to perceive by the UAV relevant for the mission

1. Run a A* search for theUGV
2. Integrate developed node costs
3. Evaluate the alternate paths, considering the UAV perception capacities





2. Navigating a rover in an unknown environment

(simulation with http://morse.openrobots.org)

2. Navigating a rover in an unknown environment

Given:

- A team of robots
- An unknown environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Environment modelling tasks
- AGV and UAV Motions
- Communications

Required models:

- Of the traversability assessment function
- Of the robots motions
- Of the communications

3. Tracking a target in a known environment

Given:

- A team of robots
- A target locked by one robot (the "pursuer")
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

➡ Find the (optimal) trajectories to keep the target in sight

3. Tracking a target in a known environment

Given:

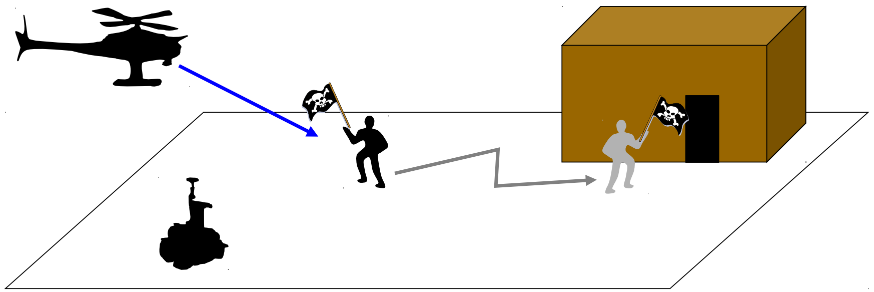
- A team of robots
- A target locked by one robot (the "pursuer")
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target "traps" (sentinel positions)
- Communications

Approach:

- The pursuer evaluate potential visibility losses



1. Target locked by the UAV

3. Tracking a target in a known environment

Given:

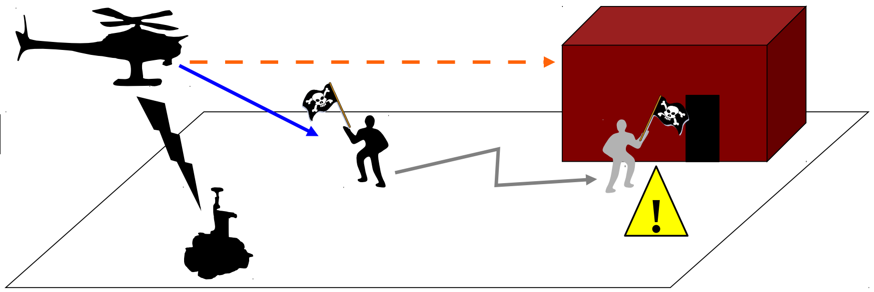
- A team of robots
- A target locked by one robot (the “pursuer”)
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target “traps” (sentinel positions)
- Communications

Approach:

- The pursuer evaluate potential visibility losses



2. Assessment of loss risk

3. Tracking a target in a known environment

Given:

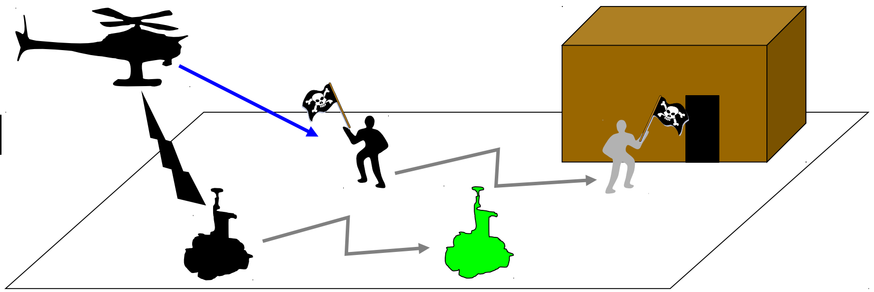
- A team of robots
- A target locked by one robot (the “pursuer”)
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target “traps” (sentinel positions)
- Communications

Approach:

- The pursuer evaluate potential visibility losses



3. The UGV is asked for support

3. Tracking a target in a known environment

Given:

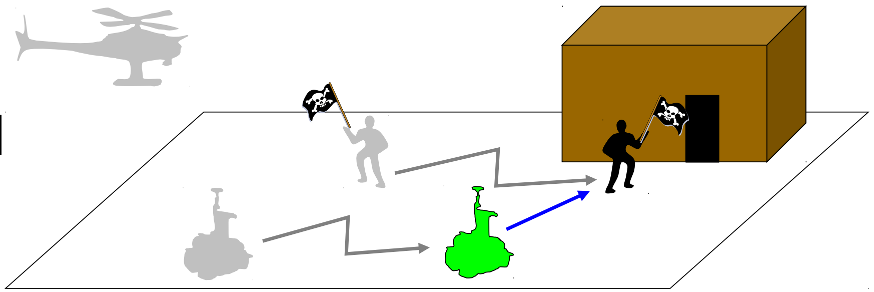
- A team of robots
- A target locked by one robot (the “pursuer”)
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target “traps” (sentinel positions)
- Communications

Approach:

- The pursuer evaluate potential visibility losses



4. Target locked by the UGV

3. Tracking a target in a known environment

Given:

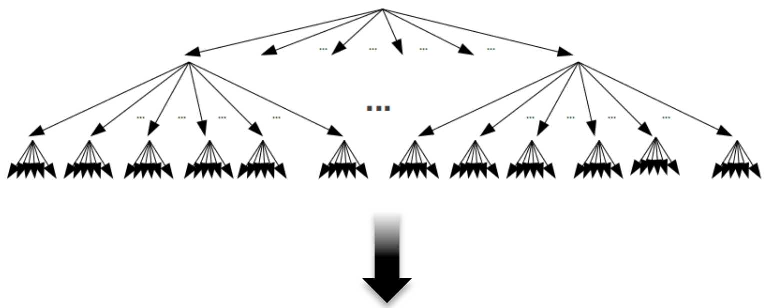
- A team of robots
- A target locked by one robot (the “pursuer”)
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target “traps” (sentinel positions)
- Communications

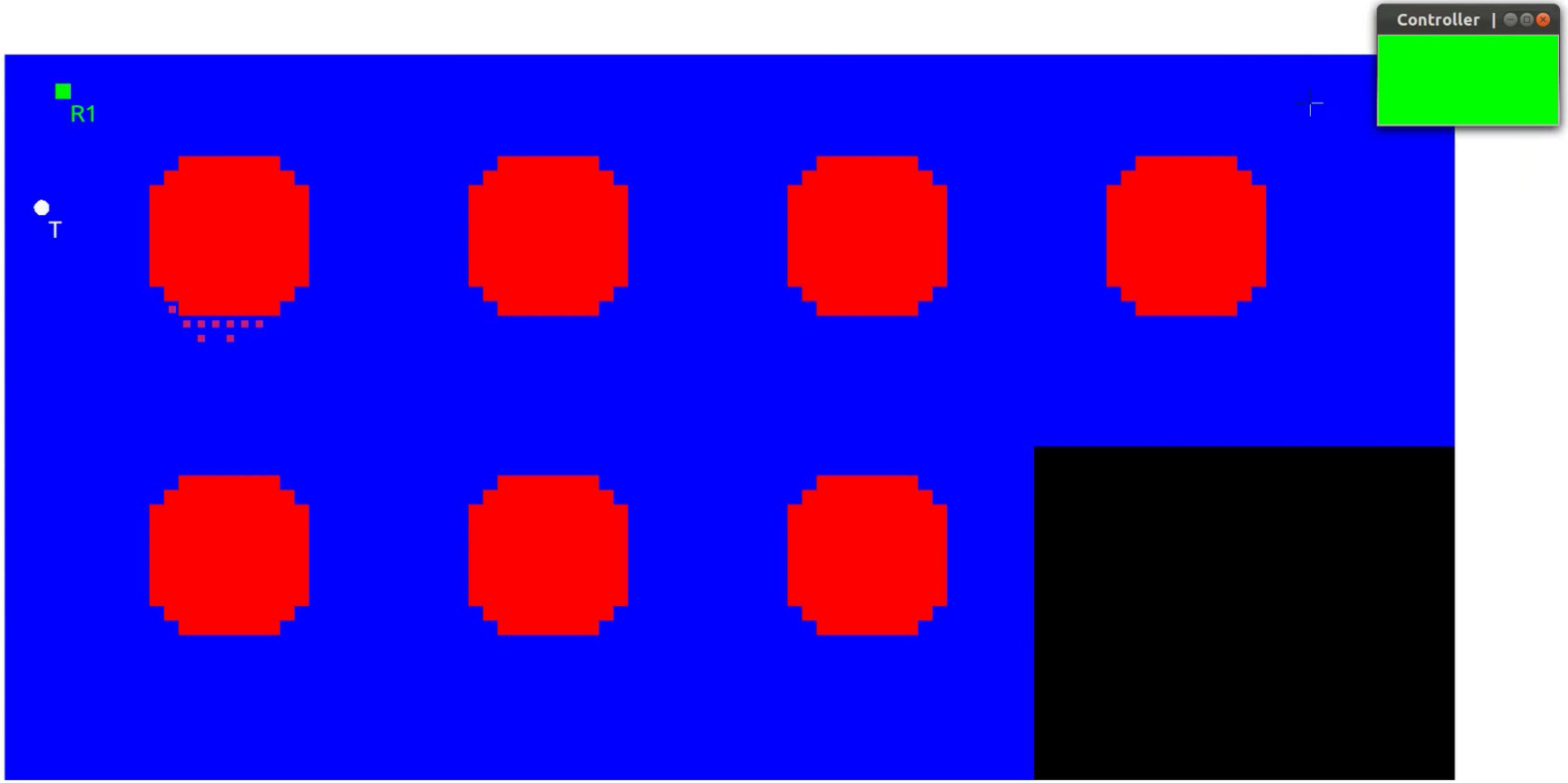
Approach:

- The pursuer evaluate potential visibility losses
- Break the search complexity by exploiting redundancies in the tree



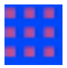
$O(m_t m_r)^h$ down to $O(h^3)$

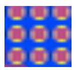
3. Tracking a target in a known environment



Target (on the ground)

Pursuer (UAV)


Target positions where line of sight can be lost for a moment, with guaranteed recovery


Target positions where line of sight can be lost without possible recovery

3. Tracking a target in a known environment

Given:

- A team of robots
- A target locked by one robot (the “pursuer”)
- A known environment
- A set of constraints to satisfy (*e.g.* communications)

Actions to plan:

- Target “traps” (sentinel positions)
- Communications

Required models:

- Of the robots and target motions
- Of the communications

Decision and environment models

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

Decision and environment models

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

	Surveillance	Rover navigation	Target tracking
Actions to simulate	• Environment observations • Motions • Communications	• Environment modeling • Motions • Communications	• Target observations • Motions • Communications
Search	Task allocation scheme	Heuristic graph search	Graph search + task allocation

Simulation = convolution of action <u>and</u> environment models → Environment models:

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

Outline

Autonomous decision making in air/ground systems

➡ On the importance of environment representations

Outline

Autonomous decision making in air/ground systems

→ On the importance of environment representations

Environment models

Decision and environment models

Planning = Simulation + Search

- Simulation of the effects of an action with a predictive model
  → by "convolving" action models with environment models

What are the main actions to plan / decide?

From an *operations* point of view:

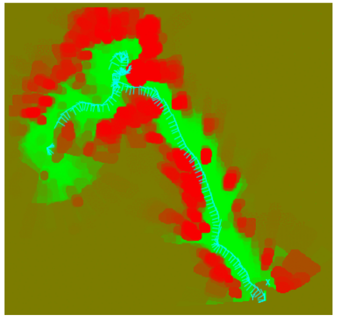
- Motions
- Environment observations (payload)
- Communications (within robots, with the control station)

Plus, from a *robotics* point of view:

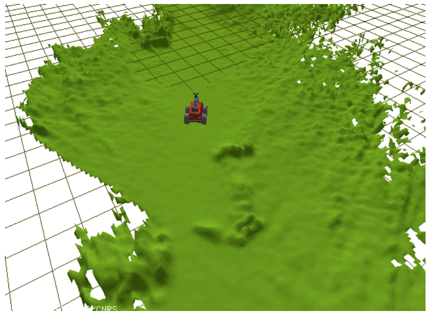
- Localization
- Environment perception and modeling

Decision and environment models

Planning motions

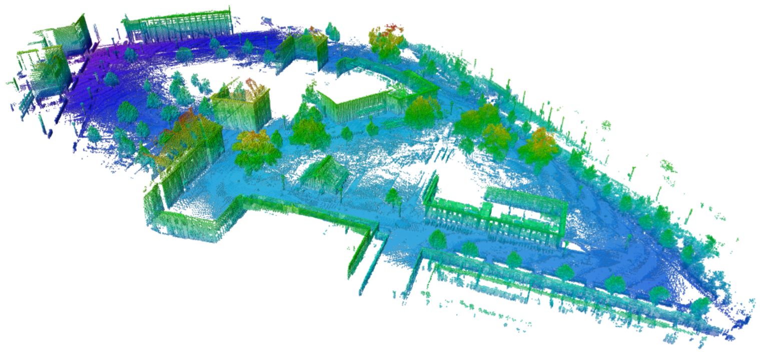


- At a coarse level (itinerary)
  ➞ notion of traversability
  (geometry, terrain nature)



- At a fine level
  ➞ geometry, terrain nature
  (*e.g.* digital terrain map)

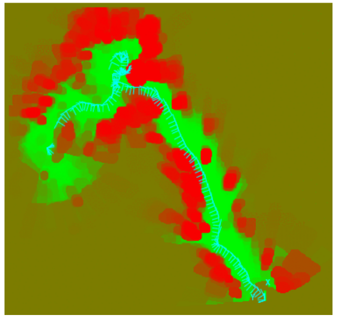
Planning observations



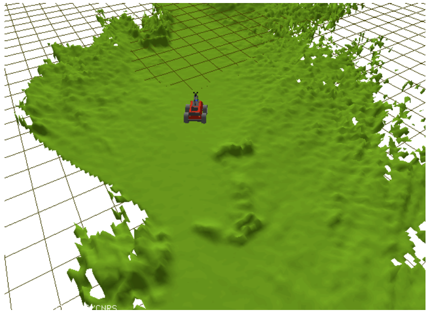
- Need to predict visibilities
  ➞ geometry (2.5D or 3D)

Decision and environment models

Planning motions

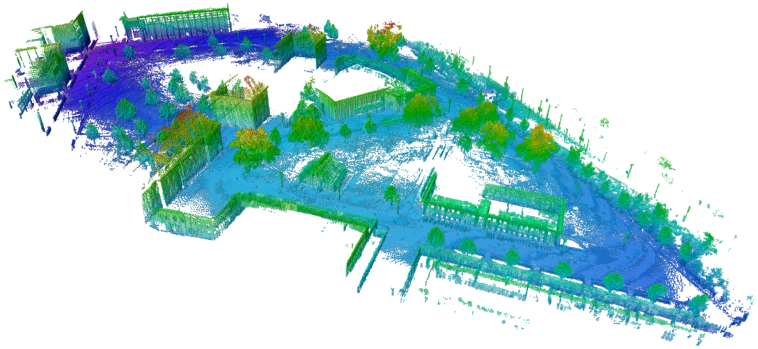


- At a coarse level (itinerary)
  ➞ notion of traversability
  (geometry, terrain nature)



- At a fine level
  ➞ geometry, terrain nature
  (*e.g.* digital terrain map)

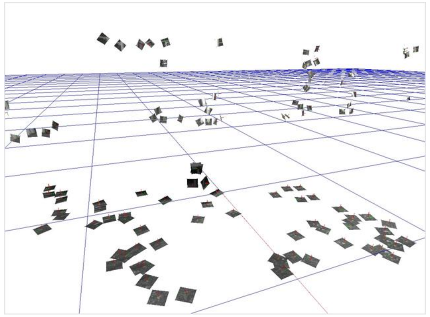
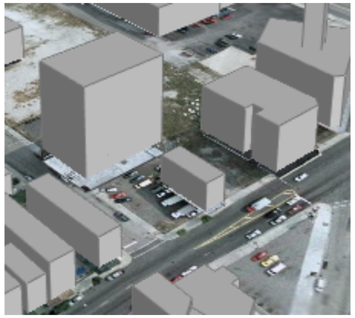
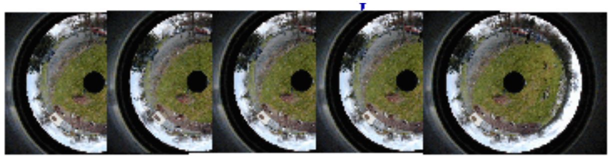
Planning communications



- Need to predict radio visibilities
  ➞ geometry, physical properties
(or rather, learnt experience)

Decision and environment models

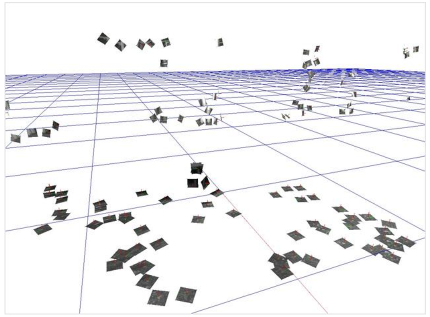
Planning localization

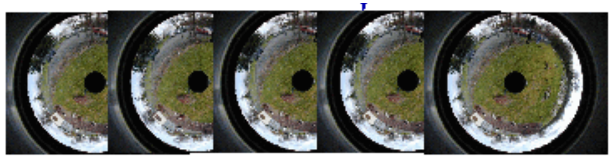




• GPS or corrections coverage
• INS / Odometry: terrain nature
• Exteroceptive sensors: landmarks or other models (geometry, appearance models, …)

Decision and environment models

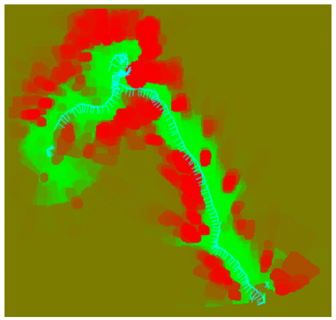
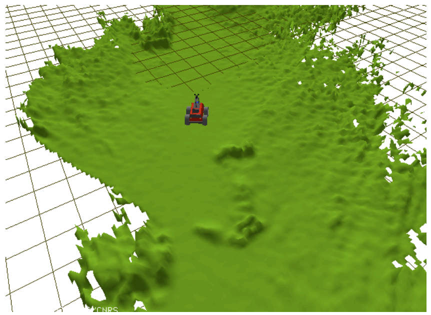
Planning localization





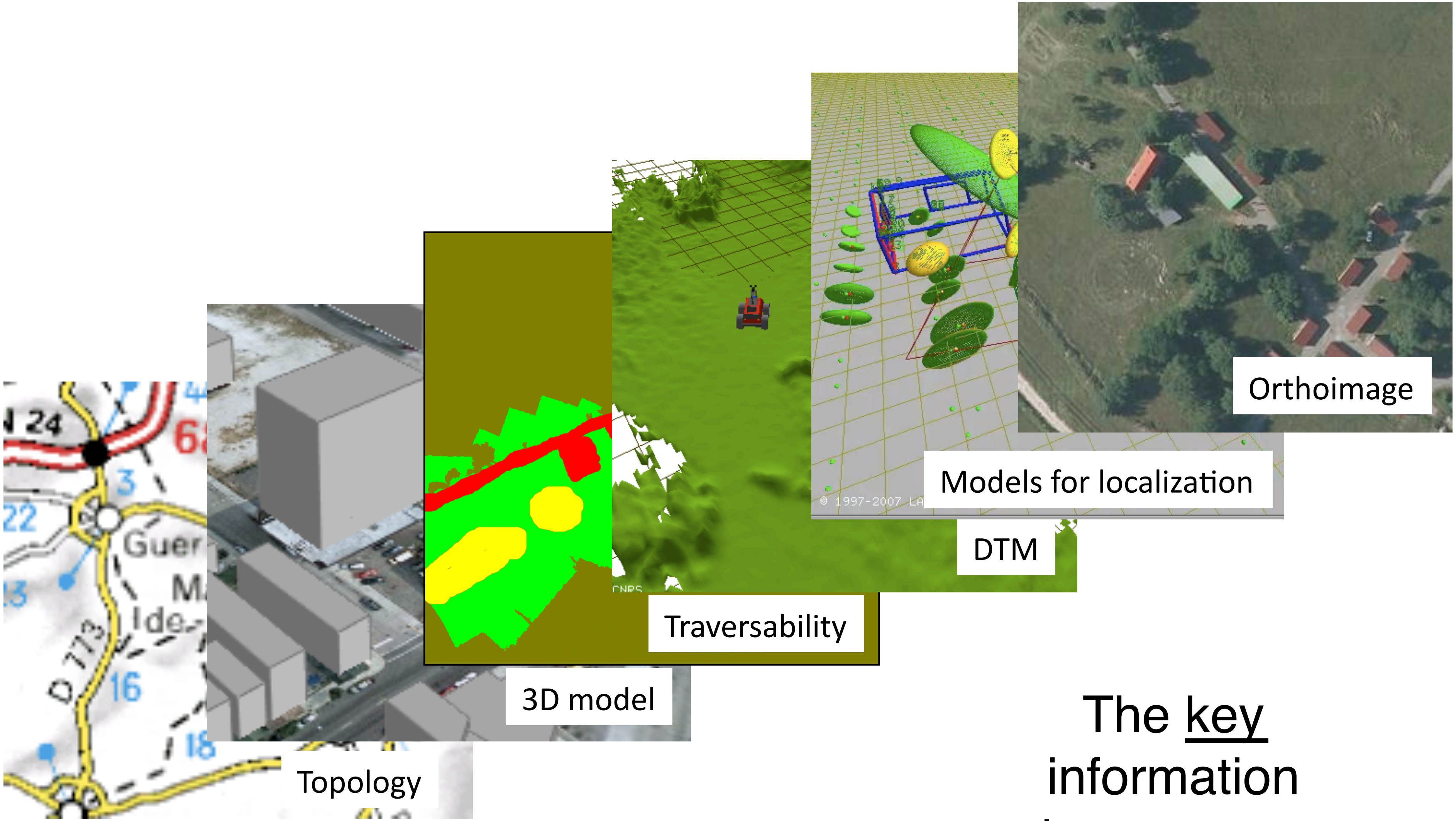
- GPS or corrections coverage
- INS / Odometry: terrain nature
- Exteroceptive sensors: landmarks or other models (geometry, appearance models, …)

Planning environment perception & modeling

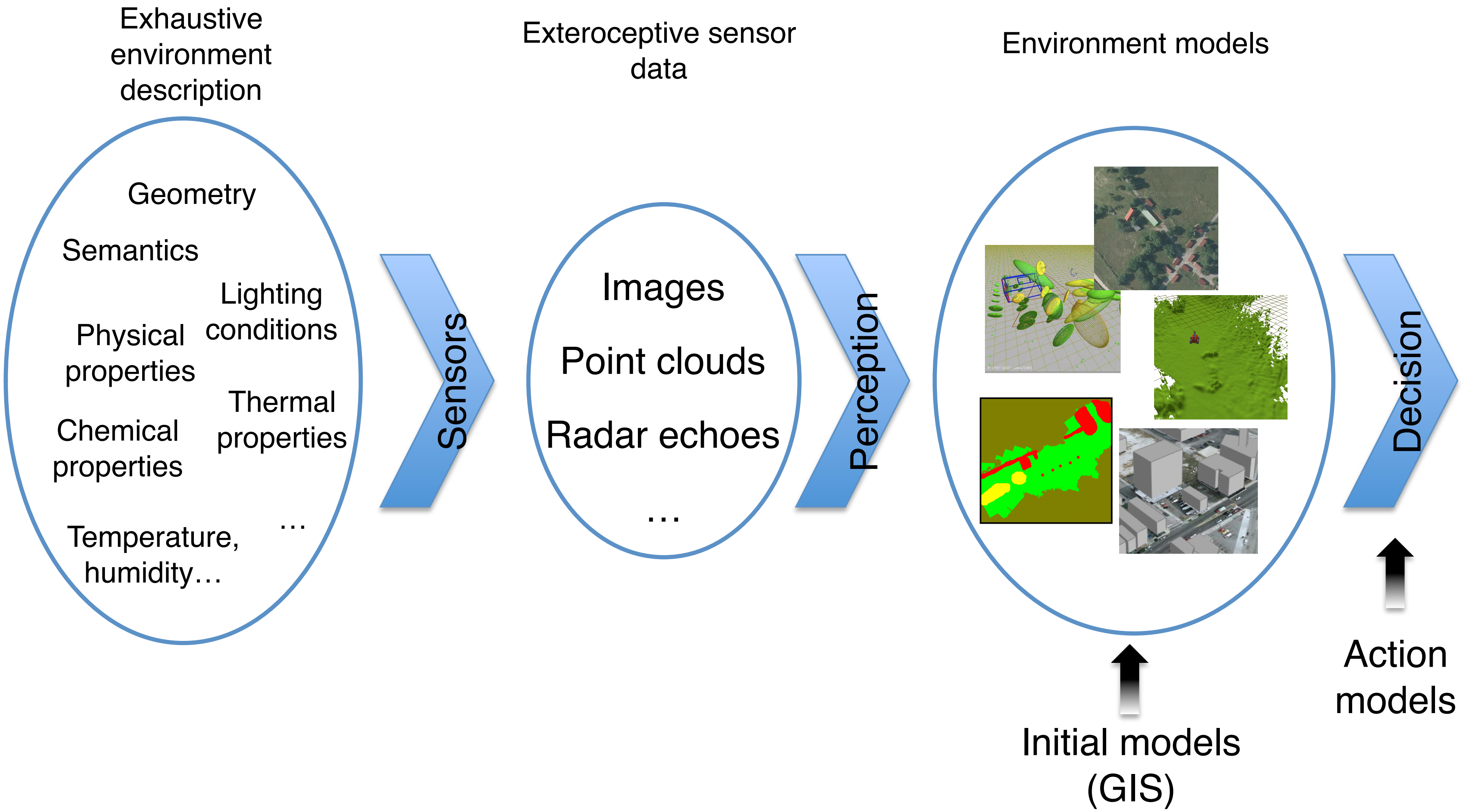
- Need to predict the *information gain*
  - → amount of information in the environment models (uncertainty, entropy…)

A database of environment models



The key information is geometry

Building envt. models: information flow

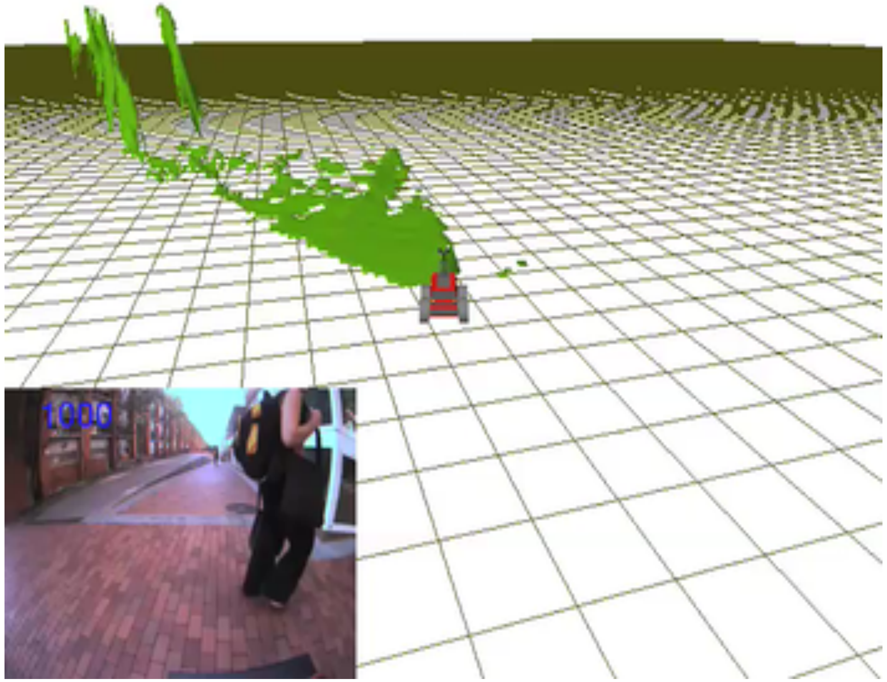


“Engineering autonomous agents […] requires a steady flow of information from sensors to high-level reasoning components” [F. Heintz, “DyKnow”]

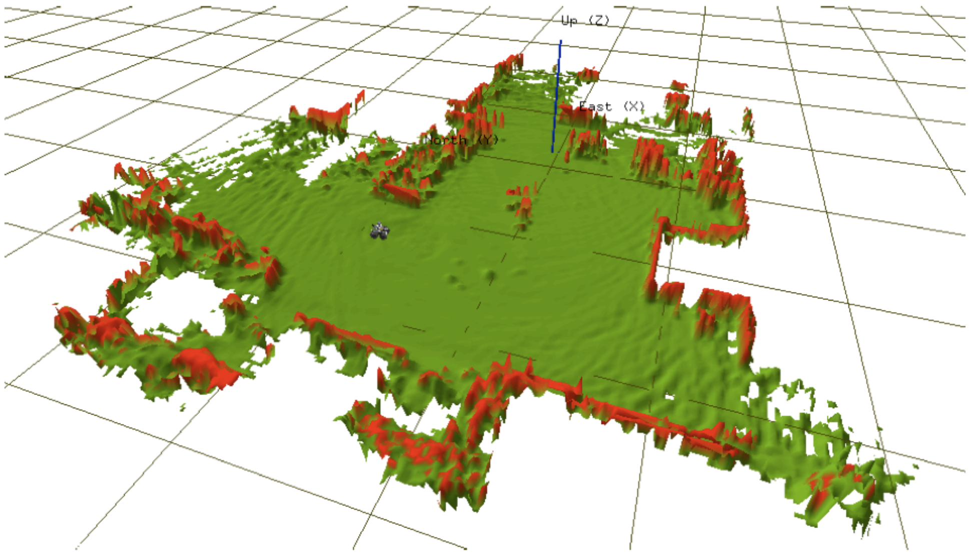
Building a digital terrain model

With a rover, using point clouds

Resampling data to obtain a $z=f(x,y)$ representation on a regular Cartesian grid



Using stereovision



Using a Velodyne lidar

(It is *essential* to maintain confidence / certainty / precision values during the process)

Building a digital terrain model

With a UAV, using a Lidar

Resampling data to obtain a *z=f(x,y)* representation on a regular Cartesian grid

[Paul Chavent @ Onera Toulouse]

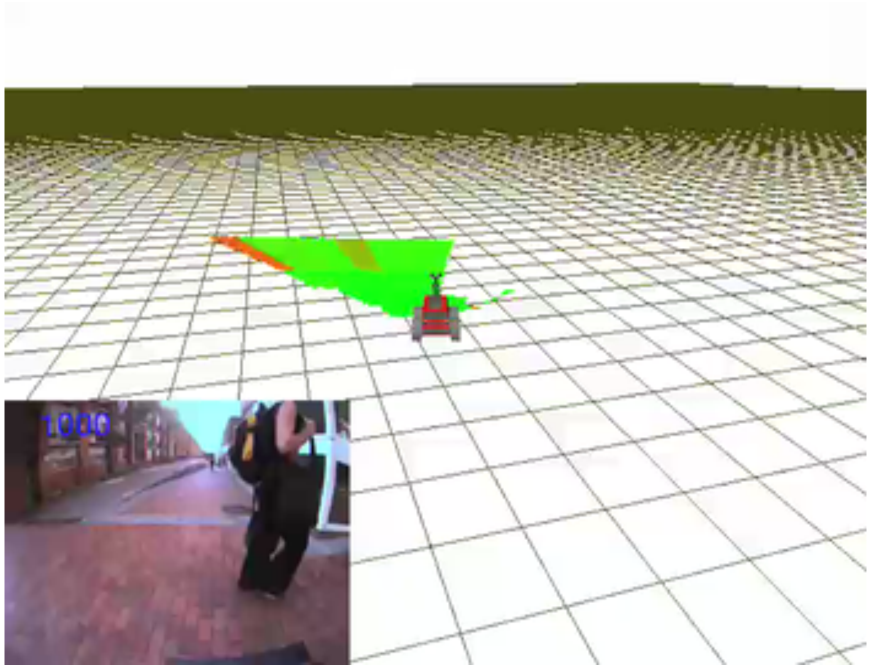
Building a digital terrain model

With a UAV, using a camera

Up-to-date commercial bundle adjustment techniques

Building a traversability model

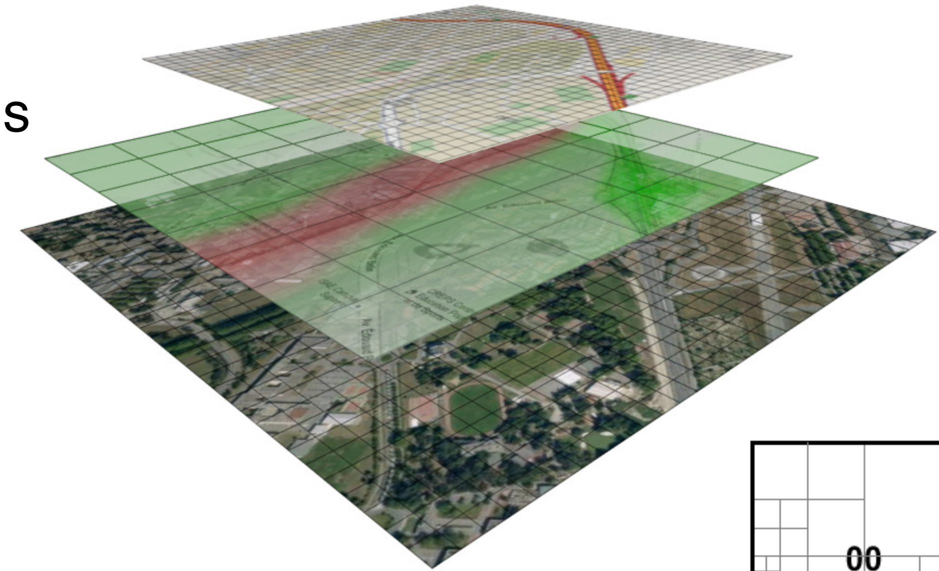
With a rover, using point clouds (here stereo)
Probabilistic labeling (Bayesian supervised learning)



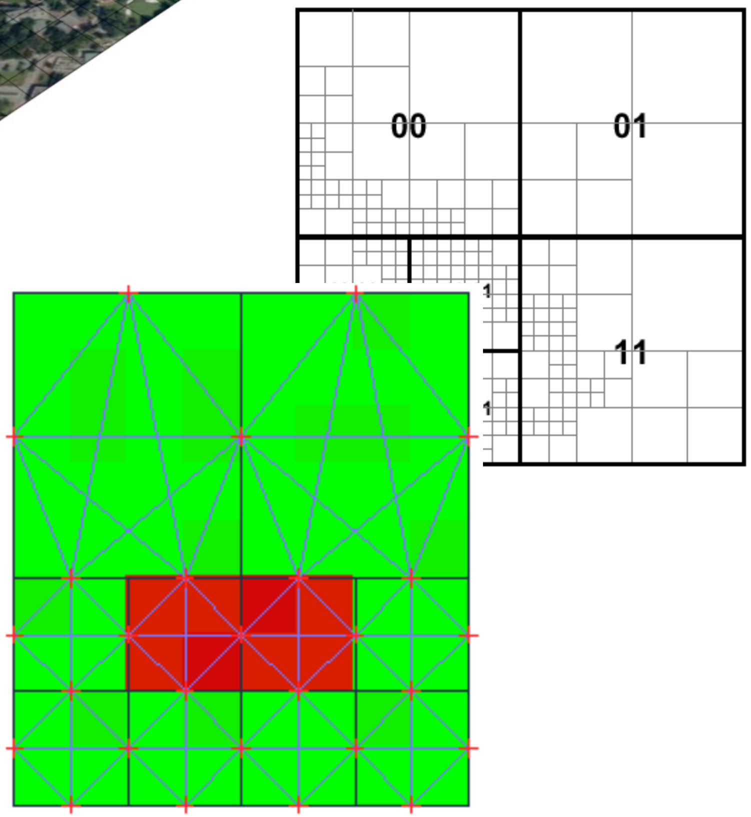
- Possibility to introduce luminance and texture attributes
- Much more up-to-date classification or learning processes exist

Terrain models: data structures

“Raster” models:
regular Cartesian grids



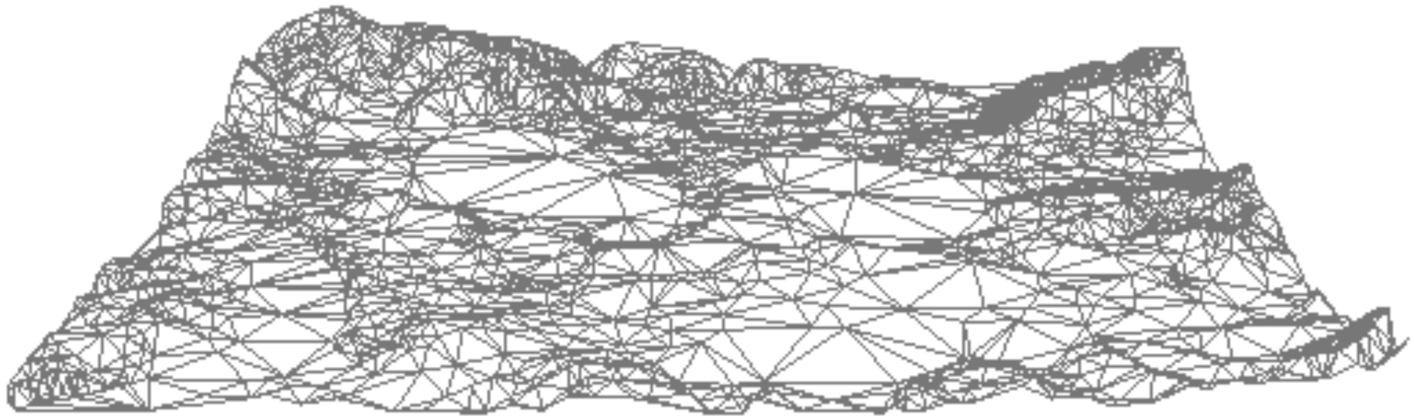
“Raster” models: hierarchical Cartesian grids or volumes



Graph structures easily derived

Terrain models: data structures

Triangular irregular meshes



Terrain models: key points

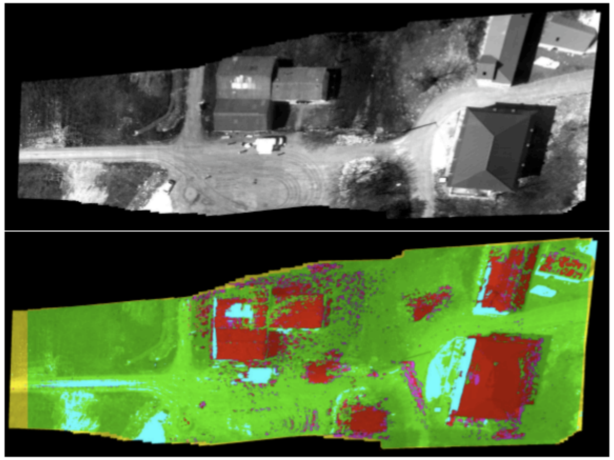
1. Whatever the encoded information (terrain class, elevation, traversability, ...), it is *essential* maintain its “quality” (confidence, precision, certainty…):

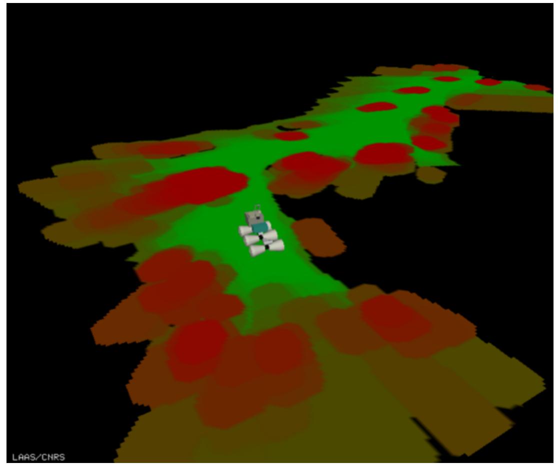
   - To fuse the various sources of information
     - initial model
     - models built by other robots
     - sensor data
   - To drive the decision processes

2. Spatial consistency is crucial

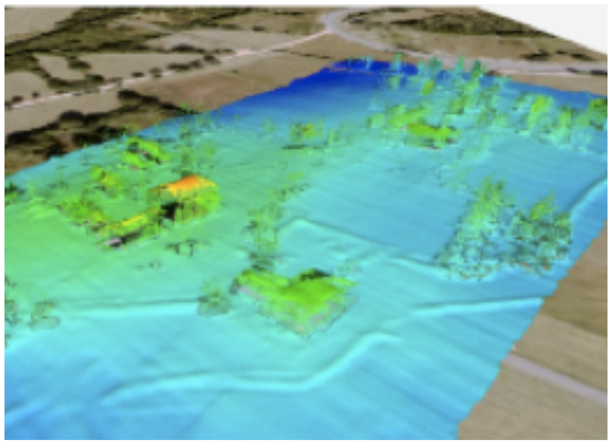
Merging air/ground models?

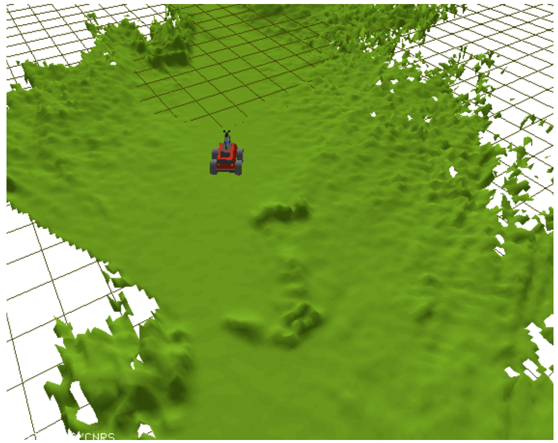
Traversability models





Digital terrain models





➡ *Inter-robot* spatial consistency required

Outline

Autonomous decision making in air/ground systems

➡ On the importance of environment representations

Environment models

➡ On the importance of localization

Outline

Autonomous decision making in air/ground systems
➡ On the importance of environment representations

Environment models
➡ On the importance of localization

Localization

On the importance of localization

Localization is required to:

- Ensure the achievement of the missions, most often defined in localization tems (“`goto [goal]`”, “`explore / monitor [area]`”, ...)

- Ensure the lowest level (locomotion) controls

- Ensure the proper execution of paths / trajectories

- Ensure the spatial consistency of the built models

On the importance of localization

Localization solutions

A variety of available information:

- Motion sensors
  Odometry, IMU, velocimeters, …

- Environment sensors
  Lidar, camera(s), radar, …

- Infrastructure sensors
  GPS, radio receivers, …

- A priori information
  Motion models, environment models (maps), …

Localization solutions

A variety of available techniques:

- Dead-reckoning
- Map-based localization
- SLAM

But… what localization?

Essential questions to answer:

1.	With which precision?	From *cm* to *meters*
2.	In which frame?	Absolute vs. local
3.	At which frequency?	From *kHz* to "sometimes"

- Ensure the lowest level (locomotion) controls
- Ensure the proper execution of paths / trajectories
- Ensure the spatial consistency of the built models
- Ensure the achievement of the missions, most often defined in localization terms ("`goto [goal]`", "`explore / monitor [area]`", …)

But… what localization?

Essential questions to answer:

1. With which precision?	From *cm* to *meters*
2. In which frame?	Absolute vs. local
3. At which frequency?	From *kHz* to "sometimes"

4. *Integrity* of the solution?

5. *Disponibility* of the solution?

cm accuracy, @ > 100 *Hz*, local frame:

- Ensure the lowest level (locomotion) controls
- Ensure the proper execution of paths / trajectories
- <u>Ensure the spatial consistency of the built models</u>

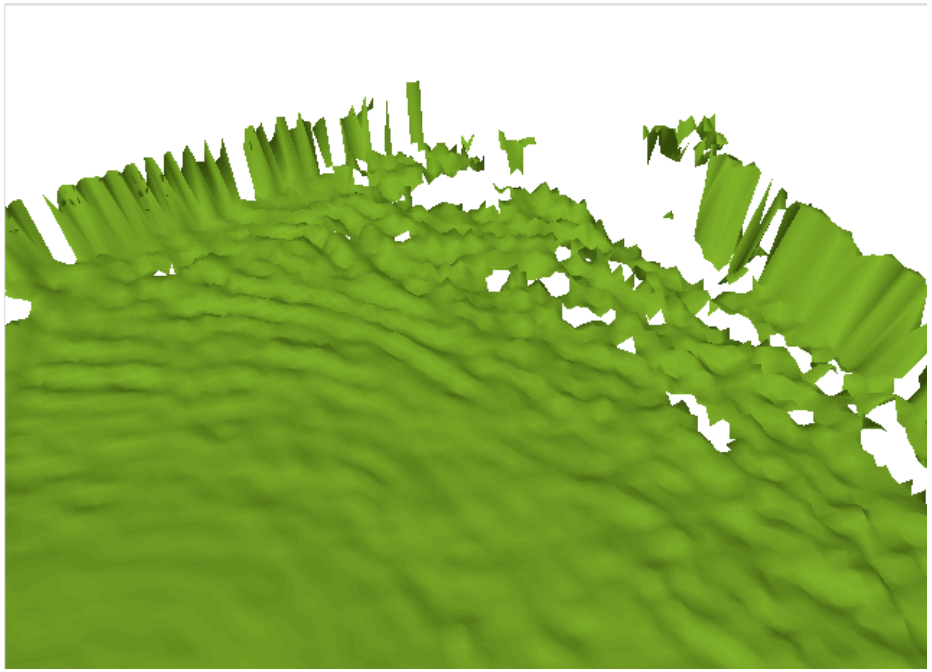
~*m* accuracy, "sometimes", global frame:

- Ensure the achievement of the missions, most often defined in localization terms ("`goto [goal]`", "`explore / monitor [area]`", …)

Localization precision required for a DTM

➡ DTM resolution ~ *10cm*, height precision ~ *3cm*

- Velodyne lidar provides chunks of 64 points @ 3.5 *kHz:*
  1° error on pitch yields a *17cm* elevation error @ *10m*

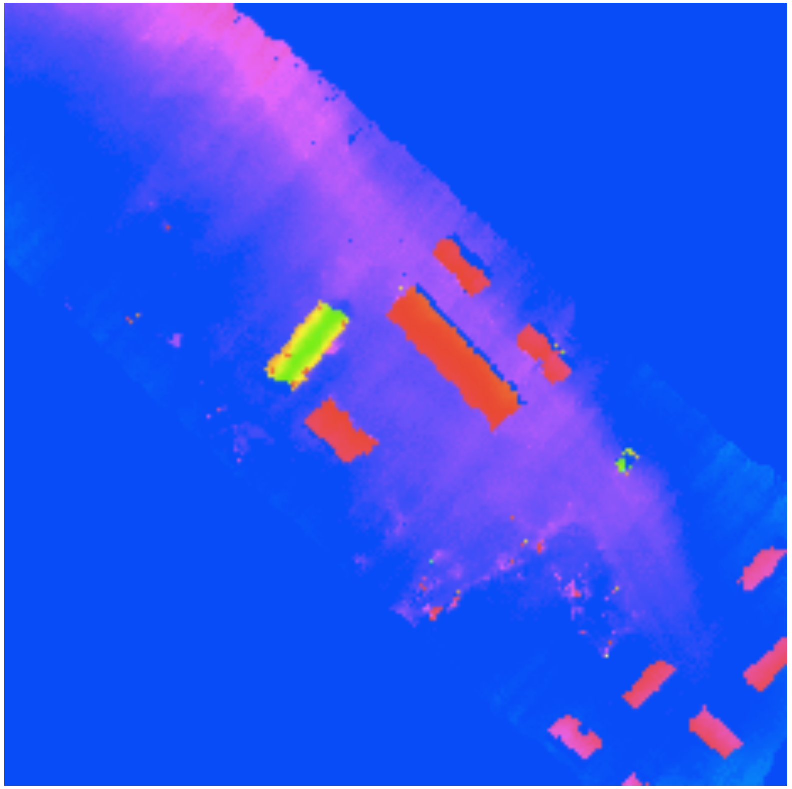


2*m/s*, GPS RTK @ 20*Hz*
+ Xsens AHRS @ 100*Hz*
+ FOG gyro @ 50*Hz*

Localization precision required for a DTM

- DTM built by an UAV with a Lidar

2*m/s*, GPS RTK @ 20*Hz*
+ INS @ x *Hz*
+ *dynamic model*
+ compass x *Hz*

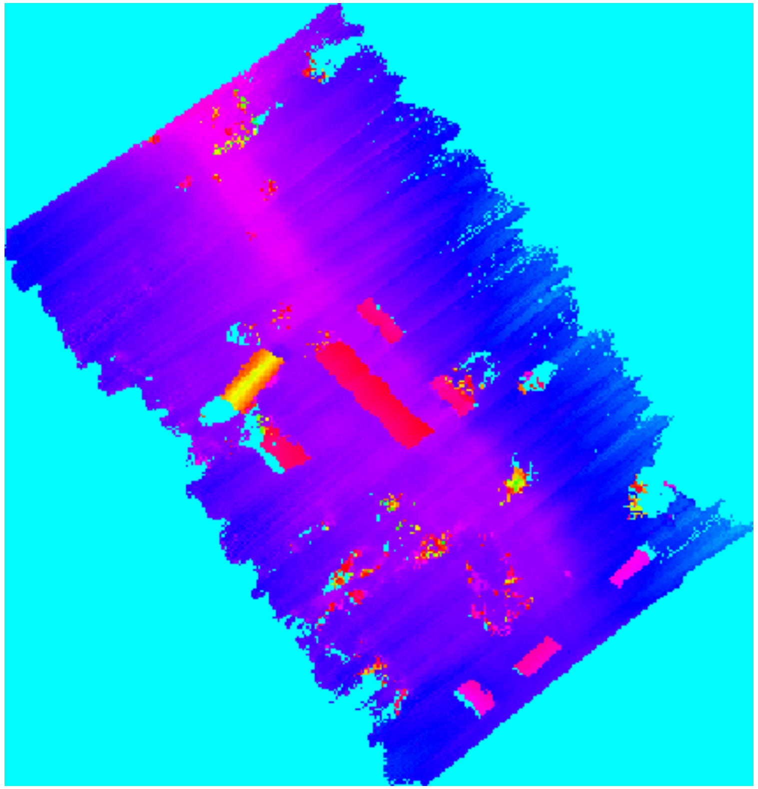


During a calm day

Localization precision required for a DTM

- DTM built by an UAV with a Lidar

2m/s, GPS RTK @ 20*Hz*
+ INS @ x *Hz*
+ dynamic model
+ compass x *Hz*



With a 10 km/h wind

Vision-based SLAM

http://rtslam.openrobots.org : a versatile EKF-based SLAM framework

1. Vision (monocular, stereoscopic, bi-cameras)
2. Point / line / planar landmarks
3. Predictions: motion model, INS
4. Additional observations : odometry (speed), GPS (position)

Vision-based SLAM

http://rtslam.openrobots.org : a versatile EKF-based SLAM framework

1. Vision (monocular, stereoscopic, bi-cameras)
2. Point / line / planar landmarks
3. Predictions: motion model, INS
4. Additional observations : odometry (speed), GPS (position)

Vision-based SLAM

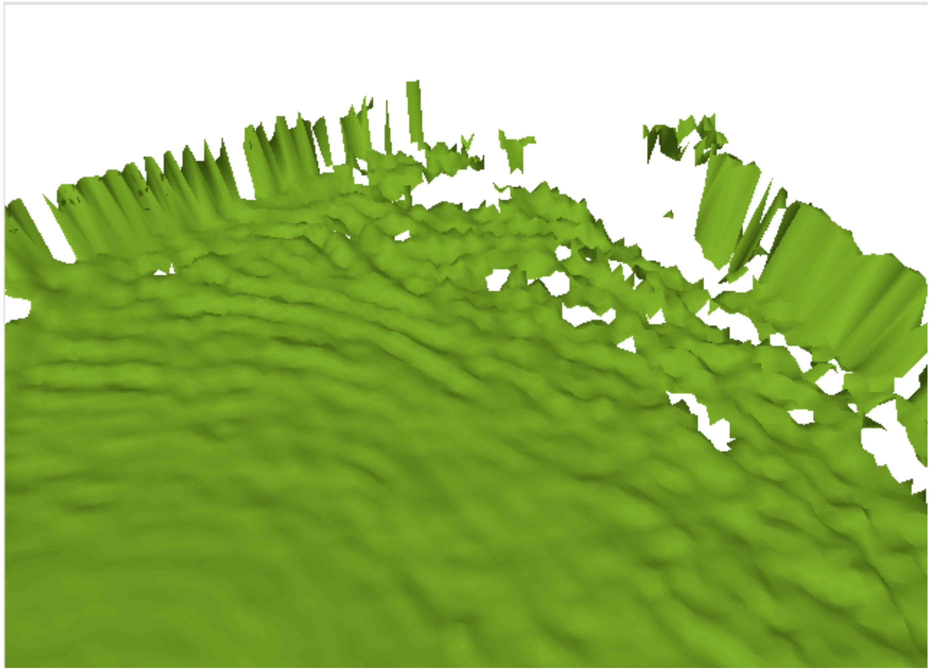
http://rtslam.openrobots.org : a versatile EKF-based SLAM framework

- Real-time (100 Hz estimates, VGA @ 50Hz), active search
- Timestamp estimates through a dedicated filter
- IMU and calibration bias estimation
- Various landmark detection / observation / parameterization strategies

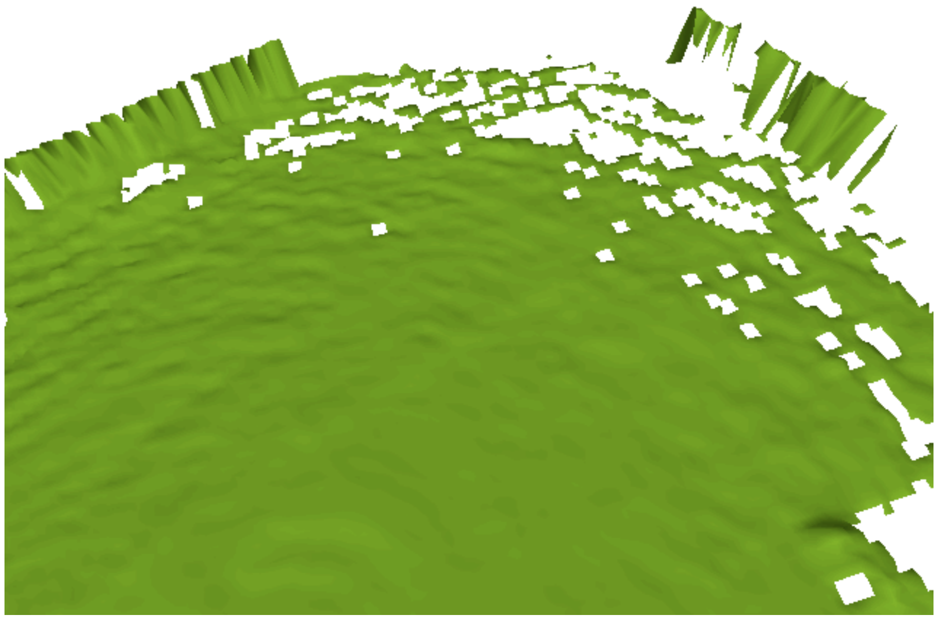
Localization precision required for a DTM

➡ DTM resolution ~ *10cm,* height precision ~ 3*cm*

- Velodyne lidar provides chunks of 64 points @ 3.5 *kHz:*
  1° error on pitch yields a 17*cm* elevation error @ 10*m*



2*m/s*, GPS RTK @ 20*Hz*
+ Xsens AHRS @ 50*Hz*
+ FOG gyro @ 50*Hz*



2*m/s*, RT-SLAM @ 100*Hz*

(known) SLAM issues

• SLAM processes complexity grows with the number of landmarks

➡ The map size can't scale up

• The consistency of Kalman filter based solutions can't be guaranteed

➡ The map size can't scale up, loop closures may lead inconsistencies

(Multi-map hierarchical SLAM)

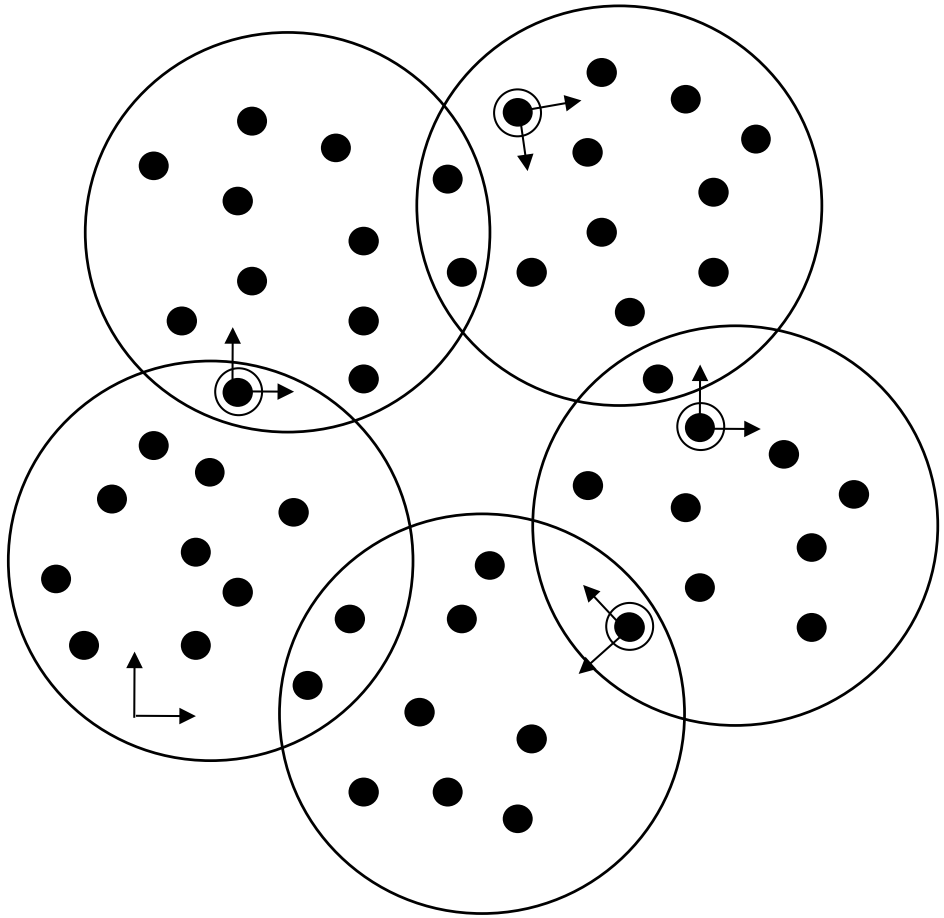
Hierarchical SLAM [Tardos-2005], a graph of "submaps":

Local maps (EKF) of current vehicle pose and landmarks pose (nodes)

Global map of relative transformations (edges)

Local maps:

- Fully correlated maps (robot and landmark states)
- No information shared between local maps
- Each map is initialized with no uncertainty



(Multi-map hierarchical SLAM)

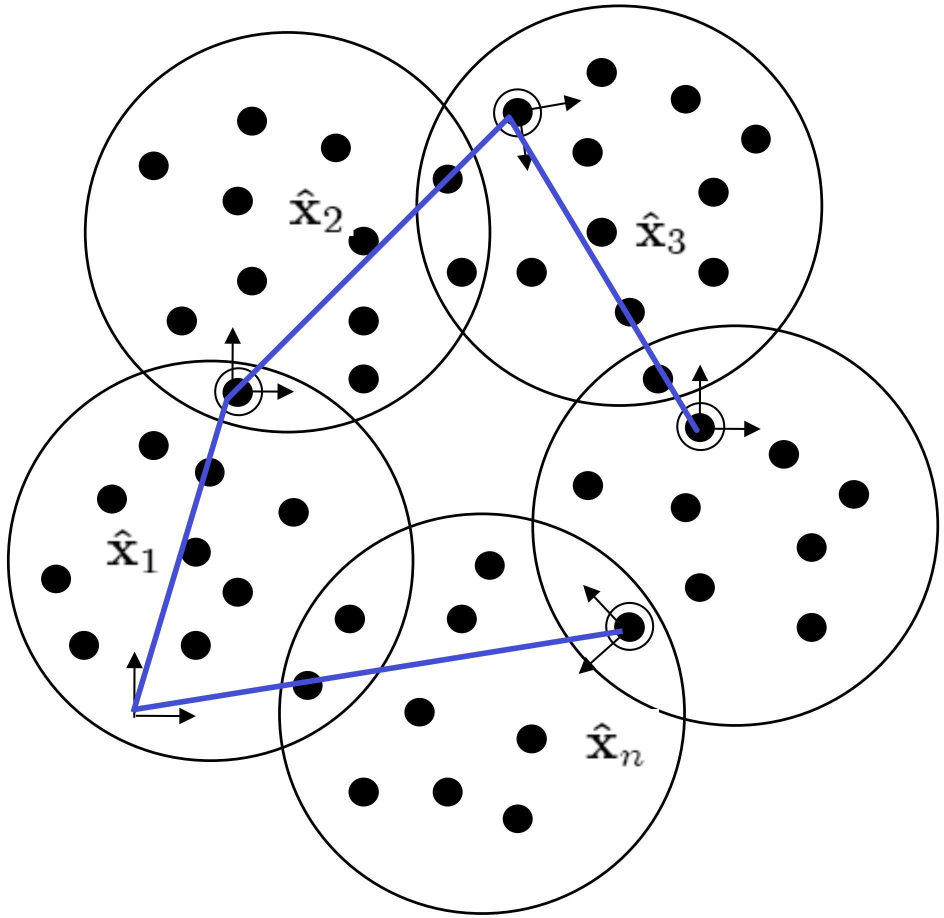
Hierarchical SLAM [Tardos-2005], a graph of "submaps":

Local maps (EKF) of current vehicle pose and landmarks pose (nodes)

Global map of relative transformations (edges)

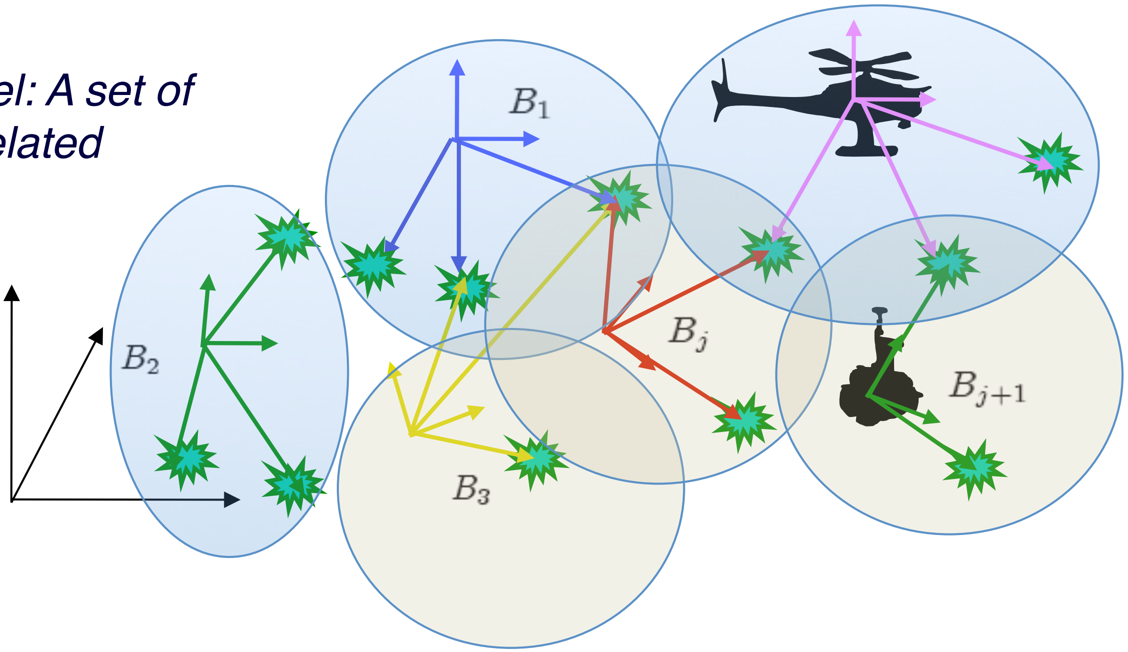
Global graph of maps:

- Robot's pose
- The state is the relative transformation between local maps
- Block diagonal covariance before loop closure

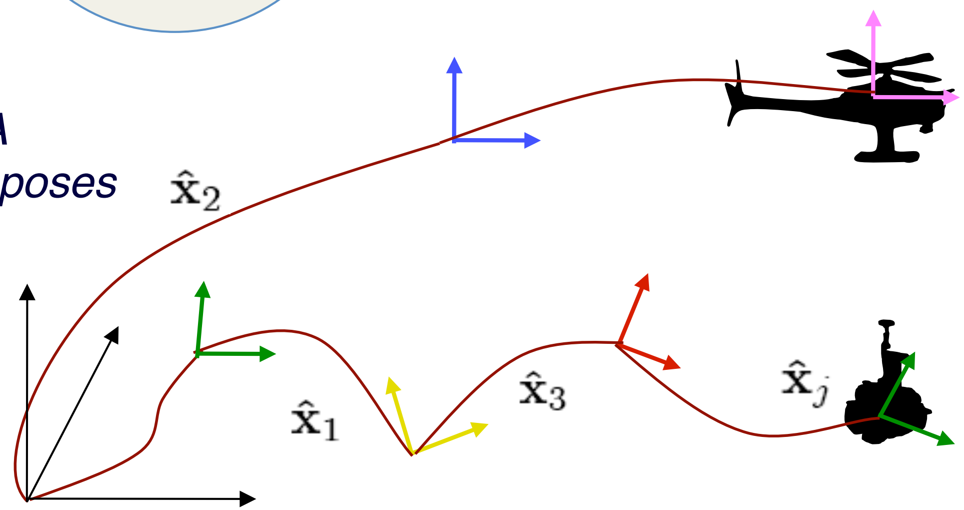


Multi-robot multi-map hierarchical SLAM

Local level: A set of fully correlated submaps



Global level: A graph of map poses

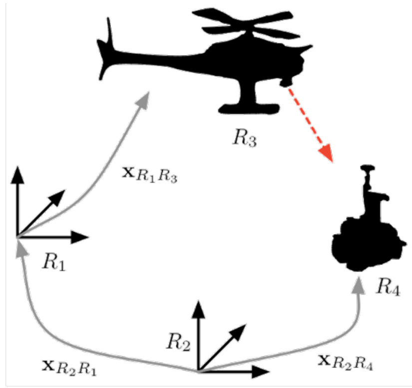


Towards a distributed framework to integrate <u>any</u> localisation information

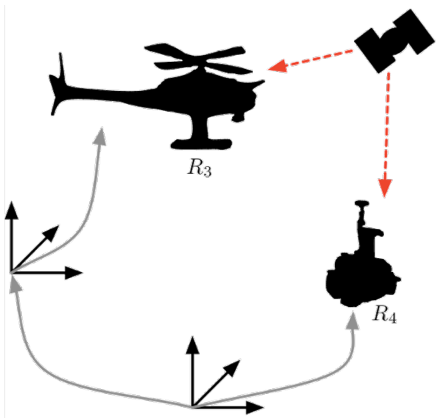
Multi-robot multi-map hierarchical SLAM

➡ Various loop-closing events

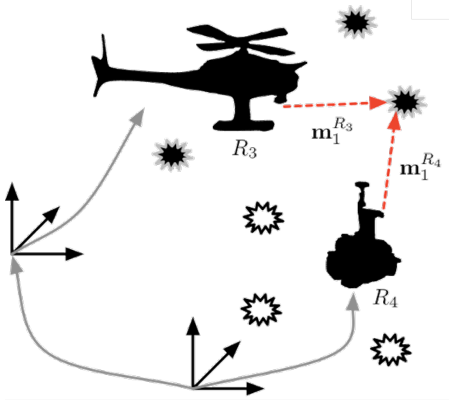
"Rendez-vous": inter-robot pose estimation



Absolute localization (GPS fix / localization wrt. an initial map)



Inter-robot landmark (or map) matches



SLAM issues

- SLAM processes complexity grows with the number of landmarks

➡ The map size can't scale up

- The convergence of Kalman filter based solutions can't be guaranteed

➡ The map size can't scale up, loop closures may lead inconsistencies

- Detecting loop closures is an issue

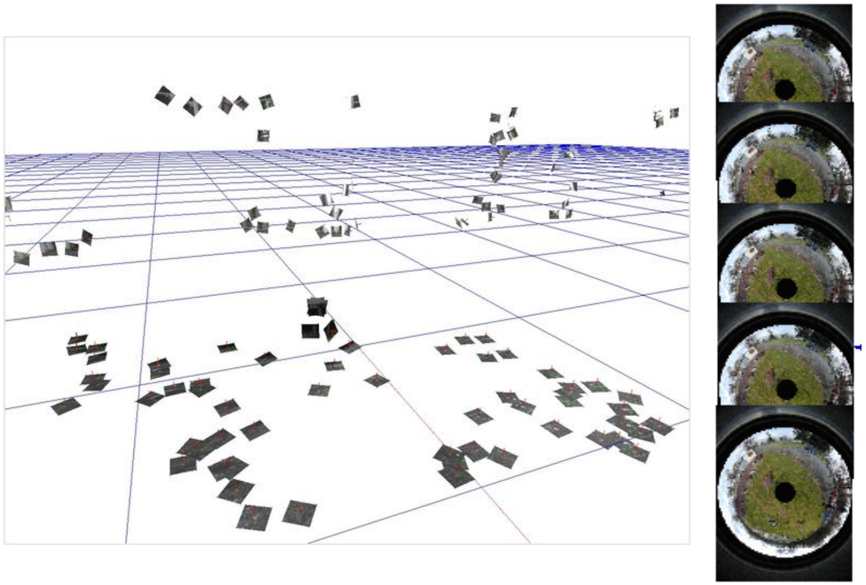
➡ Dedicated environment models are required

Detecting loop closures

- Data association is mainly a perception problem

Powerful image indexing techniques (bag of words, *e.g.* FabMap)

Can be extended to Lidar scans (at least with global signatures)



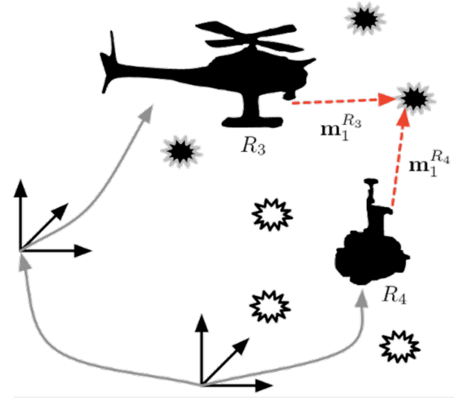
Landmark maps + image indices

Such robotcentric (or even sensorcentric) representations can not be shared / fused among robots

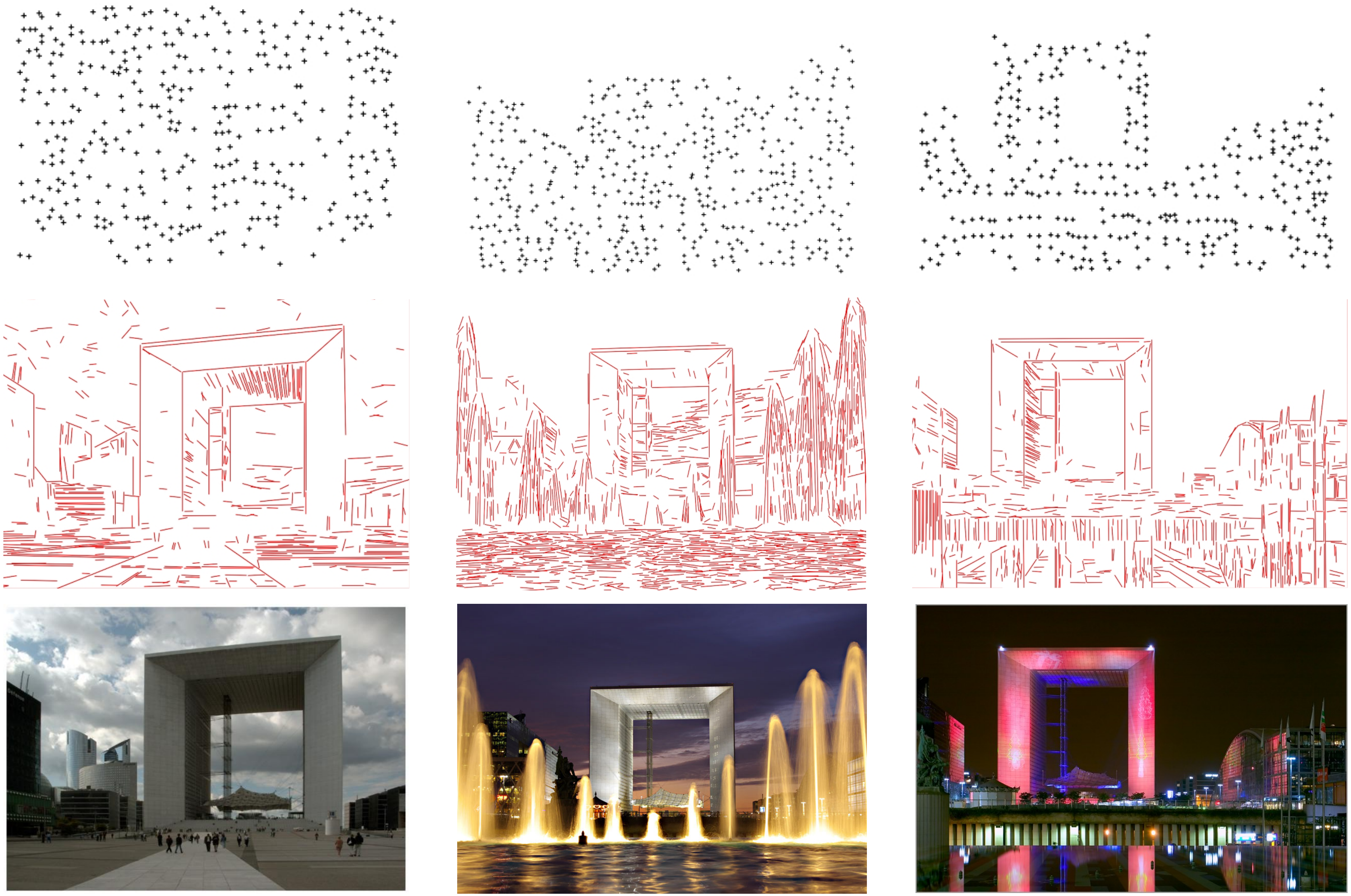
Detecting loop closures between air/ground robots

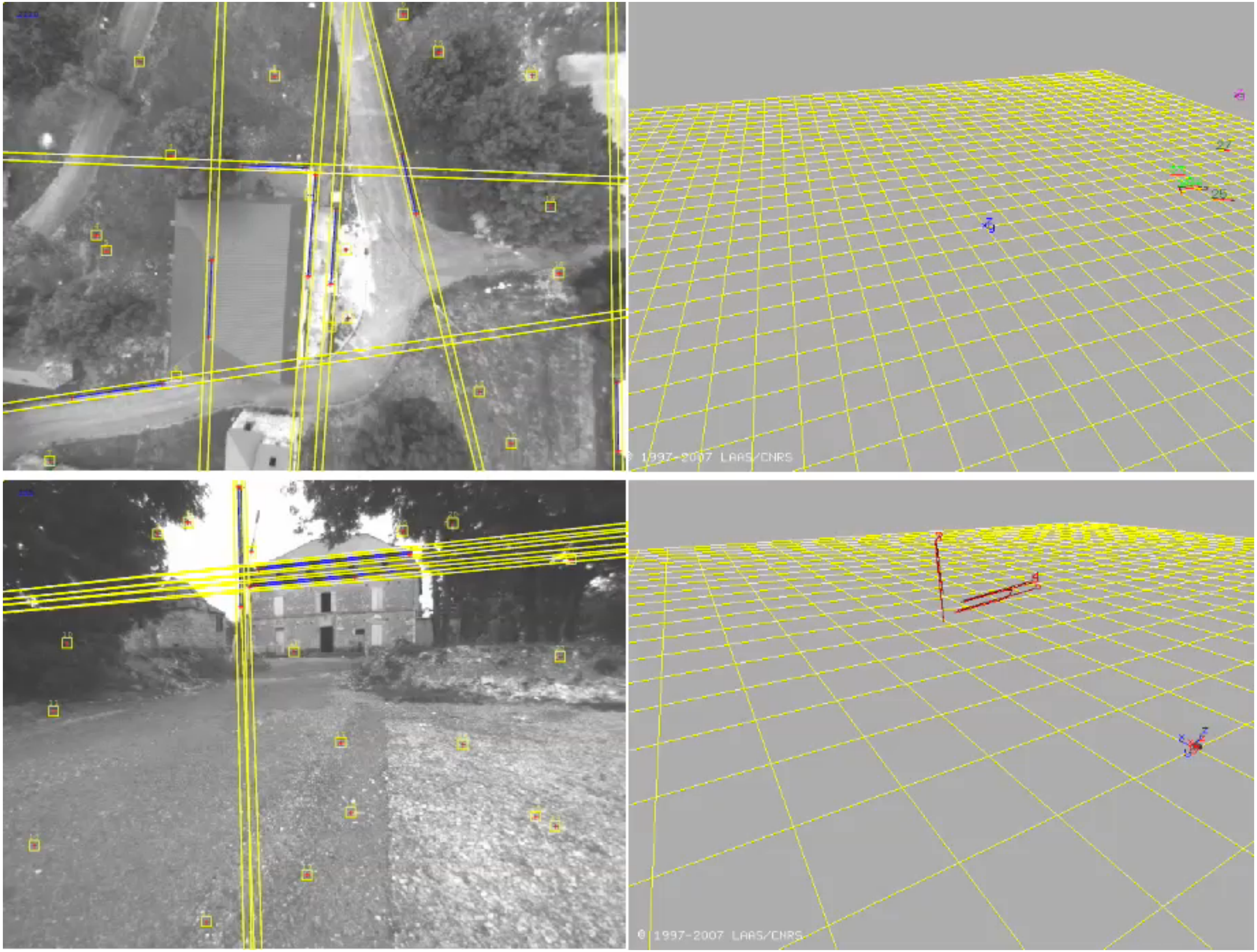
Need to focus on the M of SLAM

➡ <u>Geometry</u> is (again) the key



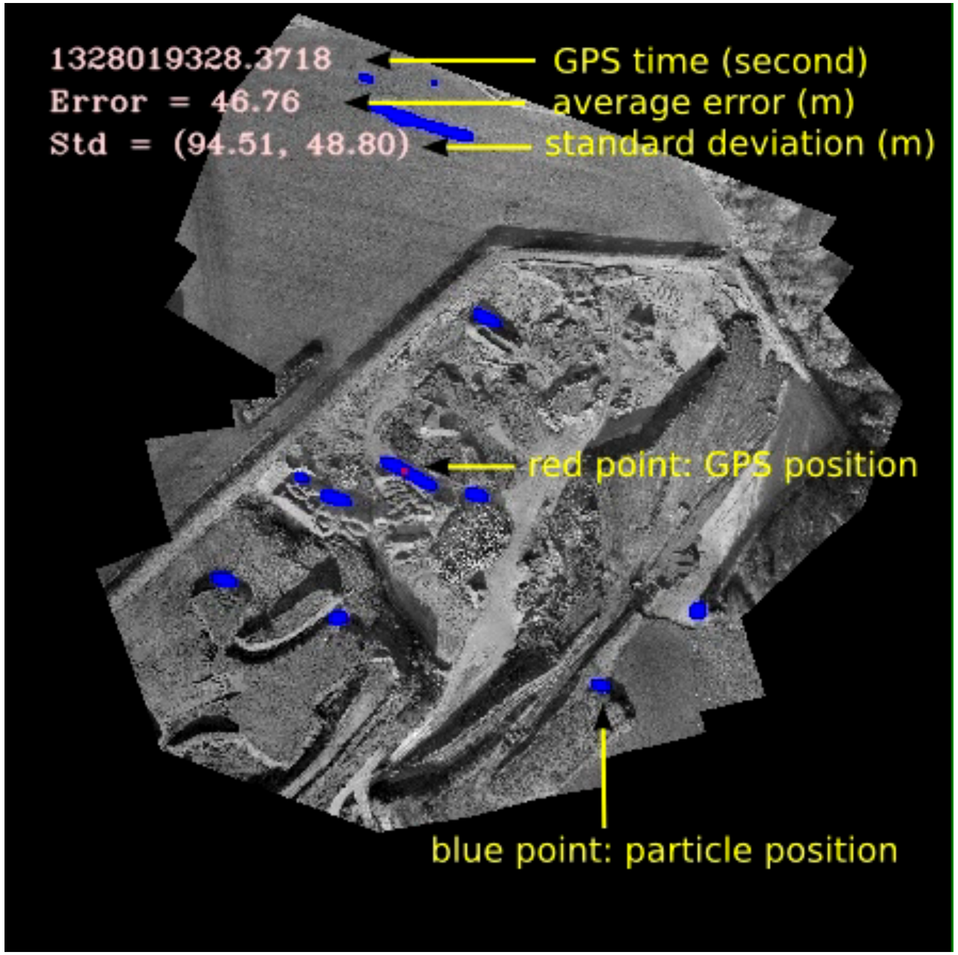
Points vs. lines in vision

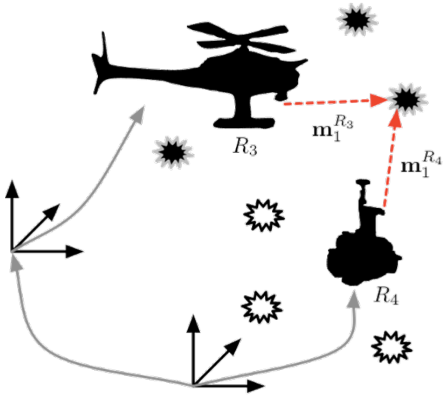



27
25
© 1997-2007 LAAS/CNRS
© 1997-2007 LAAS/CNRS

Loop closures within air/ground robots

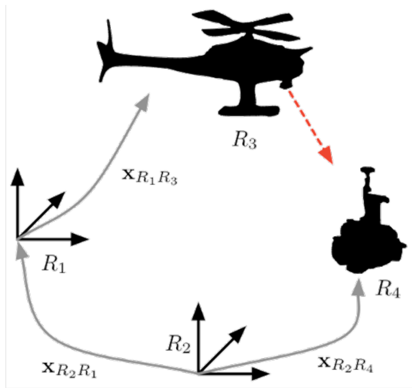
Inter-robot map matches

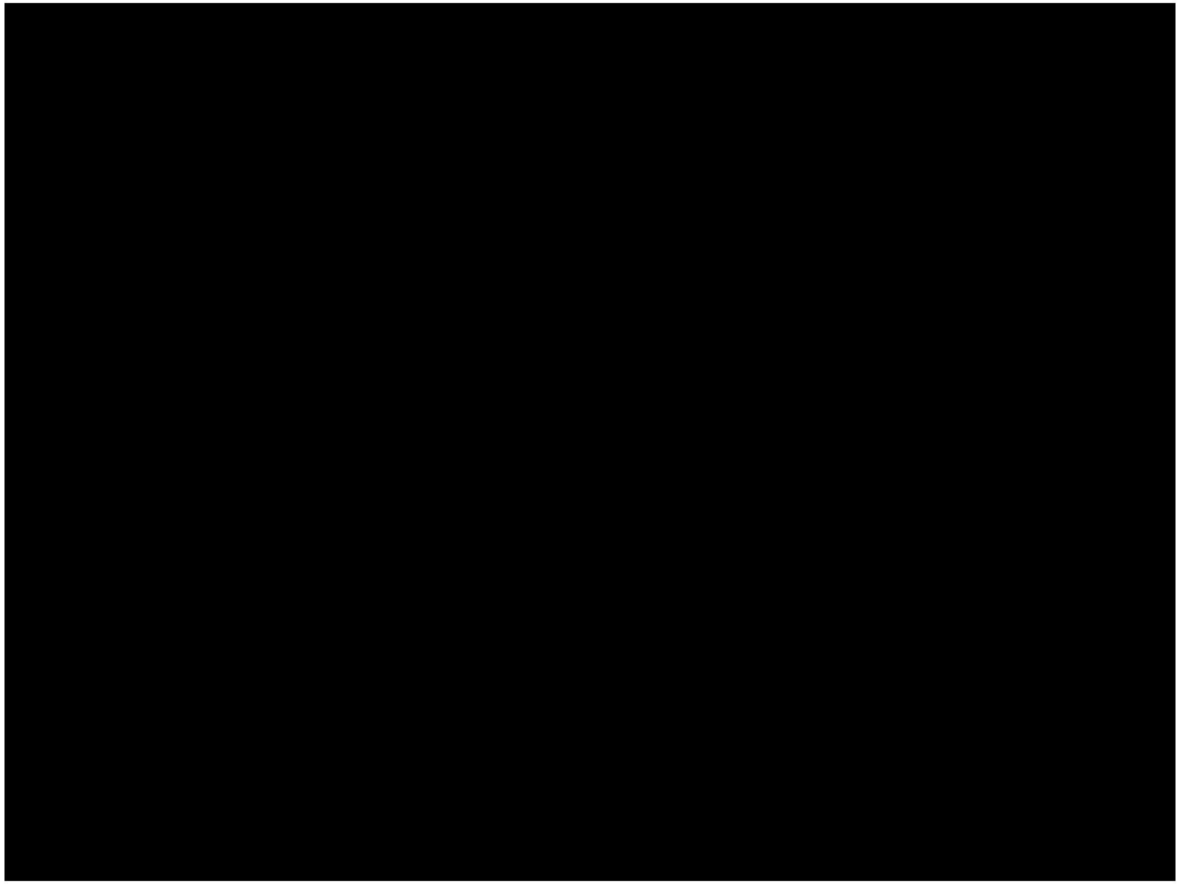




Loop closures within air/ground robots

"Rendez-vous": inter-robot pose estimation





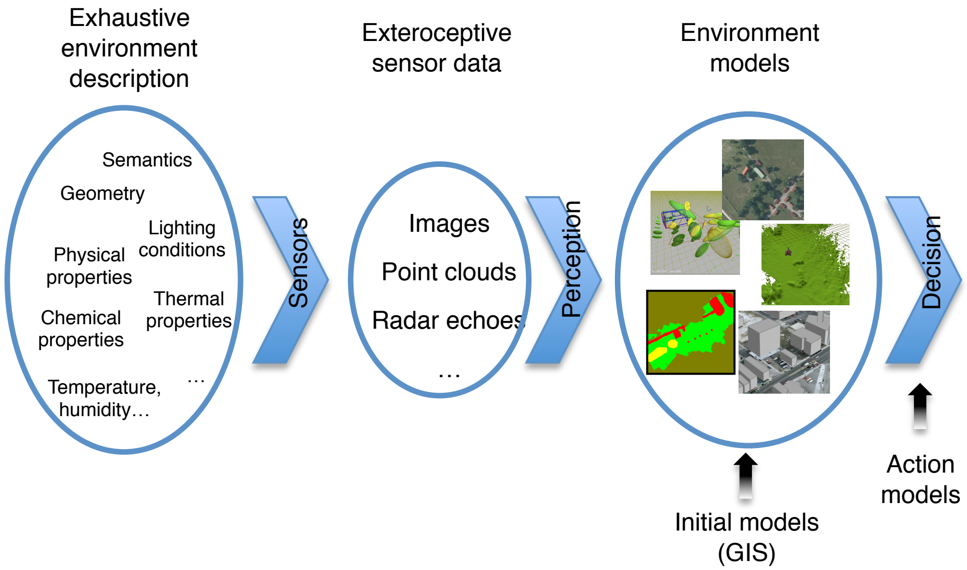
Perspectives

Keep the focus on geometric (3d, vectorized) representations

Perspectives

Keep the focus on geometric (3d, vectorized) representations

Integrate existing data (GIS)



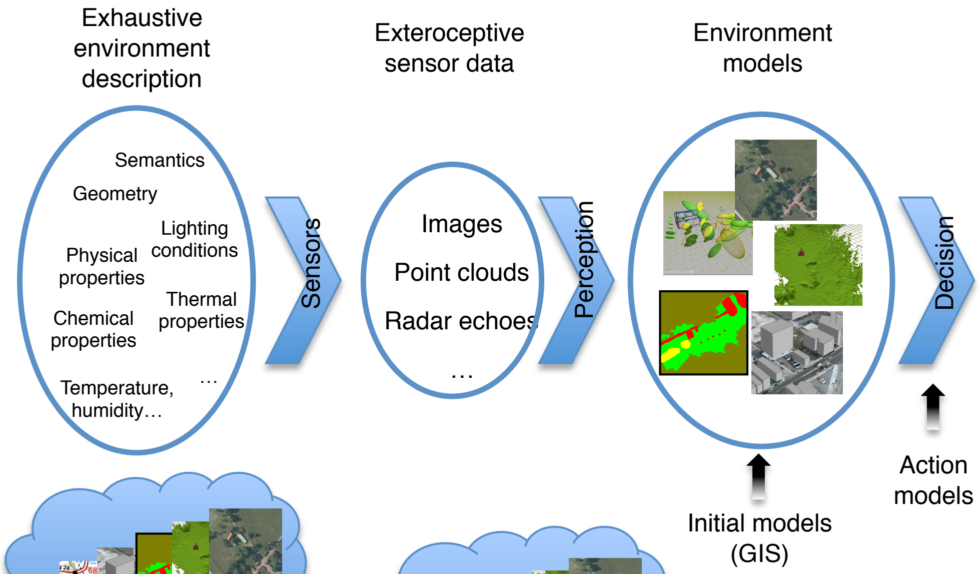
Perspectives

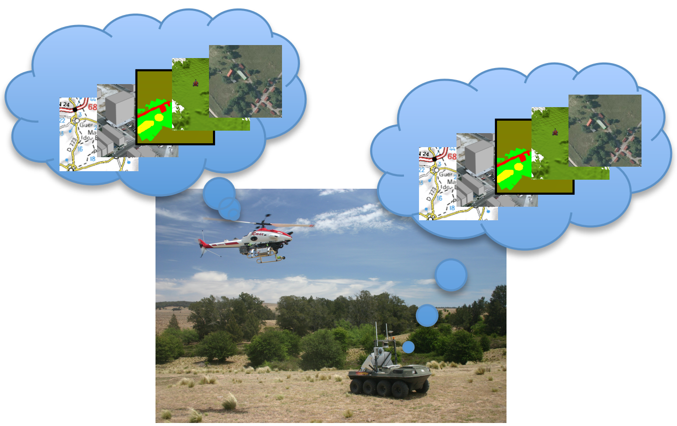
Keep the focus on geometric (3d, vectorized) representations

Integrate existing data (GIS)

Distributed models Management

- APIs for clients
- Maintain the inter-robot inter-model consistency





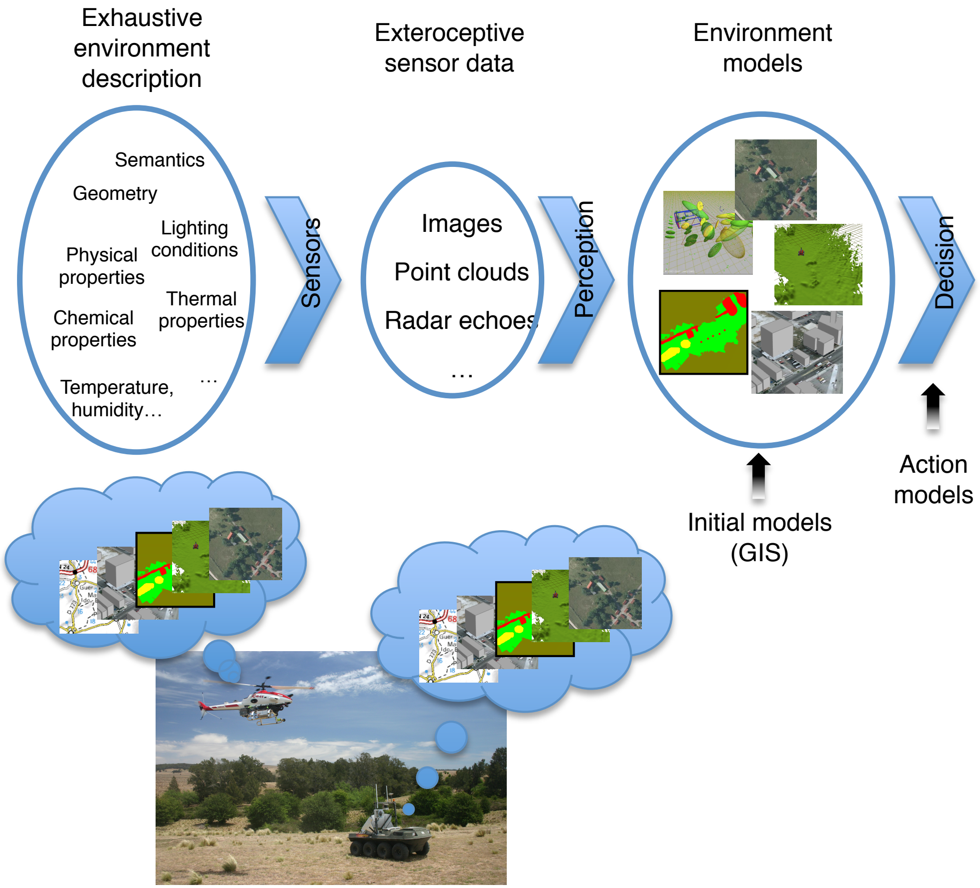
Perspectives

Keep the focus on geometric (3d, vectorized) representations

Integrate existing data (GIS)

Distributed models Management

- APIs for clients
- Maintain the inter-robot inter-model consistency



Humans in the loop: information sharing (*cf* spatial ontologies)

Summary

Autonomous decision making in air/ground systems

➡ On the importance of environment representations

Environment models

➡ On the importance of localization

Localization

➡ On the importance of the environment representations

Credits / Thanks / Acknowledgments

The following people have contributed to a small or large extent to the results and/or ideas discussed in this presentation:

Rachid Alami, Guy Le Besnerais, Cyrille Berger, Sébastien Bosh, Redouane Boumghar, Hung Cao, Paul Chavent, Arnaud Degroote, Gilberto Echeverria, Malik Ghallab, Félix Ingrand, Thomas Lemaire, Naveed Muhammad, Bach Van Pham, Cyril Robin, Cyril Roussillon, Martial Sanfourche, Joan Solà, Teresa Vidal-Calleja