Randomized Strategies for Sensor-Based Robot Exploration

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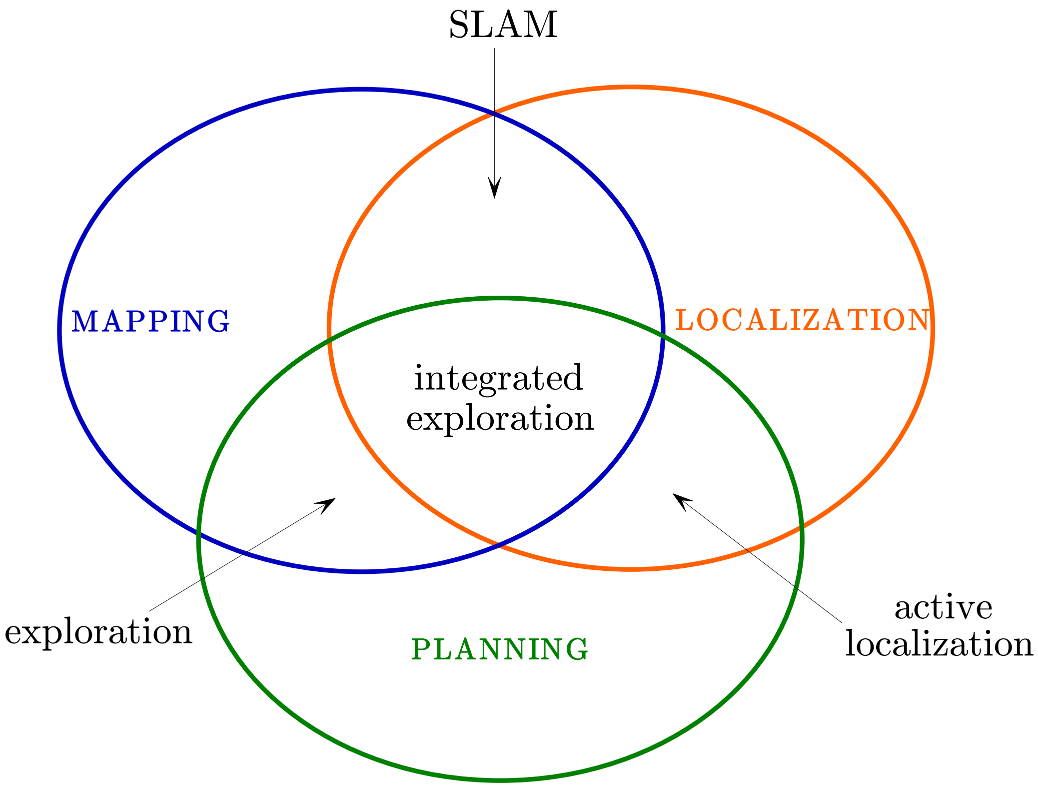
OUTLINE

- Introduction
- Exploration
- Integrated-Exploration
- Multi-robot Exploration
- Conclusions

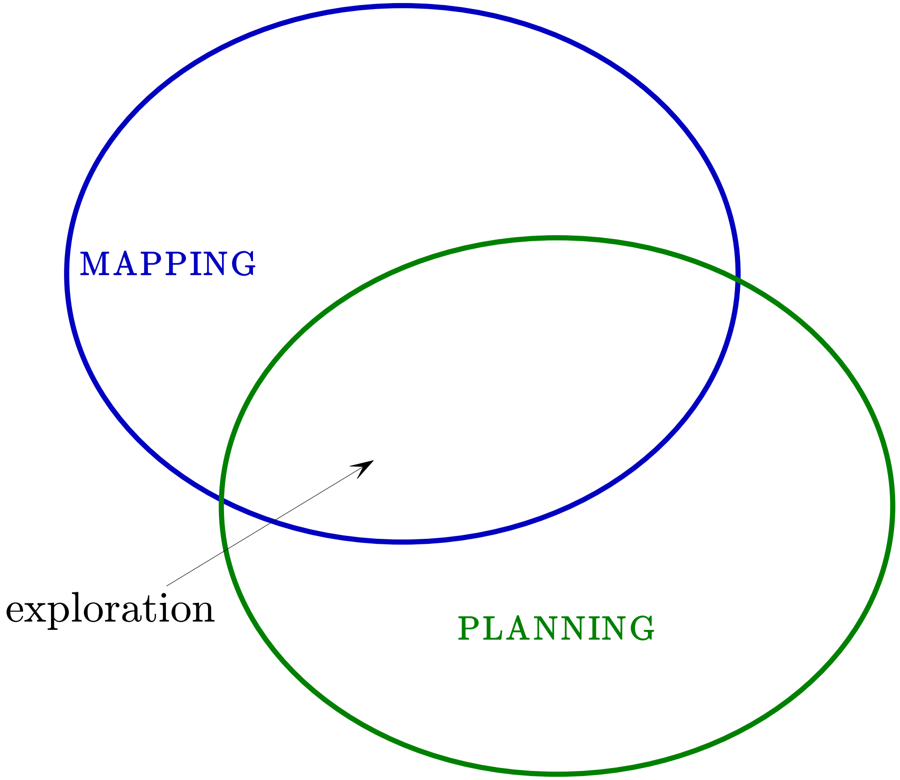
INTRODUCTION

learning an environment model requires the fulfillment of **three** different tasks: **mapping**, **localization** and **planning**

in the field of robotic exploration, these tasks are integrated in different manners [Makarenko et *al.*, 2002]



EXPLORATION



exploration

- the process of moving through an unknown environment for building a map that can be used for subsequent navigation [Yamaouchi'97]
- from a **more general** perspective: the process of selecting actions in active learning [Thrun '95]

the central problem: **how to select the next action?**

many existing techniques fall into the class of **frontier-based exploration**: the criterion is the maximization of the action's (expected) utility

$\rightarrow$ the robot moves towards the frontier between known and unknown areas to maximize the information gain coming from new perceptions

[Yamaouchi '97; Burgard *et al.*'00; Makarenko *et al.*'02; Gonzales-Banos and Latombe '02] another possibility is to use a random selection mechanism (**random walk**)

pros/cons:

- **simple** (no deliberation)
- any action sequence will be executed eventually ($\rightarrow$ **completeness**)
- pure random action selection may be very **inefficient**

in motion planning, randomized (RMP) techniques achieve high efficiency by adding **heuristics** to the basic random scheme

$\Rightarrow$ **our approach**

design an exploration method based on the **random** generation of robot configurations within the local safe region detected by the sensors, with the addition of simple **heuristics** for validation

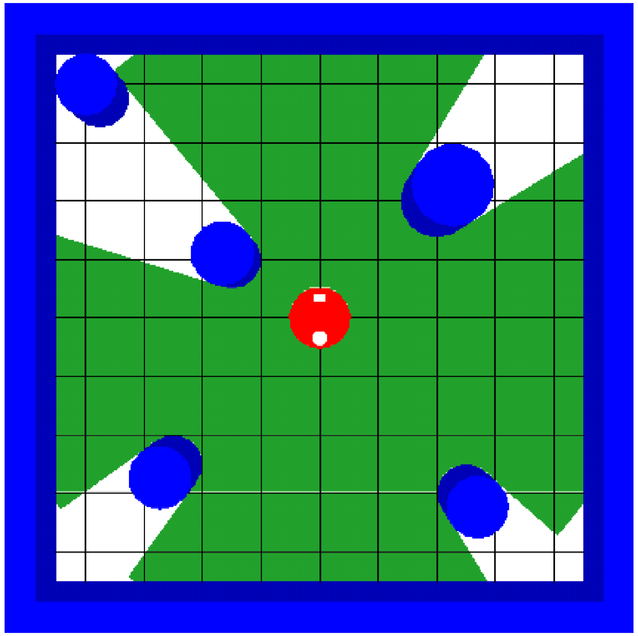
$\rightarrow$ can be considered as a **sensor-based** version of randomized planning techniques (in particular, RRT)

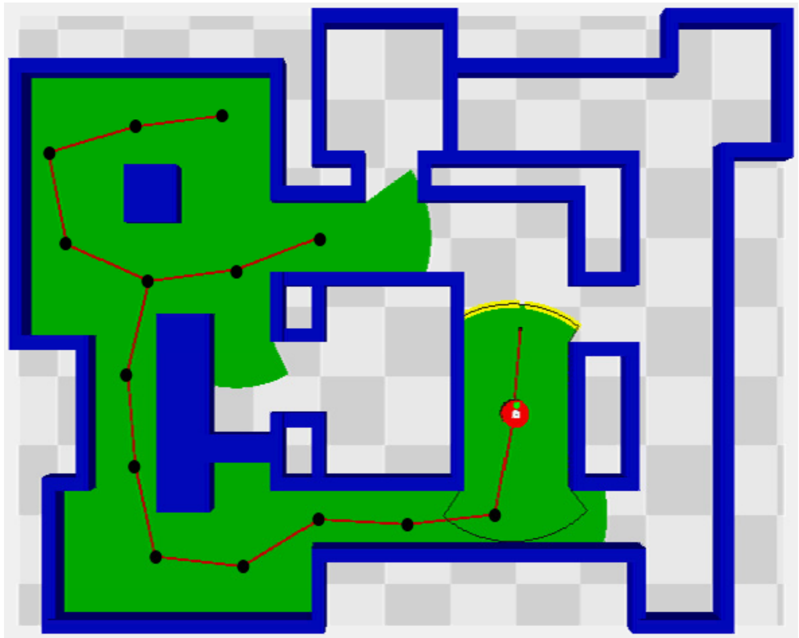
EXPLORATION VIA THE SRT METHOD

working assumptions

1. the workspace is **planar**, i.e., either $\mathbb{R}^2$ or a (connected) subset of $\mathbb{R}^2$
2. the robot is a **holonomic disk**
3. the robot always **knows** its configuration q
4. at each q, **perception** provides the Local Safe Region $\mathcal{S}$, i.e., an estimate of the surrounding free space in the form of a **star-shaped** subset of $\mathbb{R}^2$

1, 2, 3 can be **relaxed**; in 4 the estimate may be conservative





- the LSR $\mathcal{S}$ is **star-shaped**; it is the current visibility region limited by the maximum measurable range

- the map is built in the form of a Sensor-based Random **Tree** (SRT): each **node** contains a configuration assumed by the robot and the associated LSR description

basic steps

1. **LSR construction**
2. **local frontier computation**
3. if the local frontier is not empty $\rightarrow$ **forwarding**

   frontier-based random generation of a new candidate configuration q_{cand}

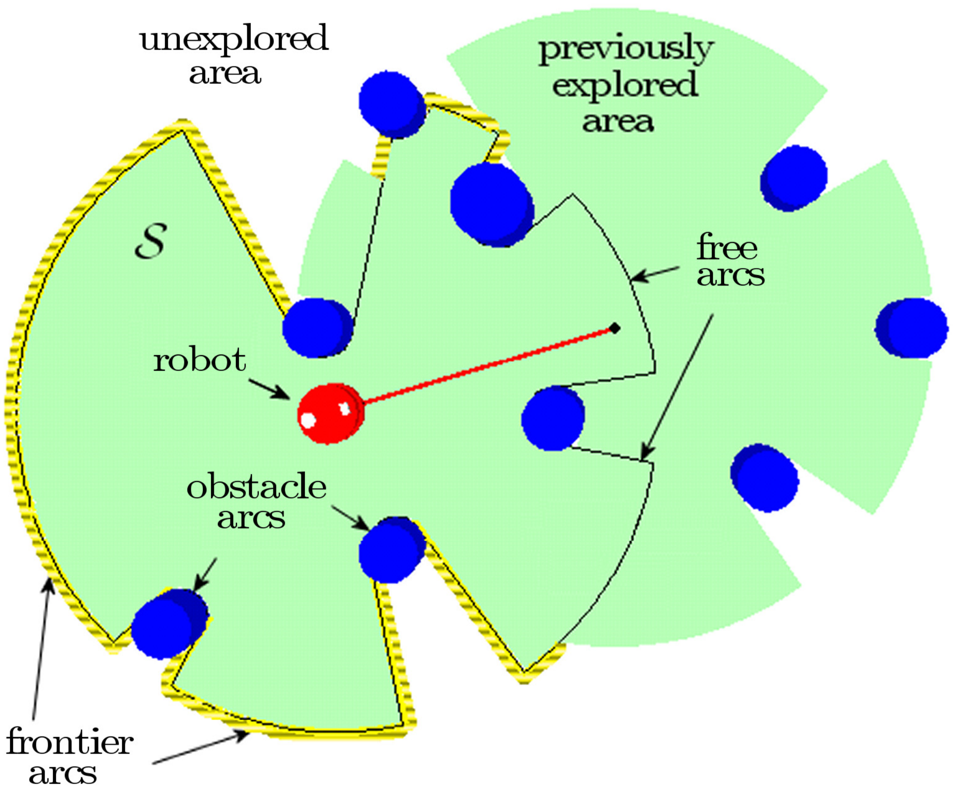
4. if the local frontier is empty $\rightarrow$ **backtracking**

   return to the parent node

LOCAL FRONTIER COMPUTATION

- the boundary of the Local Safe Region $\mathcal{S}$ is partitioned in **obstacle**, **free** and **frontier** arcs

- arcs classification is straightforward from range readings



FRONTIER-BASED RANDOM GENERATION

generation of candidate configurations is **biased** towards the frontier arcs of the Local Safe Region:

- select a **local frontier arc** using a probability proportional to the arc length (the selected arc is represented by its angular width γ and the orientation θ_m of its bisectrix)

- generate **direction** θ_{rand} according to a normal distribution with mean value θ_m and standard deviation $\sigma = \gamma/6$

- displace a new **configuration** q_{new} along θ_{rand} and inside the current LSR

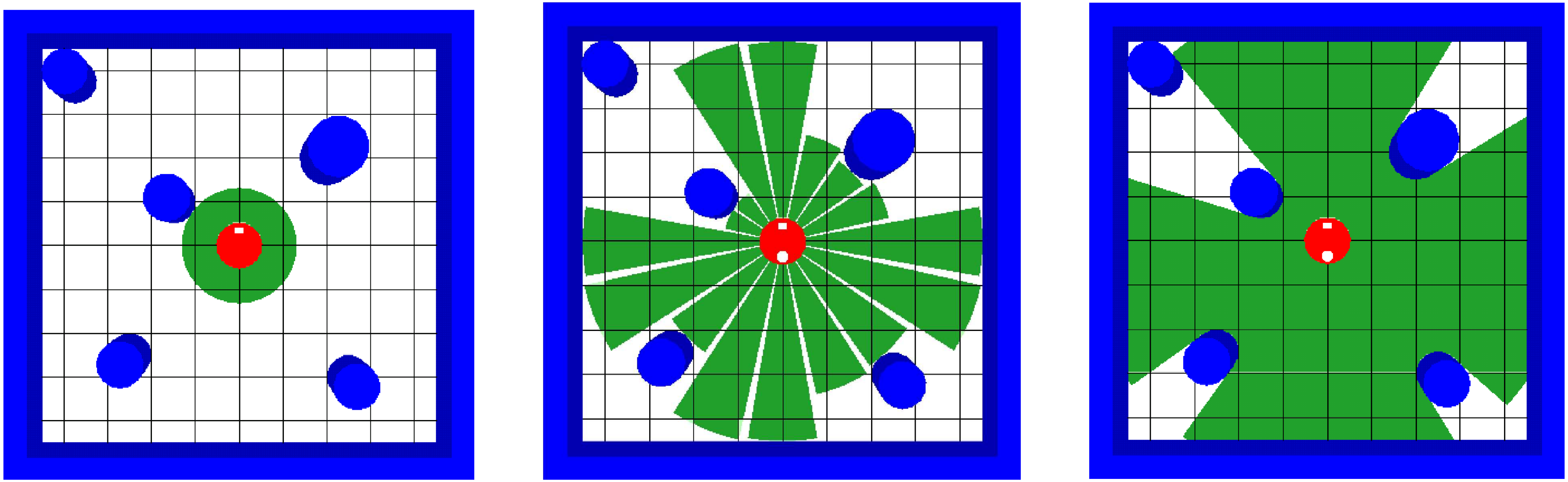
forwarding/backtracking

simulation (performed in Webots)

- MagellanPro robot with **laser range finder**
- perfect sensing and localization
- depth-first
- homing

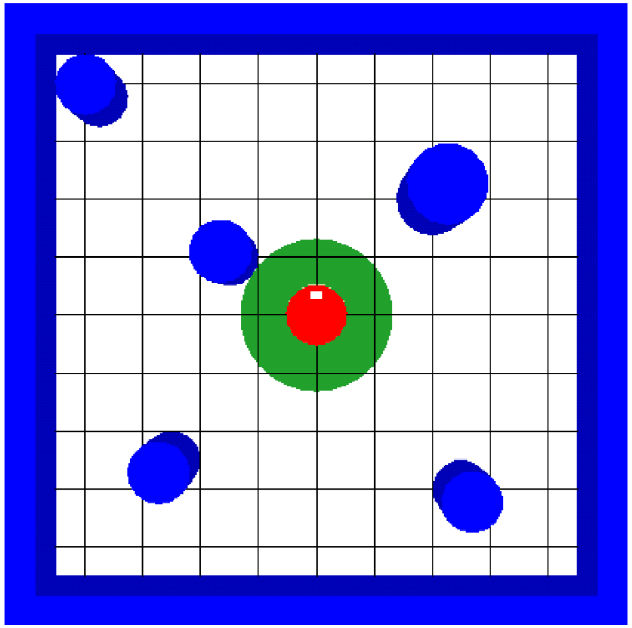
the SRT method is a **general** paradigm:

the **shape** of the Local Safe Region $\mathcal{S}$ reflects the **sensor characteristics** and the **adopted perception technique**



$\Rightarrow$ the performance **changes** accordingly

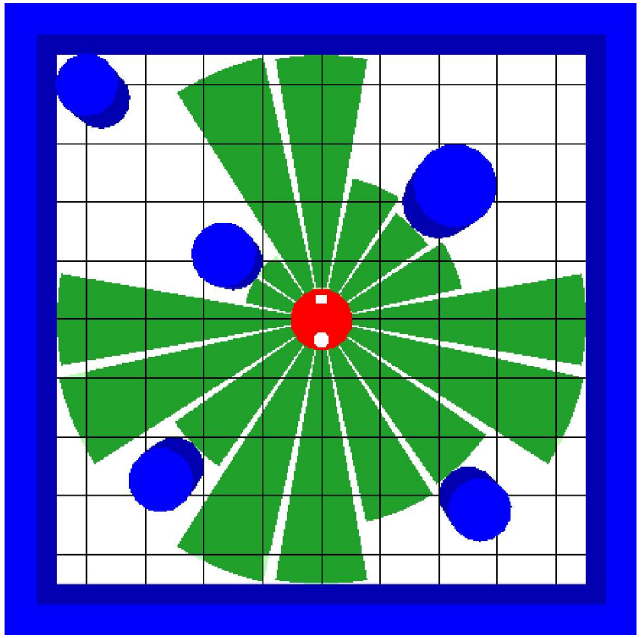
SRT-BALL



- in **SRT-Ball**, $\mathcal{S}$ is a ball whose radius is the **minimum range reading** (the distance to the closest obstacle or, in wide open areas, the maximum measurable range)
- a **conservative** perception mode suitable for **noisy/imprecise sensors**

experiment with Khepera

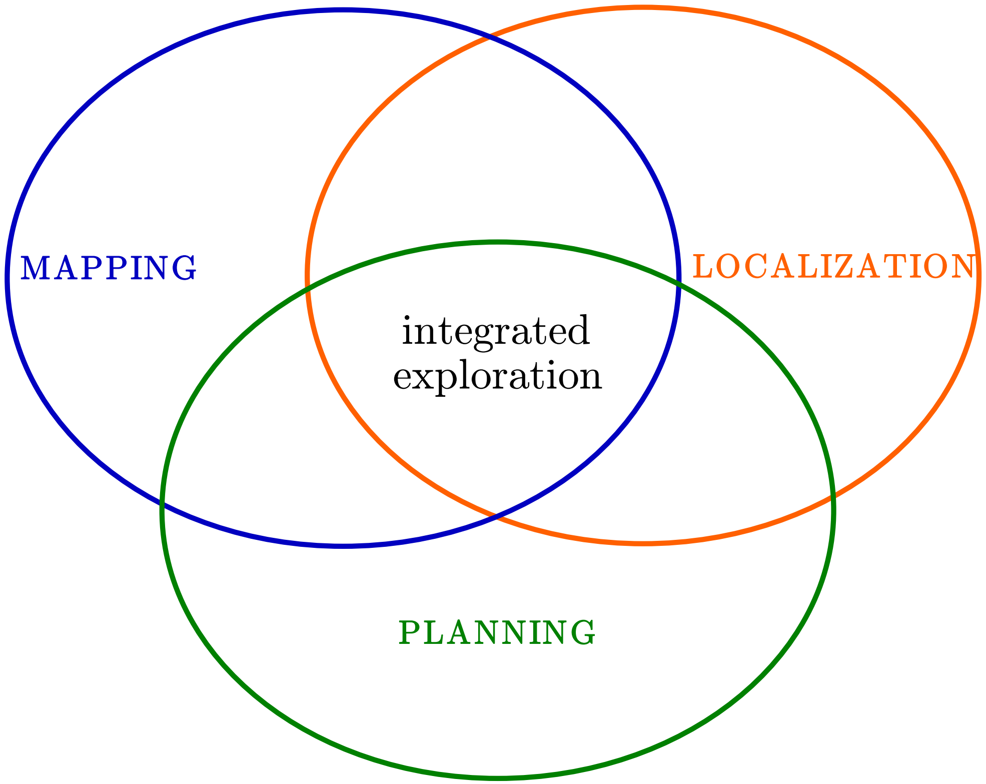
SRT-STAR



- in **SRT-Star**, $\mathcal{S}$ is the union of different 'cones' whose radius is the corresponding range reading
- a perception mode suitable for ultrasonic/infrared range finders

experiment with Magellan Pro

INTEGRATED EXPLORATION



an **efficient exploration strategy** should take into account all these three tasks when selecting a new action:

- the **energy or time cost** (planning)
- the expected **information gain** (mapping)
- the associated **localization potential** (localization)

⇒ **existing approaches**

a **utility function** is generally associated to each of these processes

the minimization of a **mixed criterion** (the total utility) combining the individual utility functions is used to select the next action

⇒ **our approach**

a **SRT-based strategy** in which the optimization of information gain and navigation cost are automatically taken into account by the local randomized strategy which proposes candidate destinations

the algorithm relies on a **feature-based continuous localization** scheme

the new robot configuration is selected so as to guarantee a minimum localization potential (number of visible features)

SRT-BASED INTEGRATED EXPLORATION

working assumptions

1. the workspace is **planar**, i.e., either $\mathbb{R}^2$ or a (connected) subset of $\mathbb{R}^2$
2. the robot is a **holonomic disk**
3. an odometric estimate $\hat{q}$ of the robot configuration is available
4. at each q, **perception** provides the Local Safe Region (LSR) $\mathcal{S}$, i.e., an estimate of the surrounding free space in the form of a **star-shaped** subset of $\mathbb{R}^2$

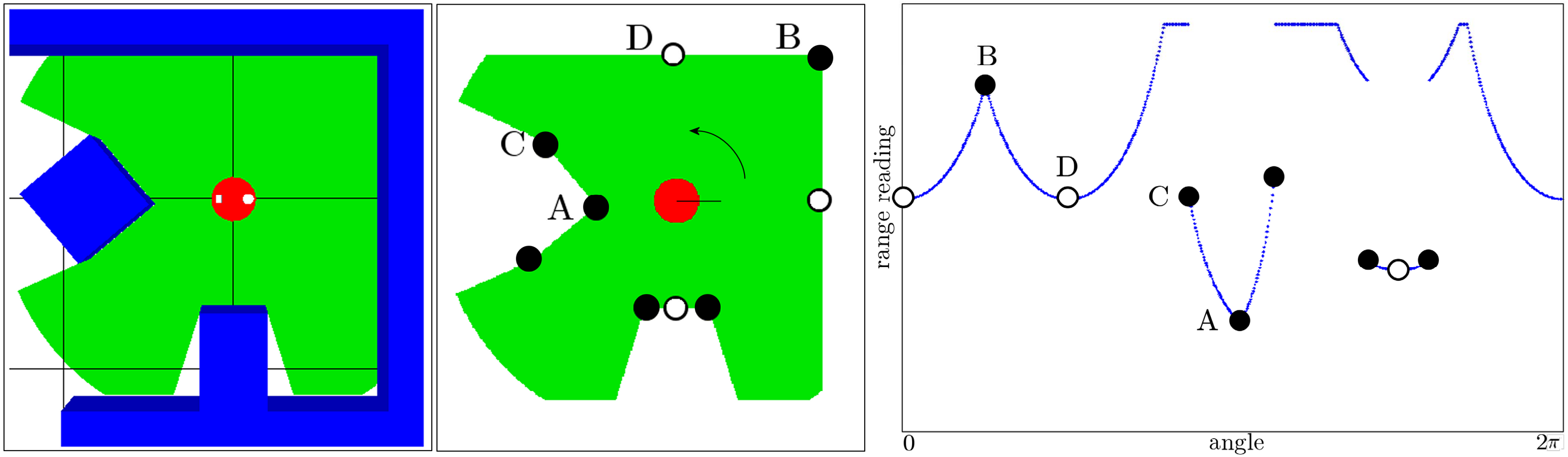
basic steps

1. **LSR construction** and **feature extraction**
2. **localization**
3. **local frontier computation**
4. if the local frontier is not empty
   - **frontier-based random generation** of a new candidate configuration q_{cand}
   - **validation**: the localizability of q_{cand} must be above a minimum threshold otherwise a new candidate configuration is generated
5. if the local frontier is empty $\rightarrow$ **backtracking** (return to the parent node)

FEATURE EXTRACTION

natural features are extracted from the LSR range readings

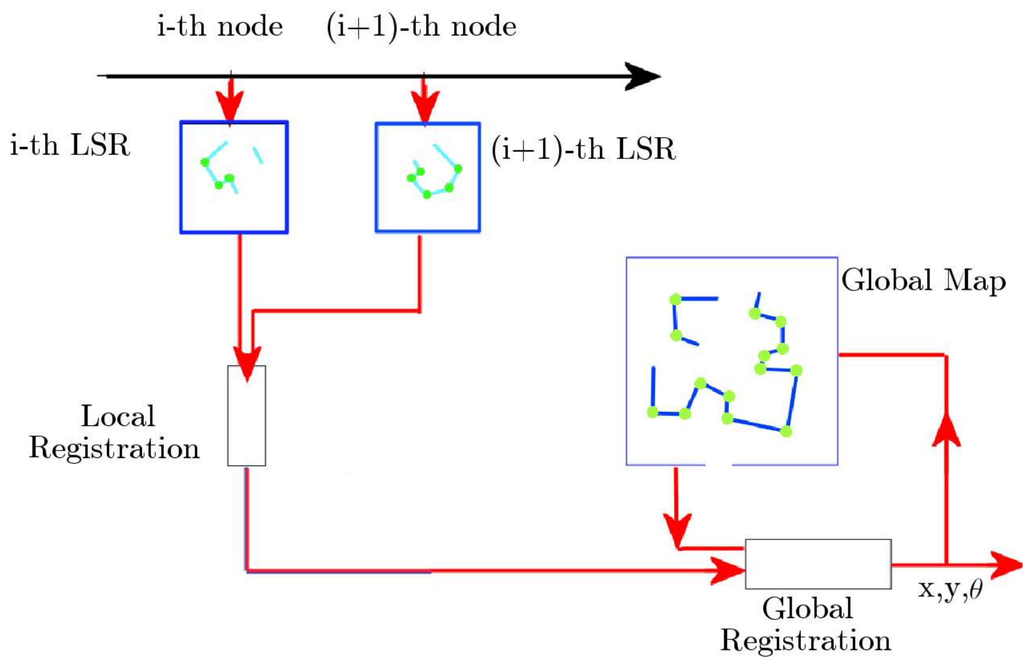
- **fixed features**: non-differentiable local minima/maxima or jump discontinuities; do not depend on the observation point
- **moving features**: differentiable local minima/maxima; depend on the observation point



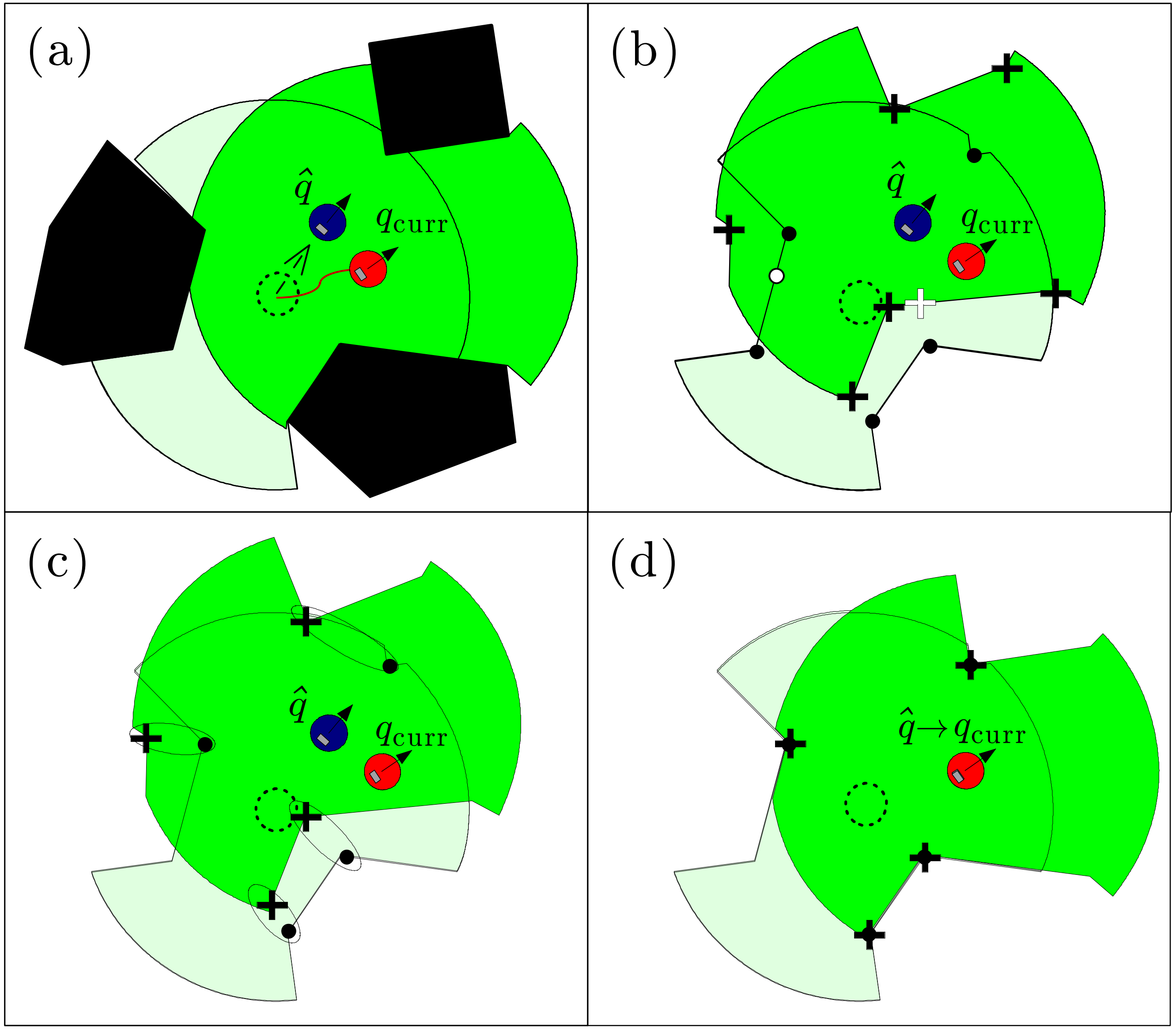
LOCALIZATION

1. **local correction**: a local alignment recovers the feature consistency between the current and the previously visited LSRs

2. **global correction**: a globally consistent alignment of the LSRs is performed when loops are detected



local registration



local registration

with localization | without localization

- actual robot (blue dot)
- estimated robot (red dot)

the **global registration** is executed whenever features of the current LSR can be associated to features in the global map that do not belong to the previously visited LSR

two approaches:

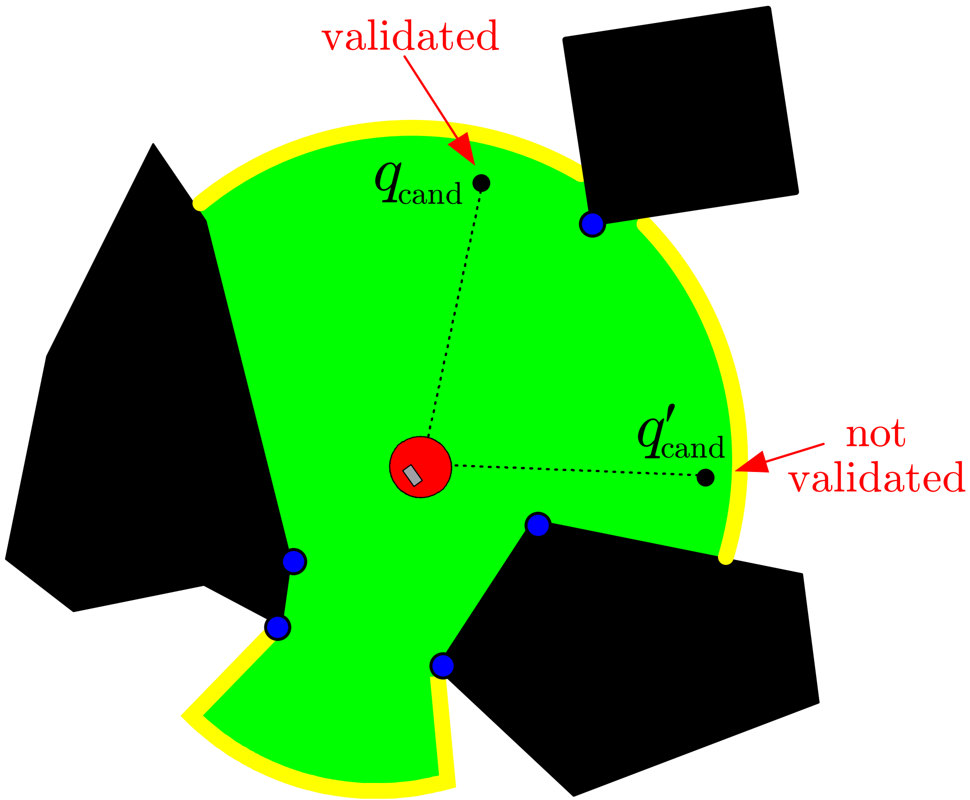
1. the local correction is performed between the current LSR and other overlapping LSRs (different from the previously visited LSR); the updated information is back-propagated along the path connecting the overlapping LSRs in order to preserve the global consistency

2. a network of pose relations is continuously updated; an energy function associated to this network is minimized [Lu and Milios, 1997]

VALIDATION

the **localizability** of a configuration q is defined as the number of features of the tree $\mathcal{T}$ that will be observable from q

a **localizability validation** is performed until a maximum number of trials is exceeded



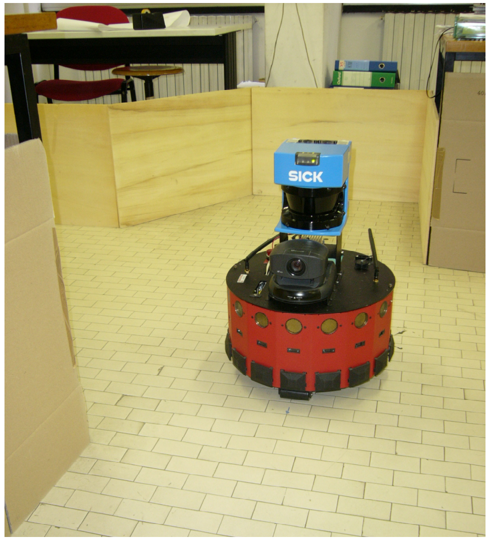
$l(q_{\text{cand}}) = 5 \quad l(q'_{\text{cand}}) = 2 \quad l_{\text{min}} = 3$

SIMULATIONS

without localization　　　　integrated exploration

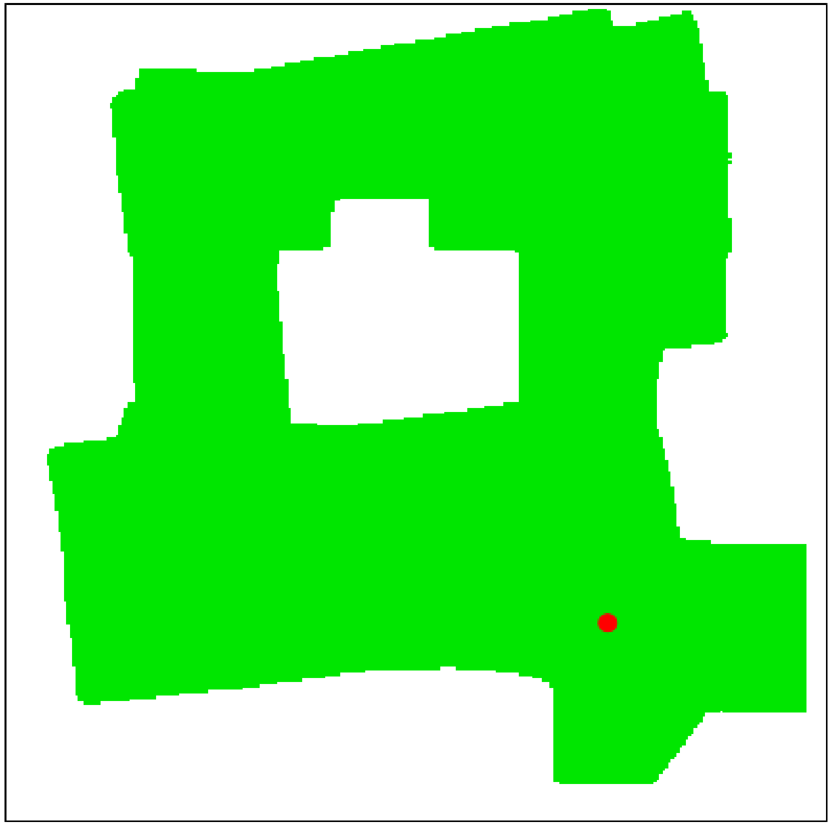
- actual robot
- estimated robot

EXPERIMENTS

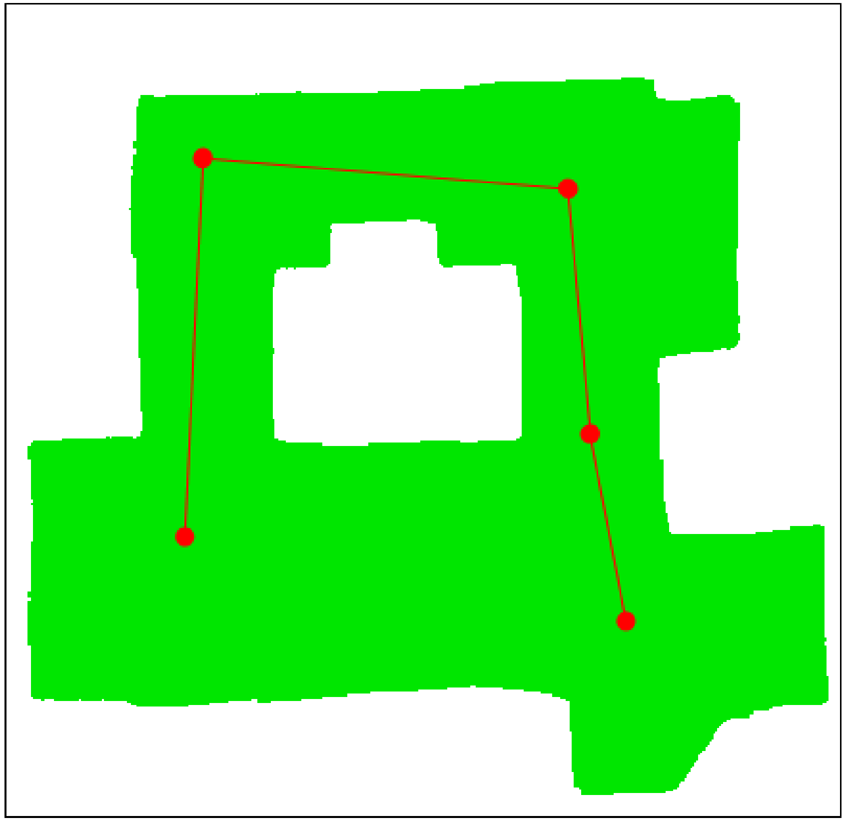


- **MagellanPro** robot: differential-drive robot
- onboard **SICK LMS 200** laser range finder with 1° angular resolution
- each LSR is built merging three different laser scans of 180° with orientations spaced at 120° increments (scans are merged using an ICP matching algorithm)

final maps in a typical experiment

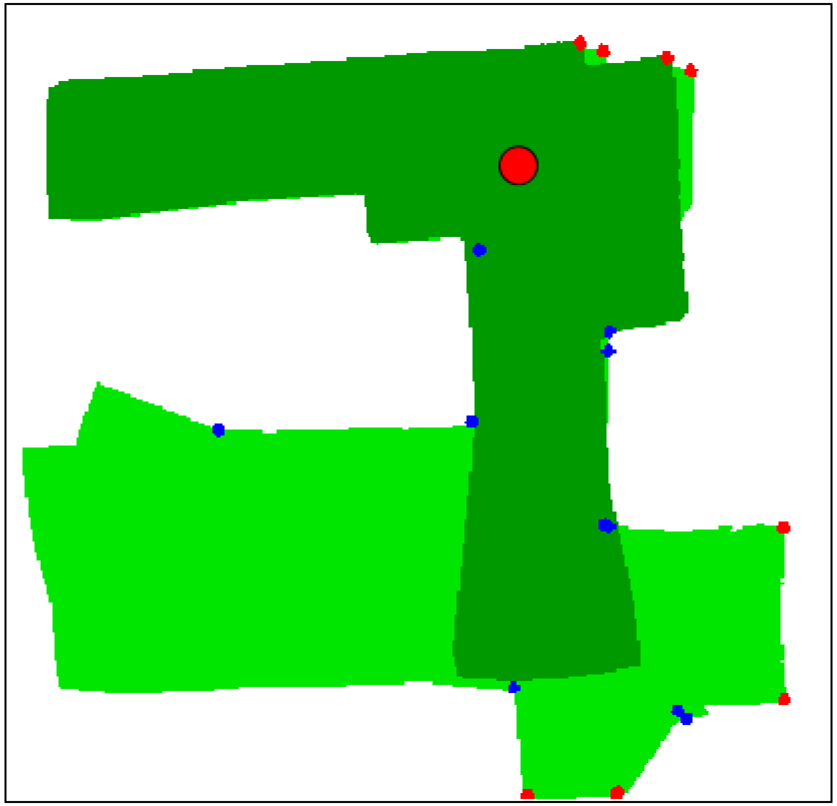


without localization

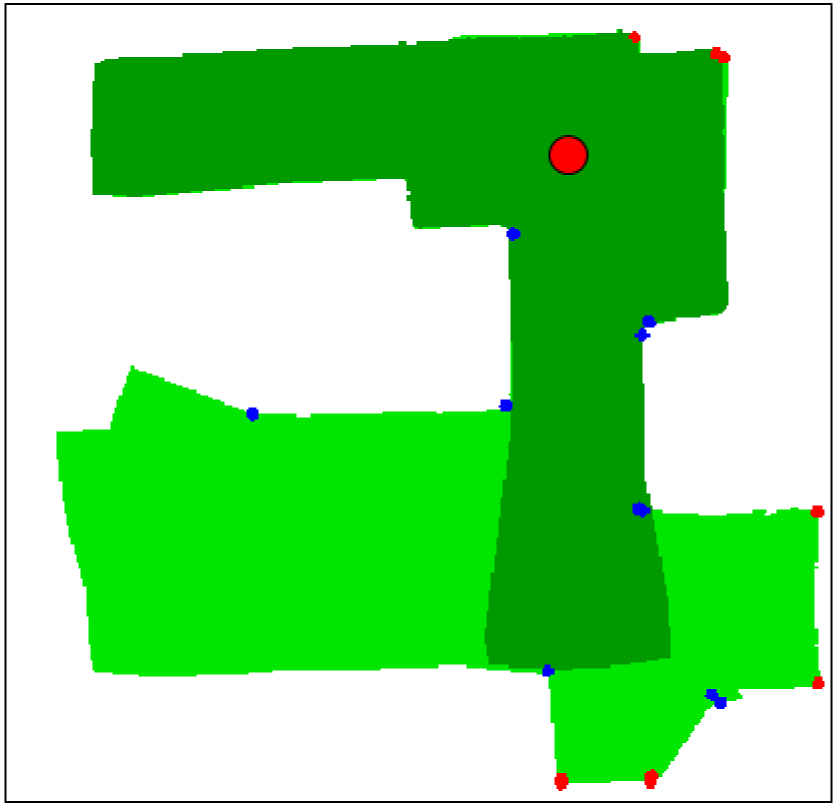


integrated exploration

a typical localization process



odometric configuration estimate

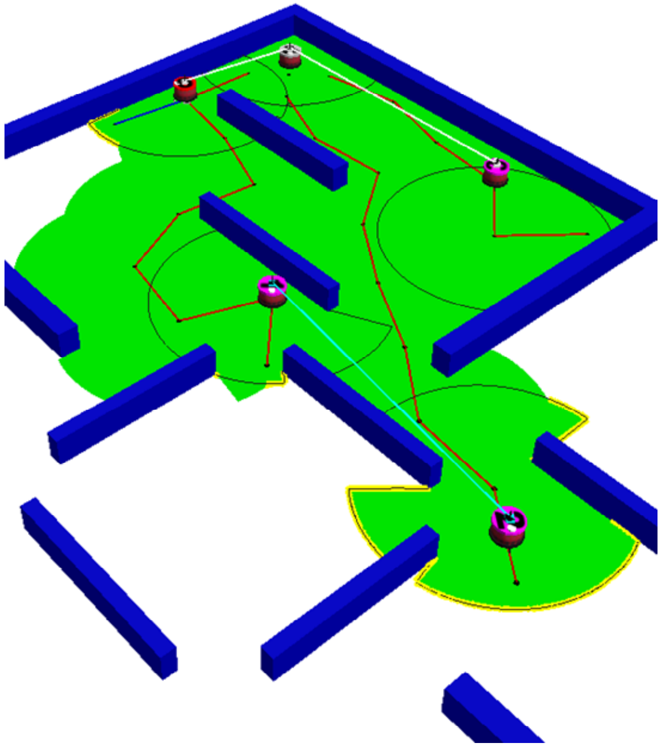


realigned

MULTI-ROBOT EXPLORATION

THE MULTI-SRT METHOD

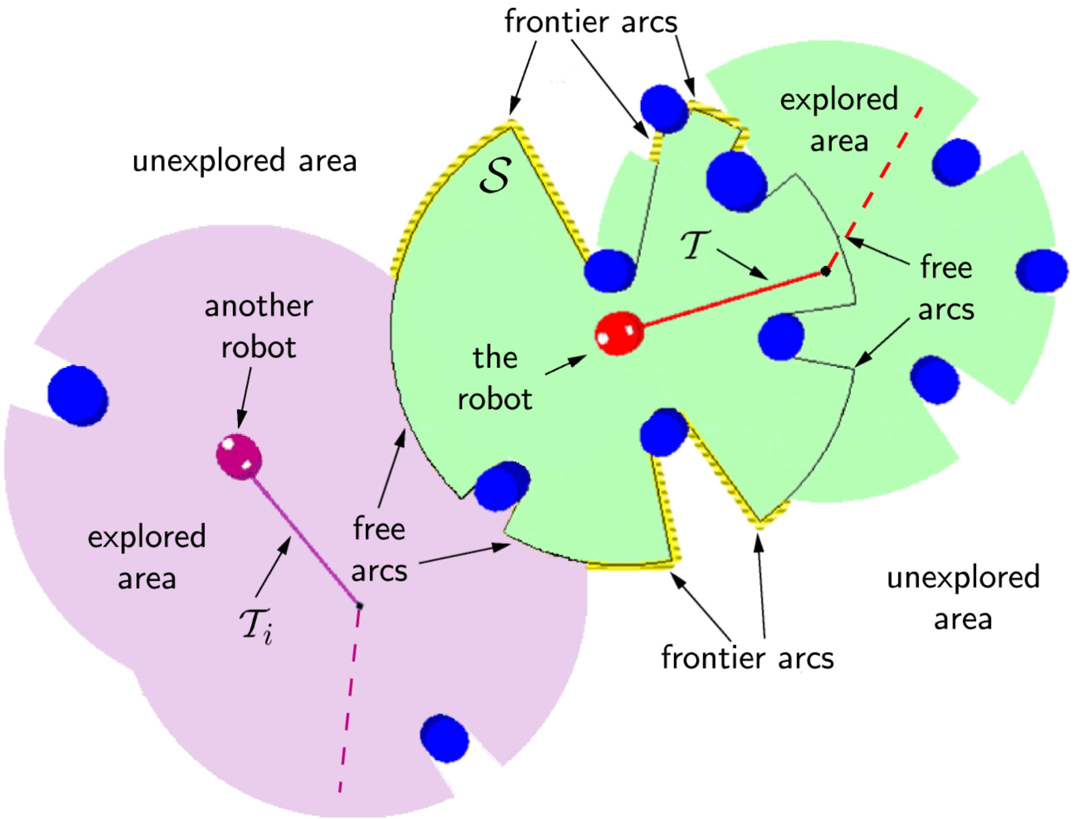
- **parallelization** of the single-robot SRT method
- **decentralized cooperation** is used to improve exploration efficiency
- **local coordination** mechanisms avoid conflicts
- robots which complete their individual exploration proceed to **support** others



a typical simulation

DECENTRALIZED COOPERATION

- each robot builds its SRT and continuously broadcasts its knowledge
- the local frontier is defined cooperatively, i.e., taking into account the area explored by other robots as well

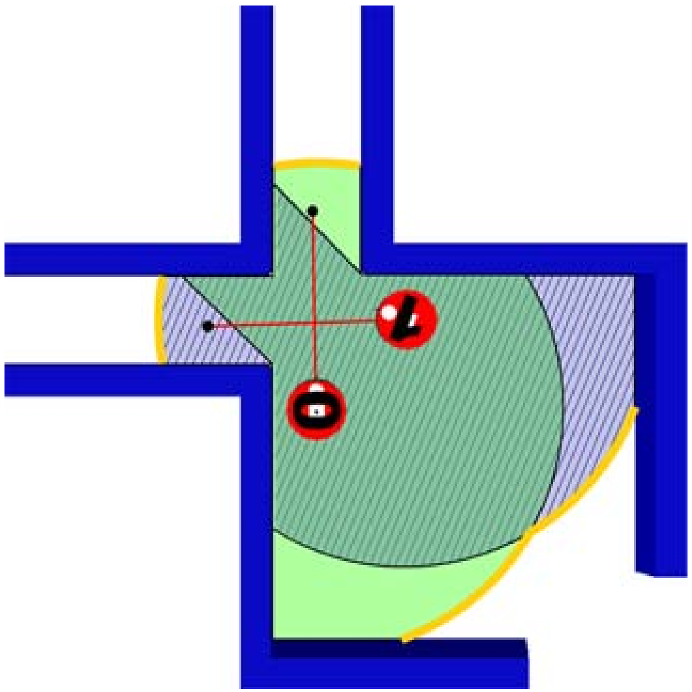


LOCAL COORDINATION

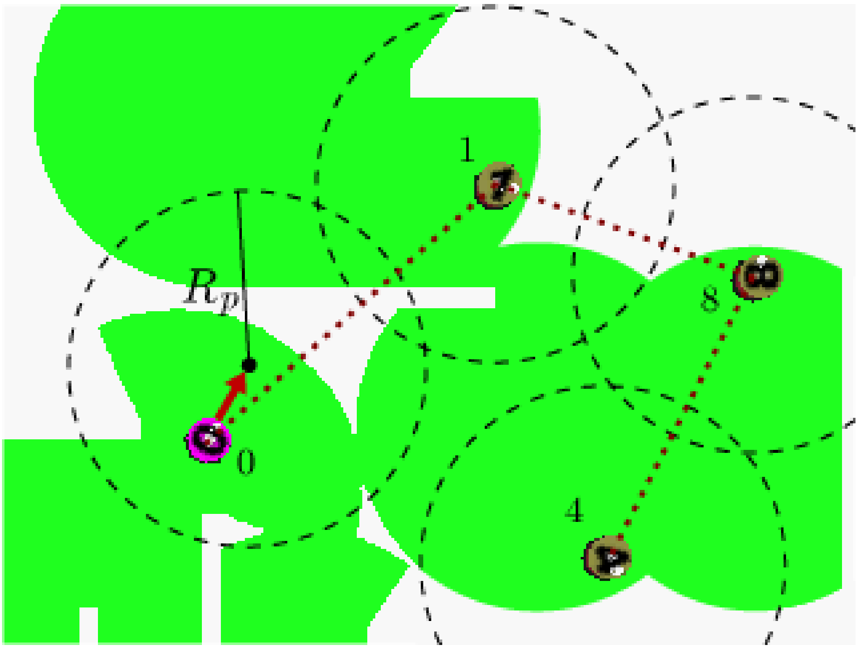
- each robot tends to move towards the frontier of its perceived Local Safe Region

- although the local frontiers of two robots are disjoint, two prospective paths may intersect

- a **local coordination** is achieved through the GPA/GEA construction

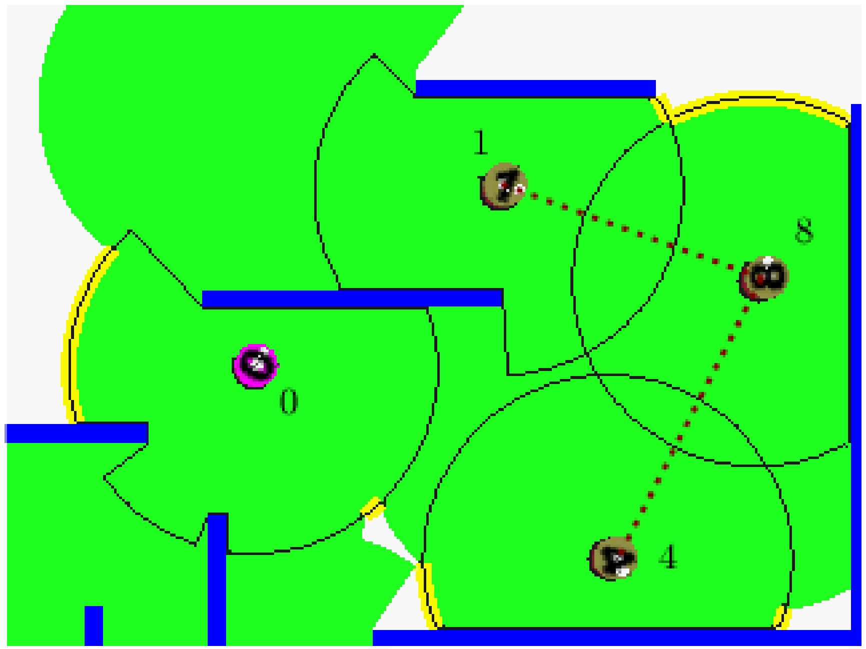


- each robot synchronizes its perception with its GPA and it cooperatively plans its next configuration with its GEA
- a **Group of Pre-engaged Agents (GPA)** is a set of robots whose next LSRs **may overlap** with each other
- a **Group of Engaged Agents (GEA)** is a set of robots whose LSRs **actually overlap** (it is a subset of a GPA)



GPA

Group of Pre-engaged Agents

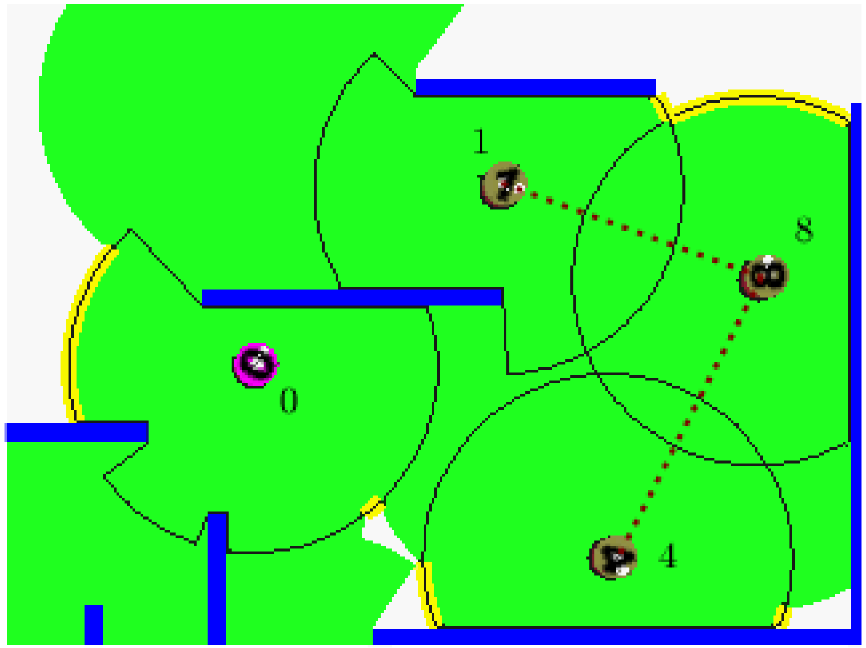


GEA

Group of Engaged Agents

for robots belonging to the same GEA

- the prospective paths are **checked** for collisions
- a **coordination phase** takes place which may either confirm or modify the current target of the robots



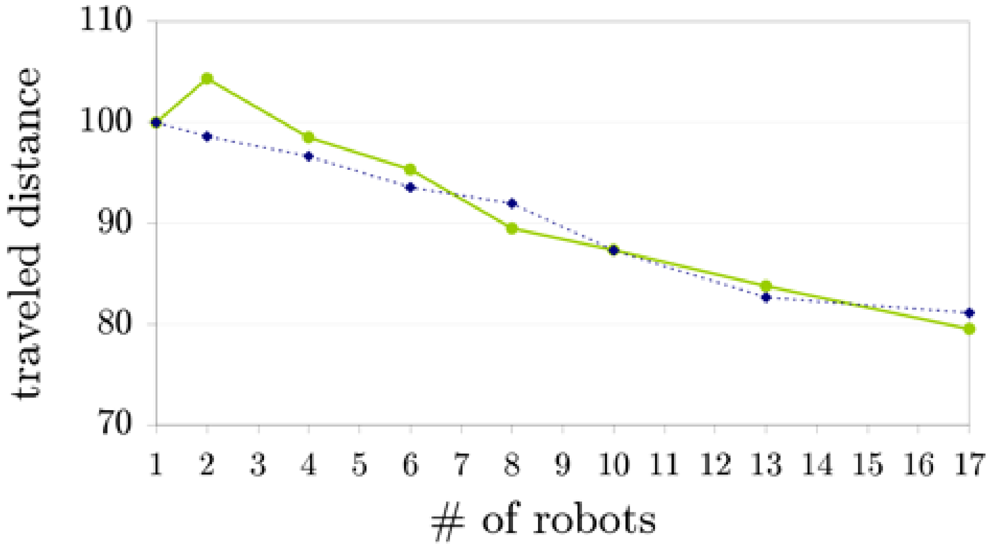
GEA

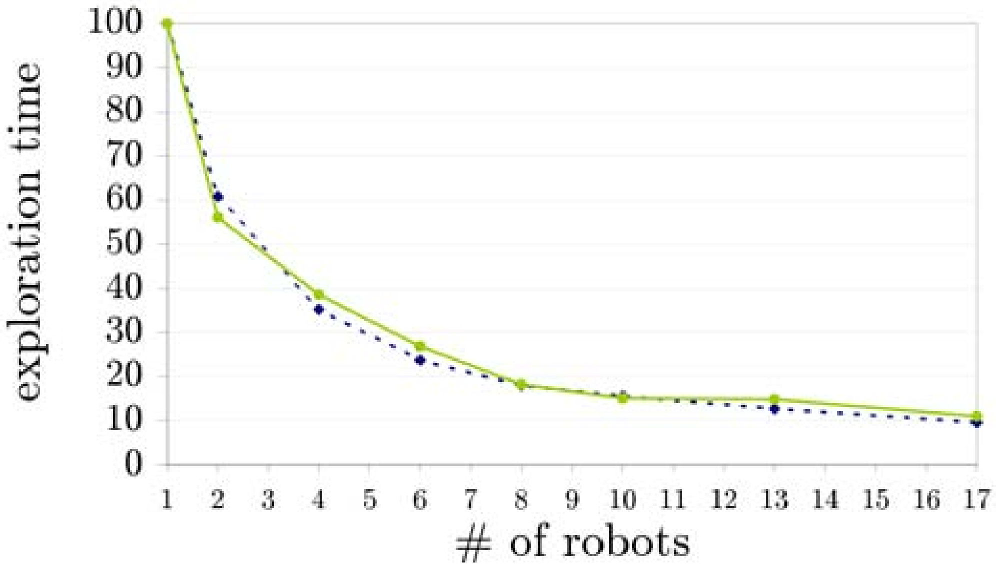
simulation

simulation

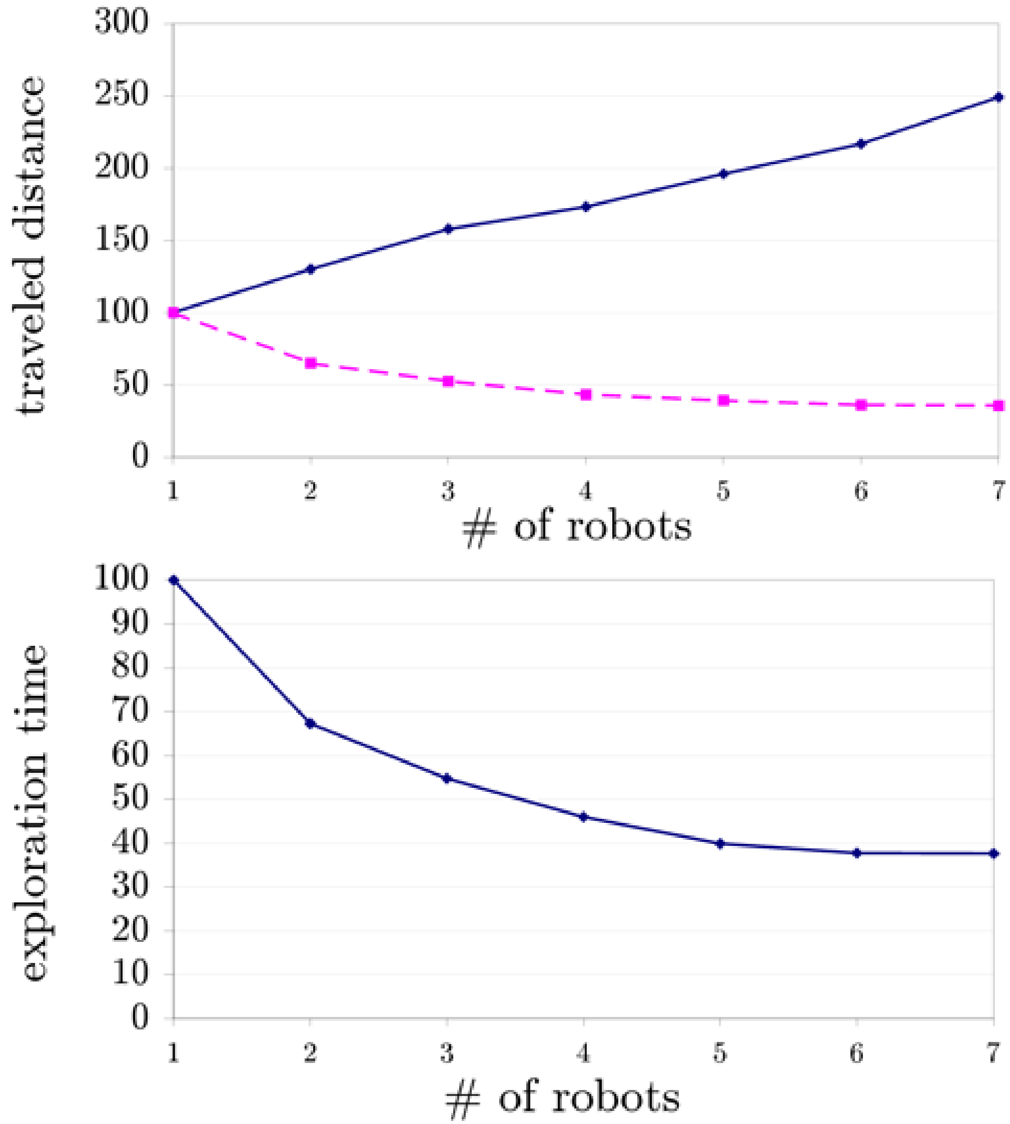
different robots can build the same tree

simulation results (garden-like environment, scattered start)





simulation results (office-like environment, clustered start)



CONCLUSIONS

- first **randomized approach** to sensor-based exploration

- natural extension to **integrated exploration** avoiding the problematic definition of mixed criteria

- parallelization and local cooperation/coordination mechanisms allow the extension to the **multi-robot** case

- the flexibility of the SRT-method allows the extension to the **manipulator** case

- many other **extensions** are possible: nonholonomic robots, mobile manipulators, snake-like robots