

# Remote operations of fleets of autonomous robots

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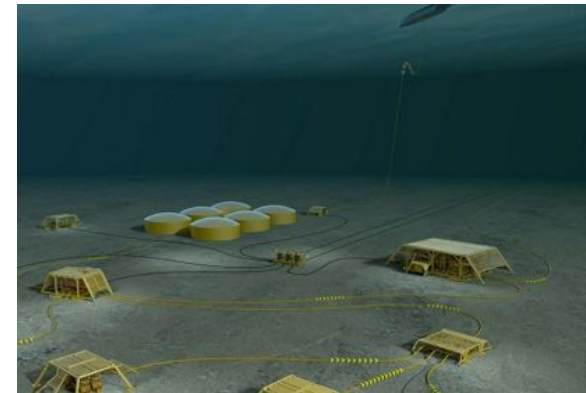
## Challenges and approach

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and Architecture of Systems*  
CNRS, Toulouse



# Remote operations

- Sites / areas where human presence is precluded



Either not possible, too risky or too costly for humans

# Remote operations

- Sites / areas where human presence is precluded
- To do what ?

Considered missions:

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

In various application contexts:

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

➔ *Information gathering and intervention missions*

# Outline

Remote operations  
of  
fleets  
of  
autonomous  
robots



Challenges  
and  
approach

# Outline

Remote operations  
of  
**fleets**  
of  
autonomous  
**robots**

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Challenges  
and  
approach

# Fleets of robots

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

# Fleets of robots

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



“Remote eye” @ CMU



On going work @ ACFR

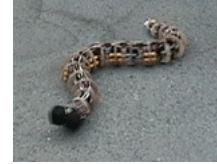


On going work @ LAAS & Onera

# 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

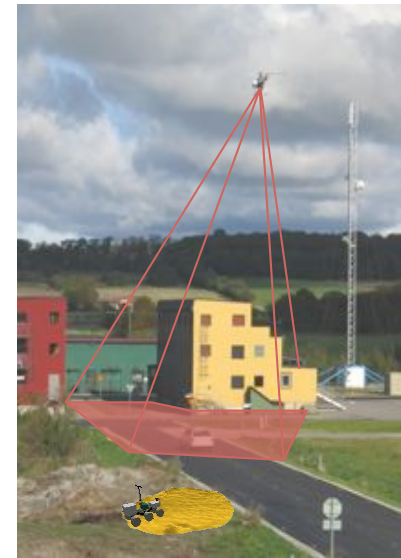


# Fleets of robots

- *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
  - ...



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# Operation of robot fleets

- No operators on site does not mean “no operators”
- Robot teams must not imply teams of operators !
  - ➔ Cooperation / coordination issues must be solved by the robots
  - ➔ *A high level* of autonomy is required
  - ➔ (still low-level controls could be achieved by operators)

# Outline

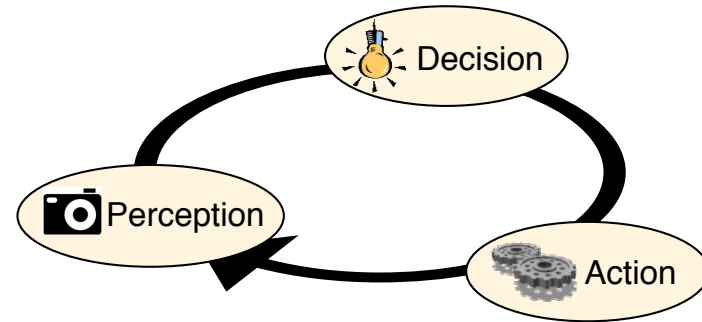
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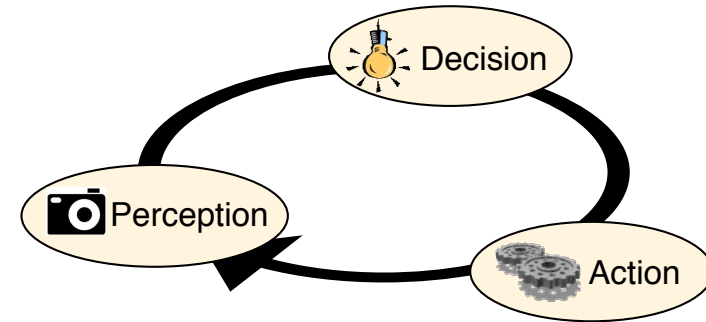
# Autonomous robots

- The three pillars of autonomy

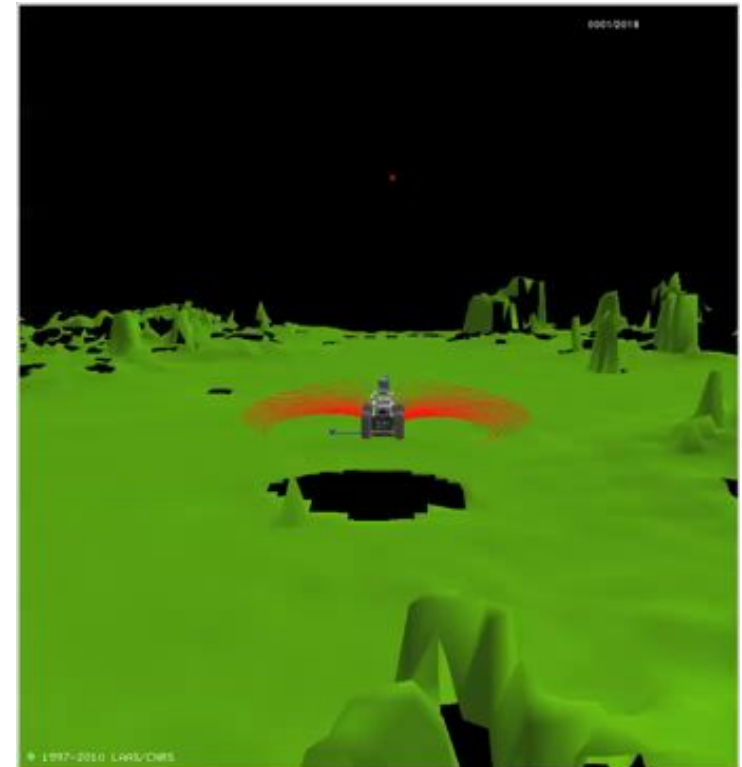


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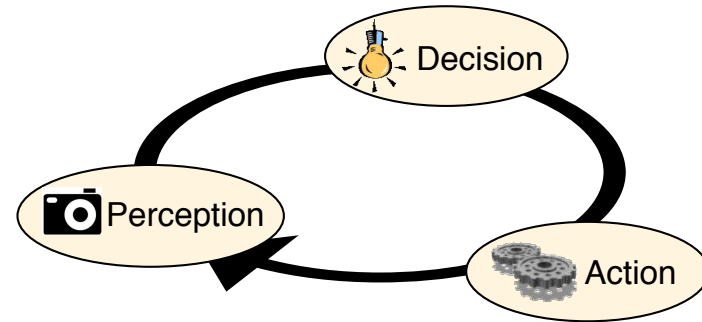


- A basic task: autonomous navigation



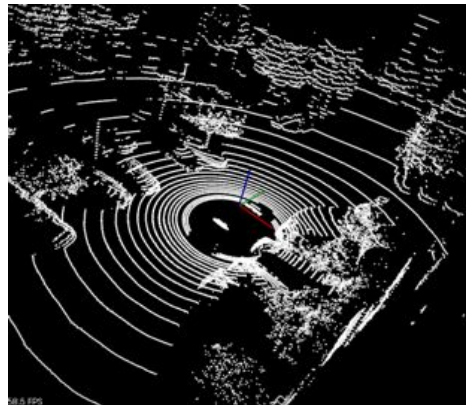
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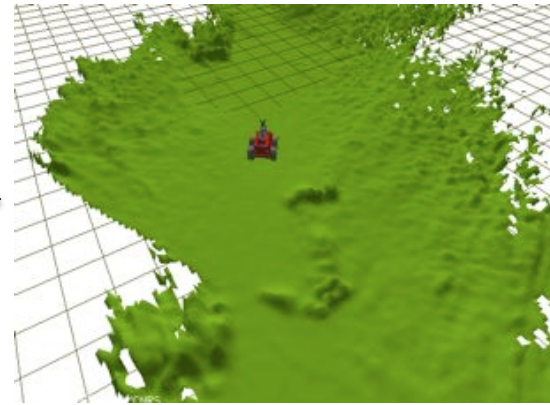


- A basic task: autonomous navigation

## 1. Perception



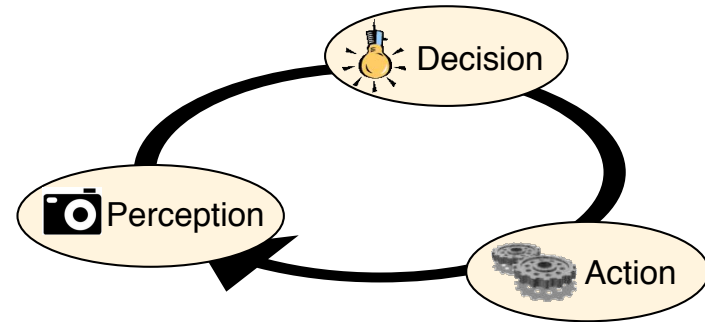
*Depth image*



*Digital terrain model*

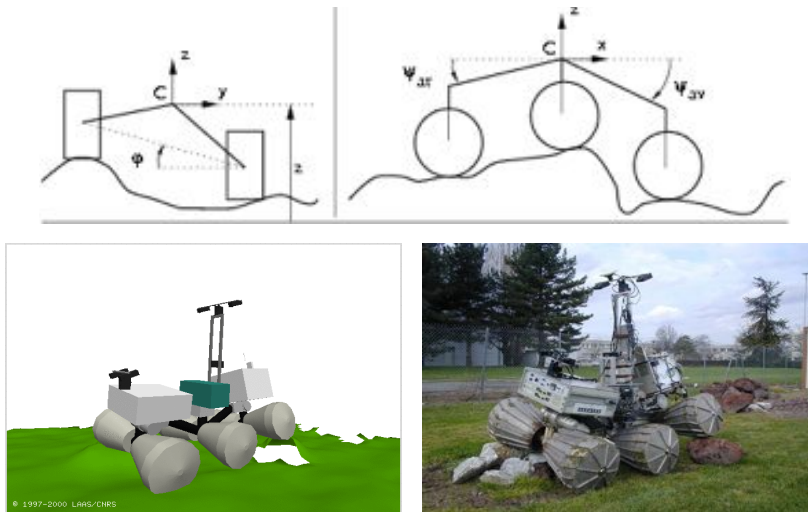
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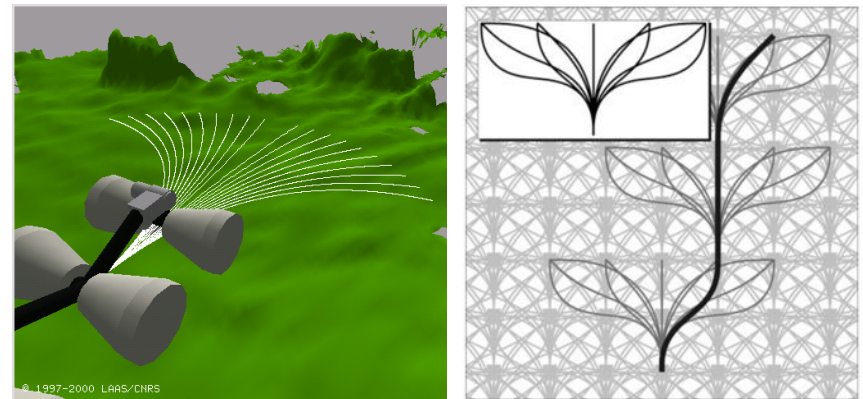


- A basic task: autonomous navigation

## 2. Decision



*Convolution of the robot model with the terrain model*

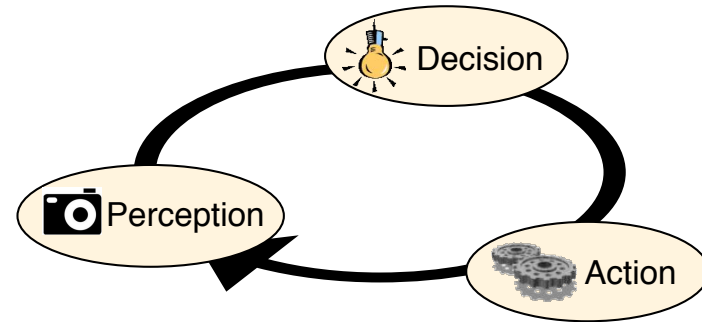


*Search*



# Autonomous robots

- The three pillars of autonomy



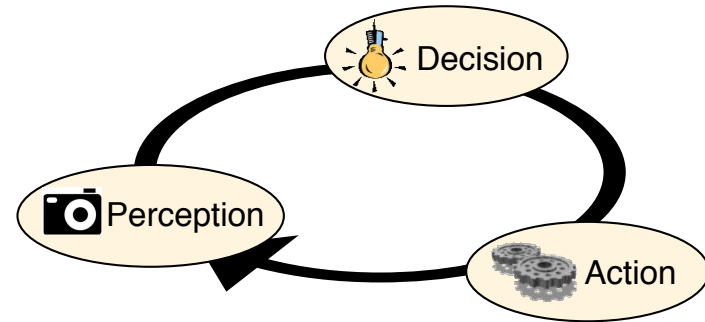
- A basic task: autonomous navigation

## 3. Action

“Just” execute the planned motions

# Autonomous robots

- The three pillars of autonomy



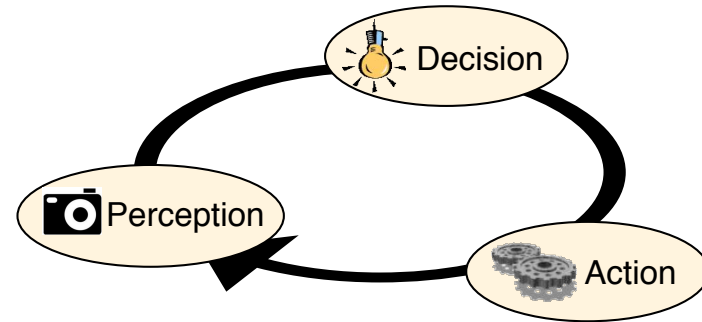
## 2. Decision

Deciding, 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

# Autonomous robots

- The three pillars of autonomy



## 2. Decision

➔ Models are at the core of autonomy

- Action models
- Environment models

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# Challenges



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

Large scale ( $km^3$ ) implies:

- Faster robots, longer missions (“lifelong autonomy”)
- Large (multi-scale) environment models
- Communication constraints
- Cooperative and coordinated perception / planning / action
- Operating robot fleets: need for advanced interactions

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# Approach (1/2)

Environment models are at the core of autonomy

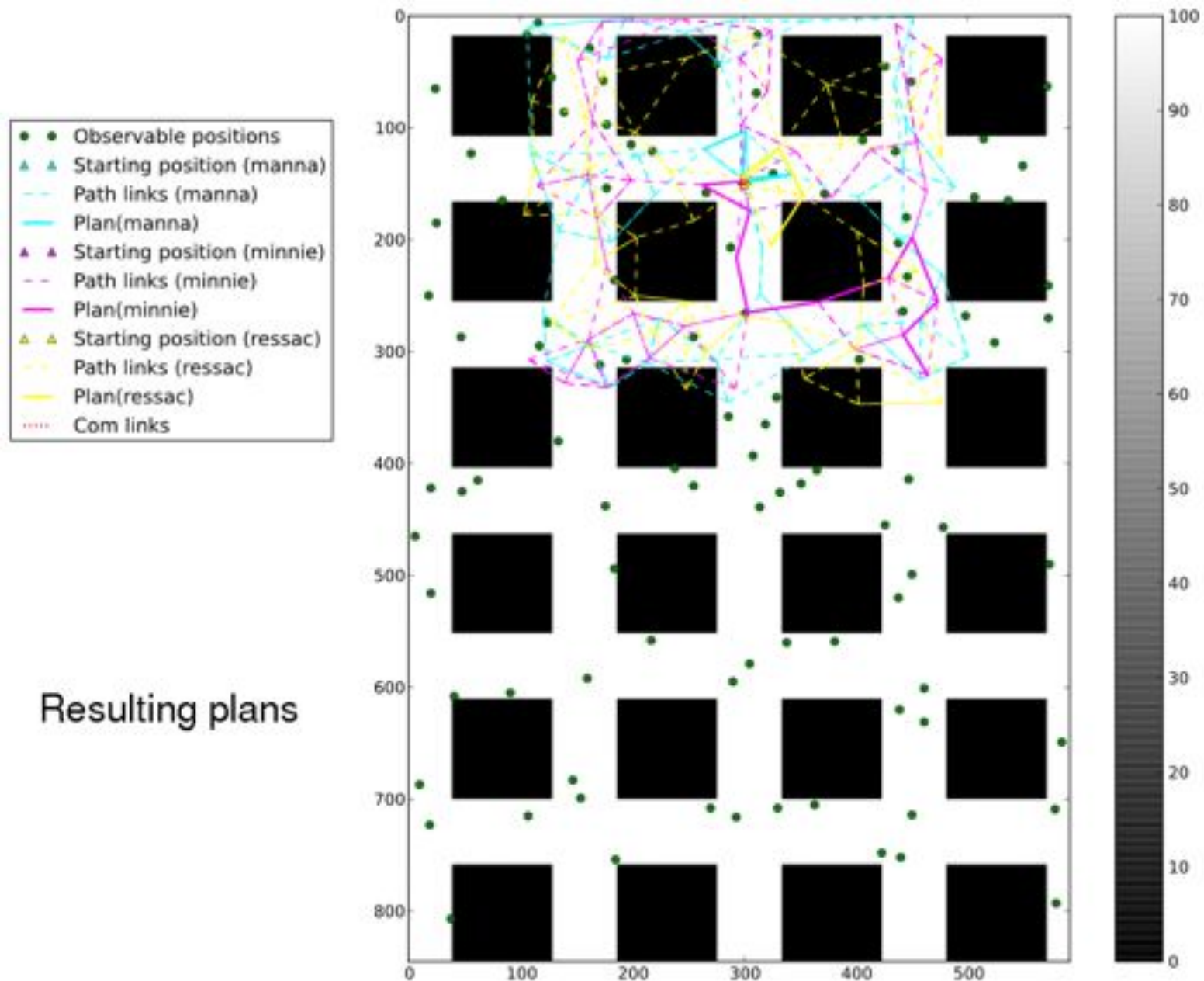
➔ Environment models are at the core of cooperation

# Illustration: planning a patrolling mission (1/2)





# Illustration: planning a patrolling mission (2/2)



# What action models have been used?

- Robot motion model

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

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

- Observation model

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

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

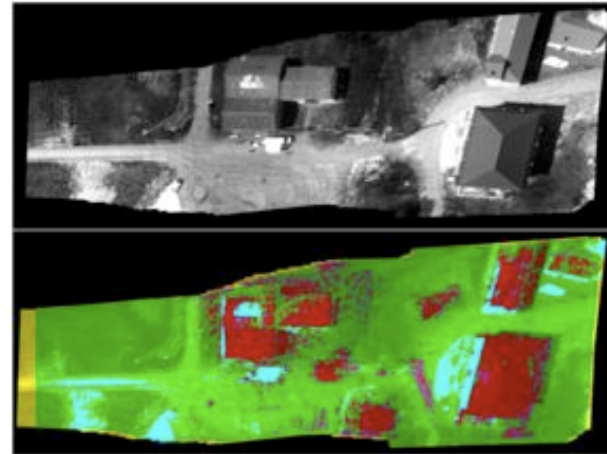
- Communication model

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

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

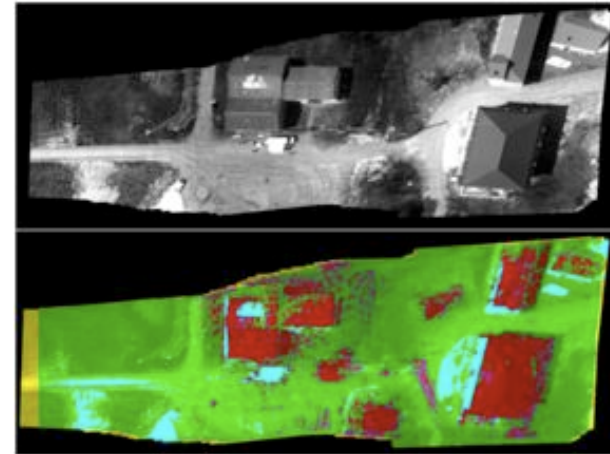
# What environment models have been used?

- To plan motions: express traversability / accessibility

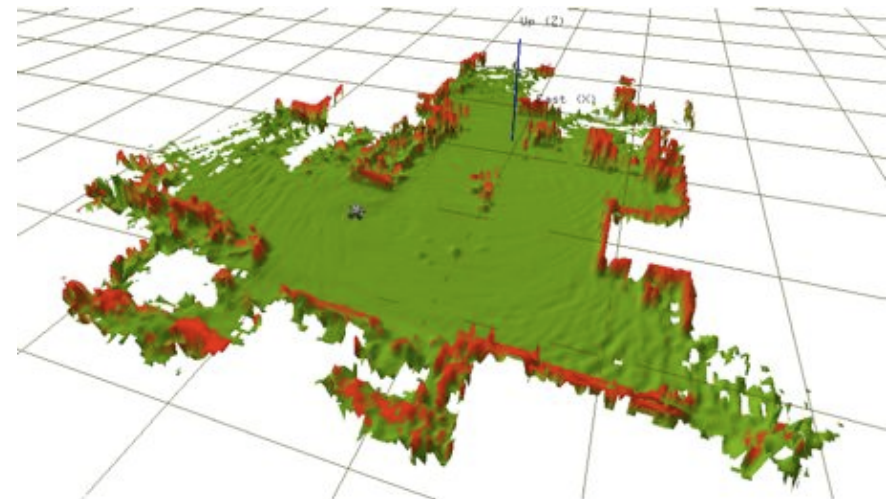


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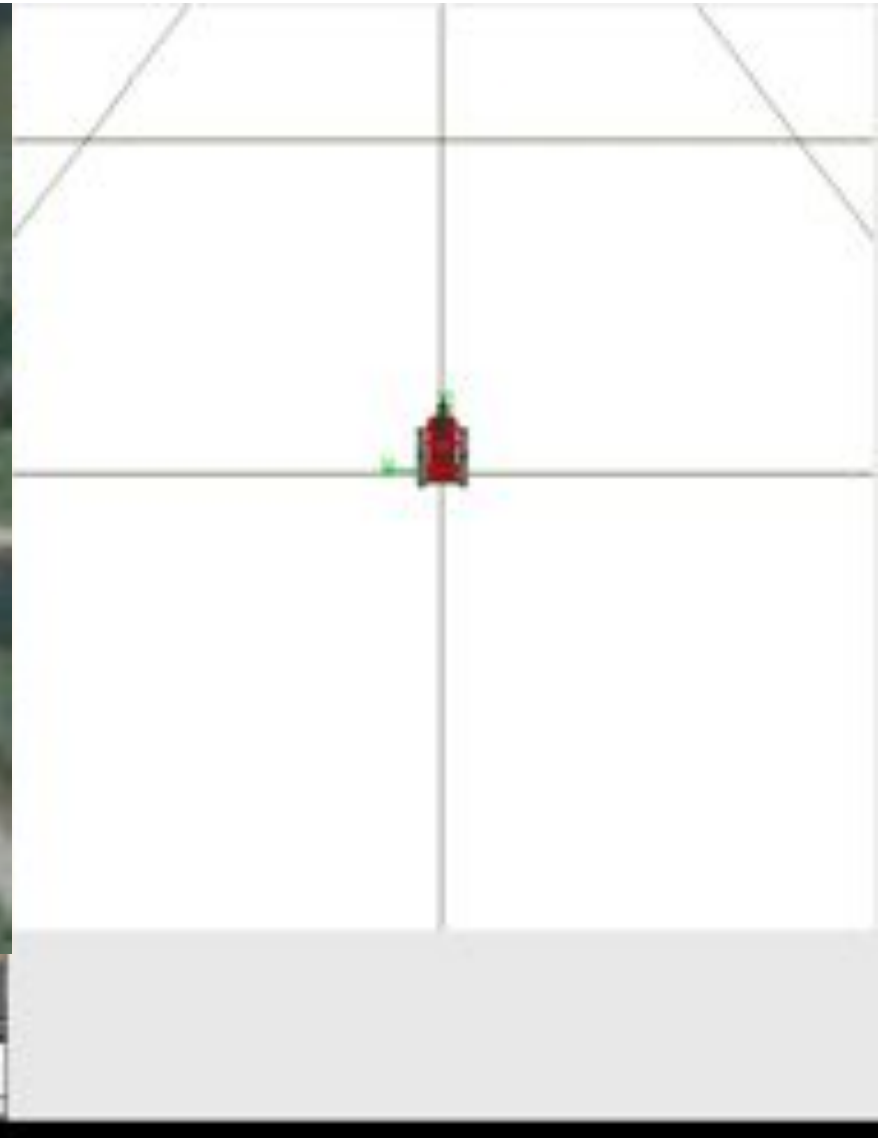
- To plan motions: express traversability / accessibility



- To plan observations: line of sight visibility
- To plan communications: line of sight visibility

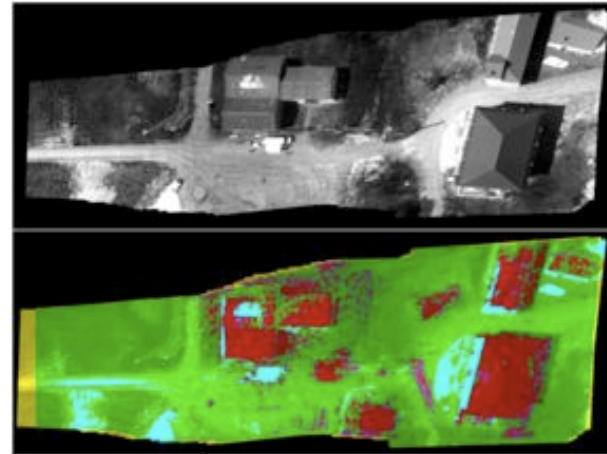


# Illustration: autonomous navigation revisited



# What environment models have been used?

- To plan AGV motions: express traversability / accessibility



- To plan AUV motions: information quality (quantity) of the traversability model

# SkyScanner

*Fleets of enduring drones to probe atmospheric phenomena within clouds*



- Mission goal:
  - 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 edge, liquid water, cloud microphysical properties
- 4D adaptive sampling
  - Servo on the gathered information to gain more information
  - Optimize the drones trajectories (trade-off: explore vs. sustain)

# SkyScanner

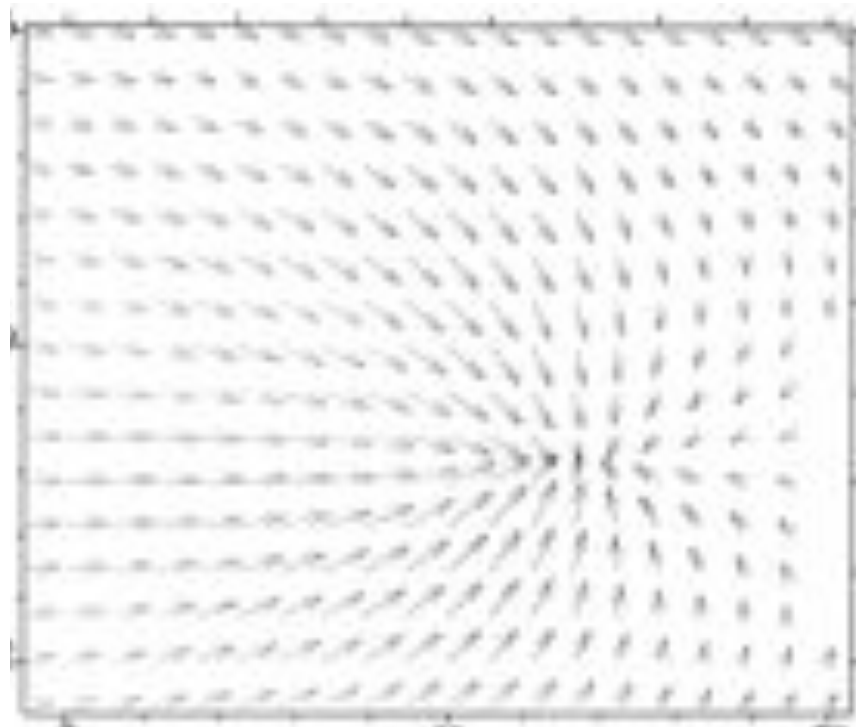
*Fleets of enduring drones to probe atmospheric phenomena within clouds*



- *A dynamic phenomenon...*
- *... observed locally*



“Air truth”

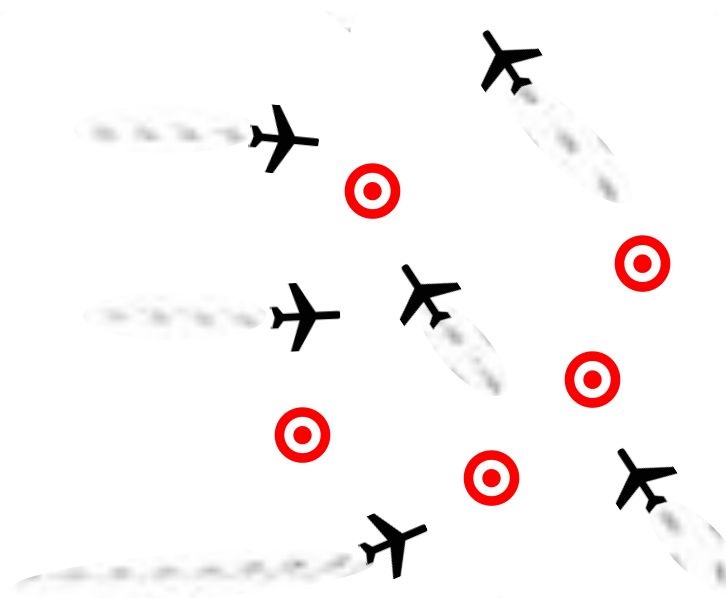




# SkyScanner

Fleets of enduring drones to probe atmospheric phenomena within clouds

- A *dynamic* phenomenon...
- ... observed *locally*



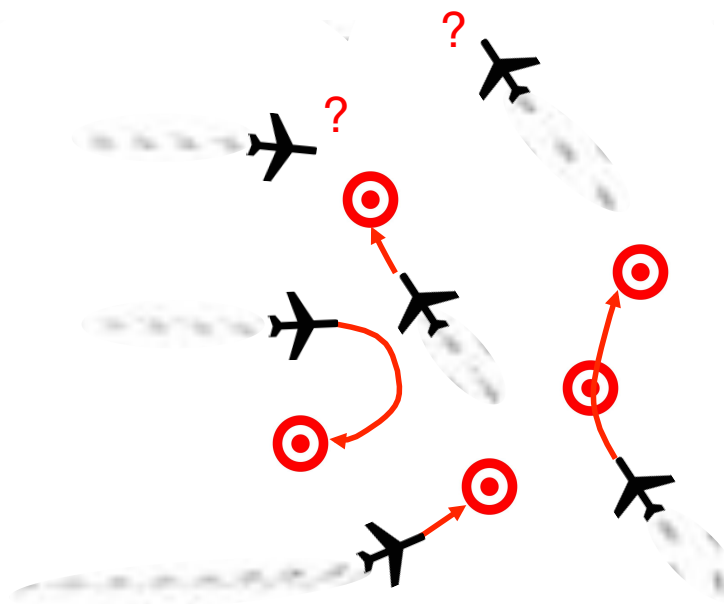
Known information  
at time  $t$

1. Where to gather new information?
2. Who is flying where?

# SkyScanner

Fleets of enduring drones to probe atmospheric phenomena within clouds

- A *dynamic* phenomenon...
- ... observed *locally*



Known information  
at time  $t$

1. Where to gather new information?
2. Who is flying where? And how?

# SkyScanner

*Fleets of enduring drones to probe  
atmospheric phenomena within clouds*

- What environment model is used?
  - “Generic” physical model of the cloud...
  - ... dynamically updated

# SkyScanner

*Fleets of enduring drones to probe  
atmospheric phenomena within clouds*

- What environment model is used?
  - “Generic” physical model of the cloud...
  - ... dynamically updated
  - Winds ~ traversability
  - Quality / quantity of information drives the sampling

# Where do environment models come from?

- A priori models
  - Orthoimages, digital terrain maps
  - CAD models
  - ...
- Models built online
  - Robot localisation is a key

# On the importance of localization

Localization is required to:

- Ensure the achievement of the missions, most often defined in localization terms (“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

# 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
- Simultaneous Localization and Mapping (“SLAM”)



# But... what localization?

Essential questions to answer:

- |                          |                                 |
|--------------------------|---------------------------------|
| 1. With which precision? | From <i>cm</i> to <i>meters</i> |
| 2. In which frame?       | Absolute vs. local              |
| 3. At which frequency?   | From <i>kHz</i> 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:

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| 1. With which precision?                 | From <i>cm</i> to <i>meters</i> |
| 2. In which frame?                       | Absolute vs. local              |
| 3. At which frequency?                   | From <i>kHz</i> to “sometimes”  |
| 4. <i>Integrity</i> of the solution?     |                                 |
| 5. <i>Disponibility</i> of the solution? |                                 |

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

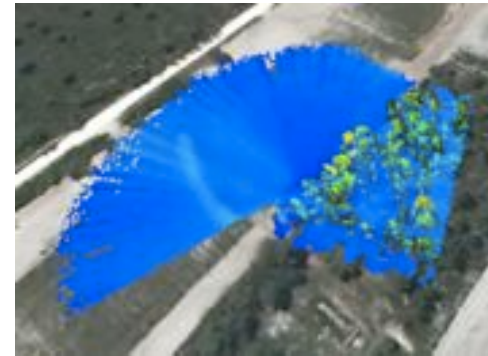
- Ensure the lowest level (locomotion) controls
- Ensure the proper execution of paths / trajectories
- Ensure the spatial consistency of the built models

~*m* accuracy,  
“sometimes”,  
global frame

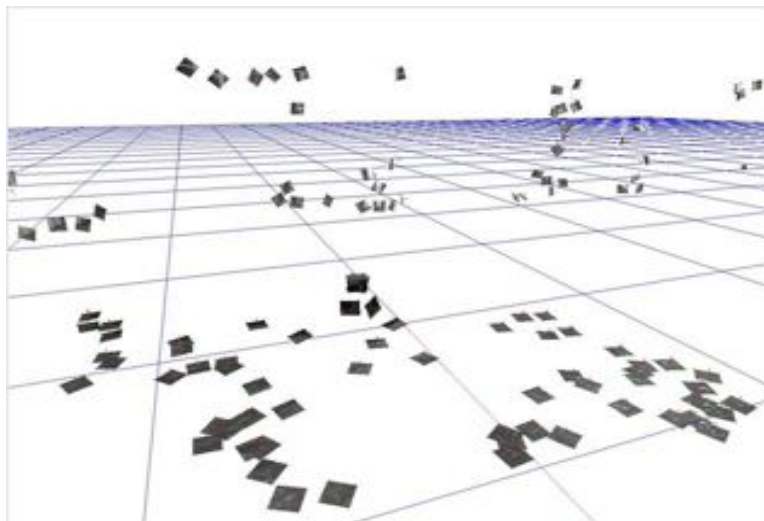
- Ensure the achievement of the missions, most often defined in localization terms (“goto [goal]”, “explore / monitor [area]”, ...)

# What environment models are used for localisation?

- Geometric models (a priori of built by the robots)



- Dedicated models (e.g. “landmarks”, “views memory”)

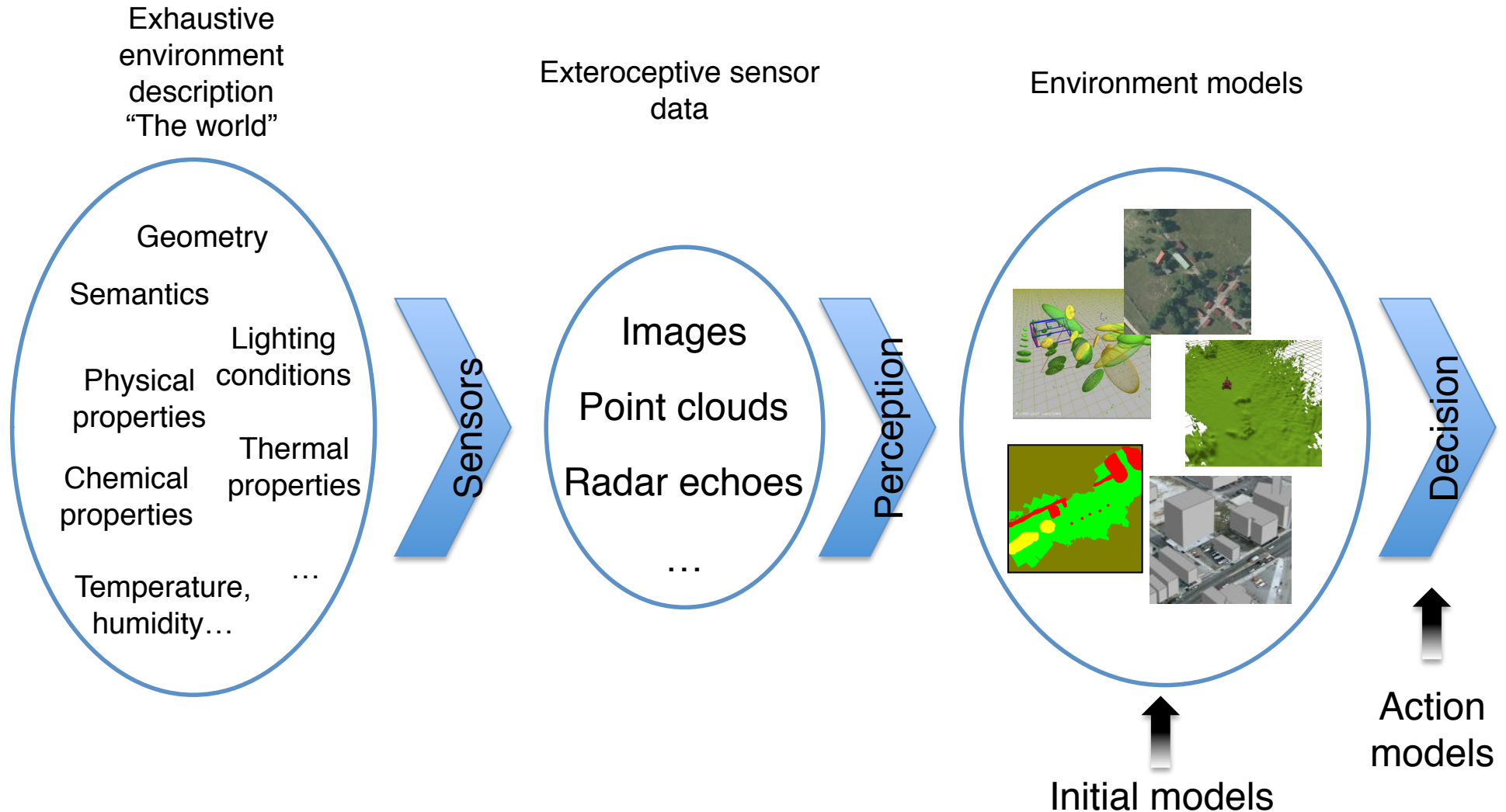


# Wrap up: a patrolling mission



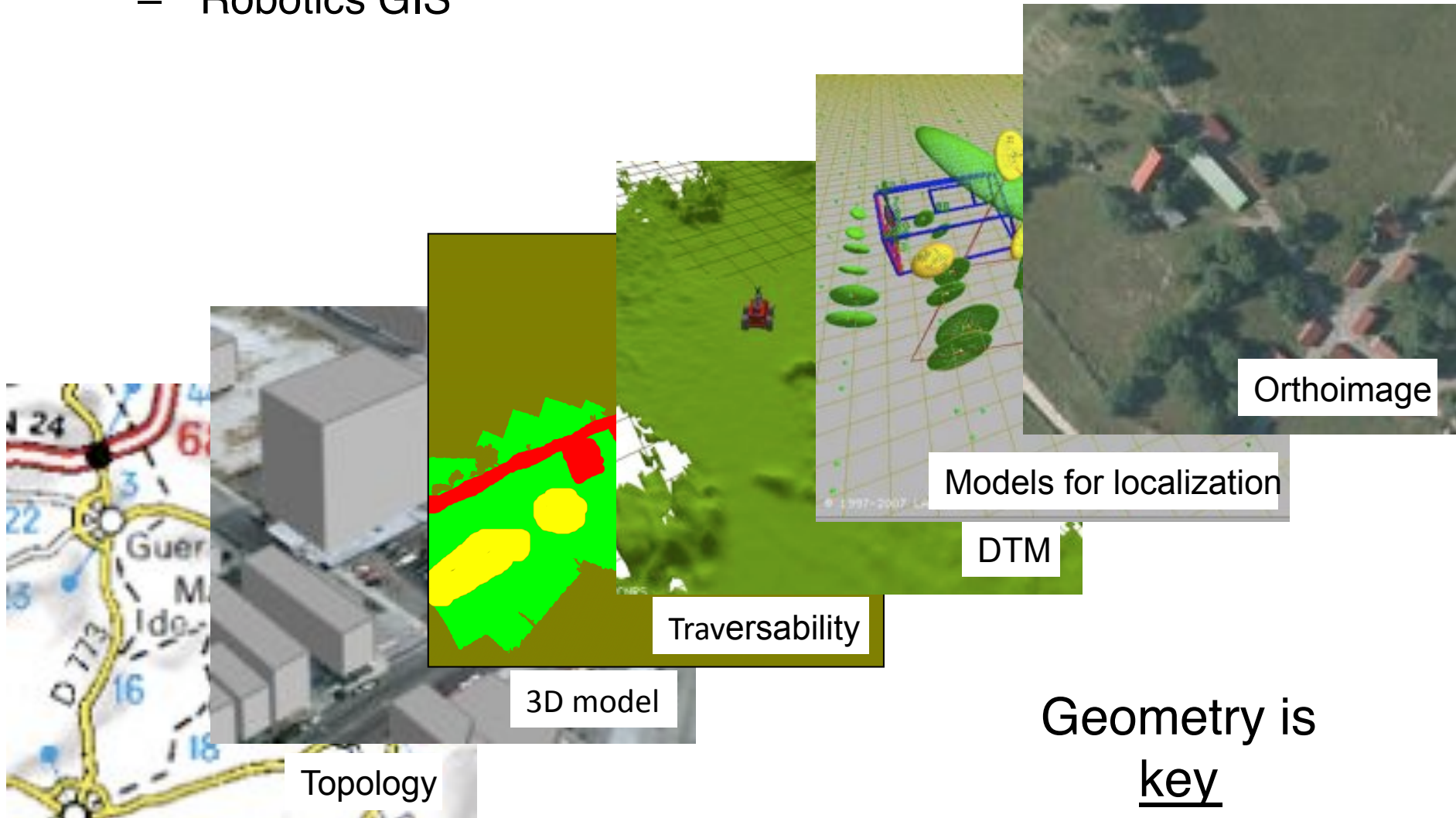
# Summary on environment models

- Information flow



# Managing environment models

- A variety of *dedicated* models has to be maintained
  - “Robotics GIS”



Geometry is  
key

# Managing environment models within a team

Distributed models management:

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



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# Approach (2/2)

Environment models are at the core of autonomy

➔ Environment models are at the core of cooperation

➔ Environment models are at the core of operator interactions

# Conclusions

- 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
- Info-centric view + operator control impacts the overall system architecture
  - “Resource oriented architecture”
  - Operator / robot information sharing: spatial ontologies?
  - (plus: adjustable autonomy)