Cooperative Frontier-Based Exploration Strategy for Multi-Robot System

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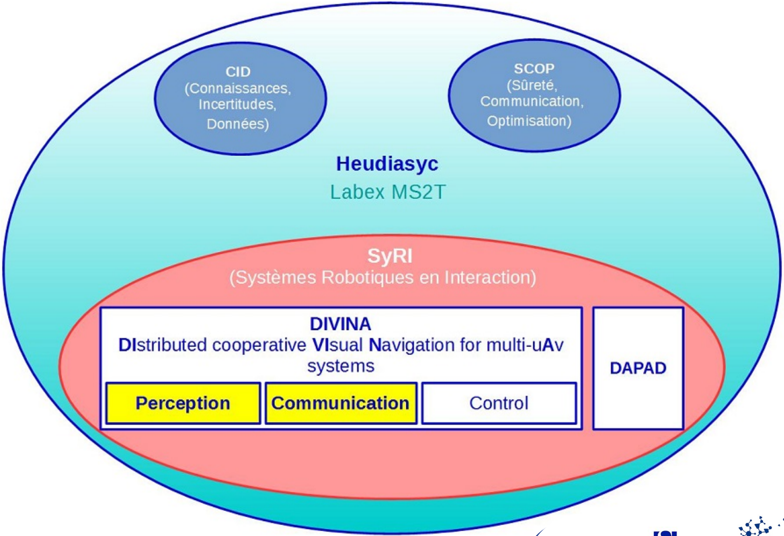
Séminaire Systèmes Robotiques en Interaction
26 juin, 2018.

Plan

- Introduction
- Exploration strategy
- MAV fleet coordination
- Simulation study
- Conclusions

Introduction

Context



Introduction
Applications

Search and rescue.
(http://www.onyxstar.net/\search-and-rescue-by-drone/)

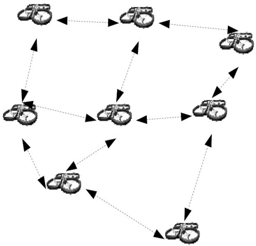
Reconnaissance and surveillance.
(http://www.directindustry.fr/prod/riegl-lms/product-15822-1937769.html)

Infrastructure inspection.
(https://uavamerica.com/infrastructure-inspection-a-customer-perspective/)

Exploration.
(http://www.geologyin.com/2014/08/drones-for-geology.html)

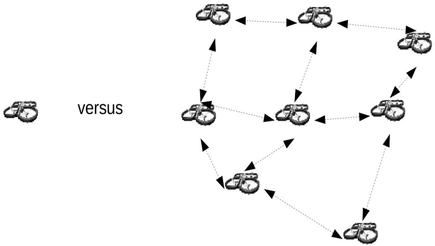
Introduction
Motivations

versus



Introduction

Motivations

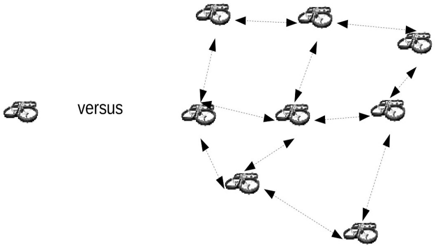


Fleet of MAVs deployment

- + Scalability
- + Limited failure risks
- + Performances increase
- + Less time execution
- + Area coverage improvement

Introduction

Motivations



Fleet of MAVs deployment

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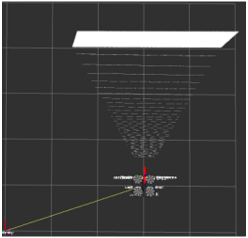
SENSOR? EXPLORATION? COORDINATION?

DATA? WHEN? TO WHOM?

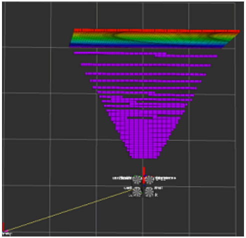
Plan

- Introduction
- Exploration strategy
  - Map construction
  - Frontier points and information gain computation
  - Frontier points processing
  - Goal assignment
- MAV fleet coordination
- Simulation study
- Conclusions

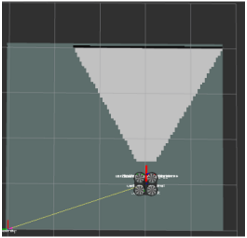
Map construction



T1 →



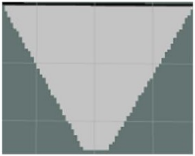
T2 →



3D Point cloud 3D voxels 2D cells

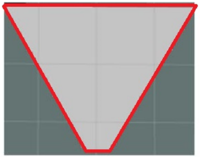
T1: Occupancy grid mapping framework
T2: 2D projection onto the plane $z = 0$

Frontier points and information gain computation



Occupied
Unknown
Free

Frontier points and information gain computation



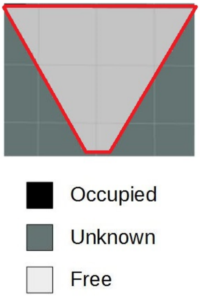
Occupied
Unknown
Free

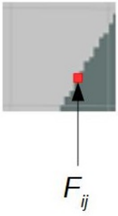
Frontier points

- Frontier points are cells that lie between *unknown* and either *free* or *occupied** cells

* will be discarded later

Frontier points and information gain computation





Frontier points

- Frontier points are cells that lie between *unknown* and either *free* or *occupied** cells

Information gain

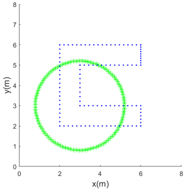
- The information gain of F_{ij} represents the number of *unknown* cells adjacent to it

* will be discarded later

Frontier points processing

Frontier points of local maps.

Two MAVs:



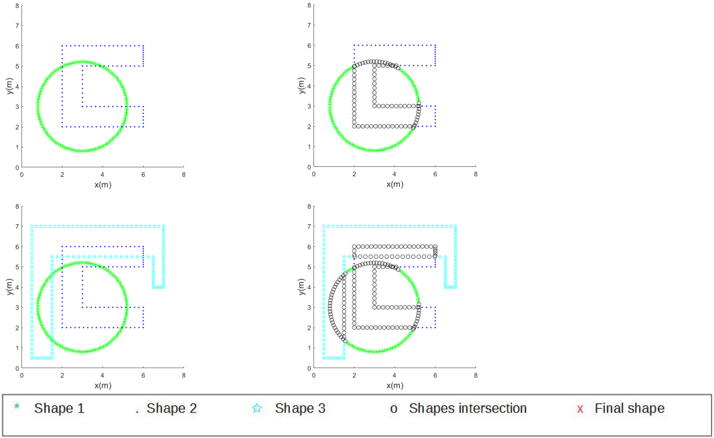
Three MAVs:

Frontier points processing

Frontier points of local maps. Frontier points in overlap.

Two MAVs:

Three MAVs:

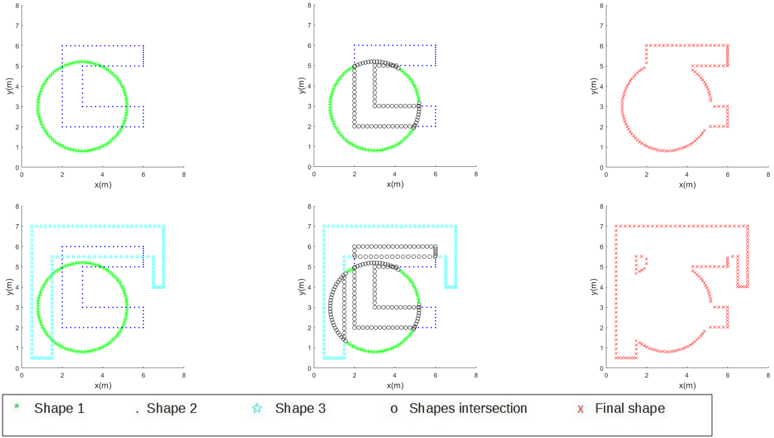


Frontier points processing

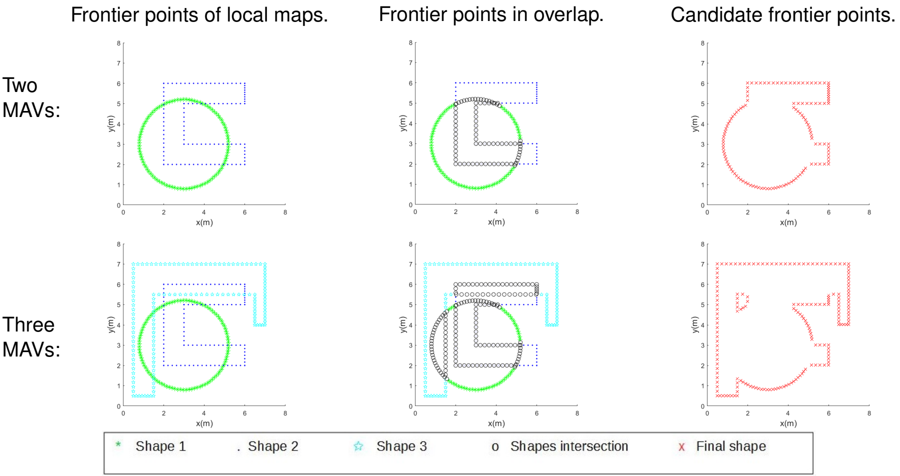
Frontier points of local maps. Frontier points in overlap. Candidate frontier points.

Two MAVs:

Three MAVs:



Frontier points processing



Delete the frontier points adjacent to *occupied* cells.

Goal assignment

multi-MAV

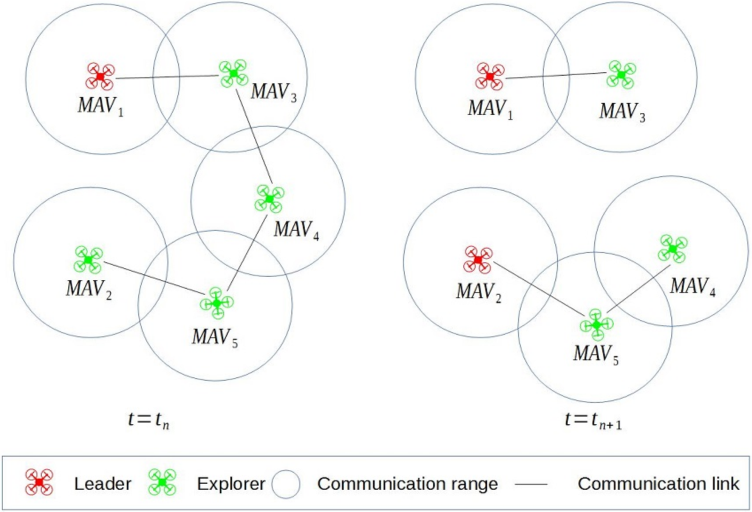
Input : Candidate targets $t_j \in G$ with their respective information gain $I(t_j)$, states of MAVs s_i in the cluster C, number of MAVs in the cluster n_C
Output : $\theta(i,j)$ assignment of MAV_i with target j

Assigned targets $\mathcal{G} = \emptyset$
while *MAV_i still without target goal* **do**
    // Compute the utility of reaching each target:
    while $t_j \notin \mathcal{G}$ **do**
        $U(t_j) = I(t_j)\exp(-\lambda.(dmin(s_i,t_j) + n_C / \sum_{k=1,k\neq i}^{n_C}(dmin(s_k,t_j))))$
    end
    // Compute the target that maximizes the utility:
    $t_{j'} = argmax_{t_j \in G \cap \mathcal{G}} U(t_j)$
    // Assign target j' to MAV_i:
    $\theta(i,j')$
    // Schedule the information gain of the remaining candidate targets:
    while $t_j \in G \cap \mathcal{G}$ **do**
        if $dist(t_{j'},t_j) <= thresholdRange$ **then**
            $I(t_j) = I(t_j)(1-\exp(-\gamma.\|t_{j'} - t_j\|))$
        end
    end
    // Remove the target goal $t_{j'}$:
    $\mathcal{G} = \mathcal{G} \cup t_{j'}$
end

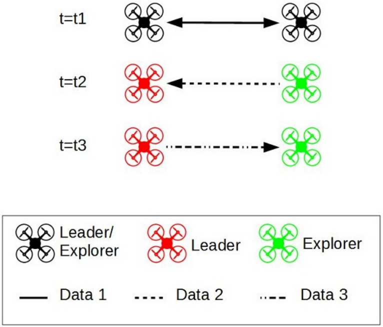
Plan

- Introduction
- Exploration strategy
- MAV fleet coordination
  - Clusters and status selection
  - Exchanged data
  - MAVs interaction
  - Strategies to face some issues
- Simulation study
- Conclusions

Clusters and status selection



Exchanged data



Data 1

- Identification Number *id*
- State s_i

Data 2

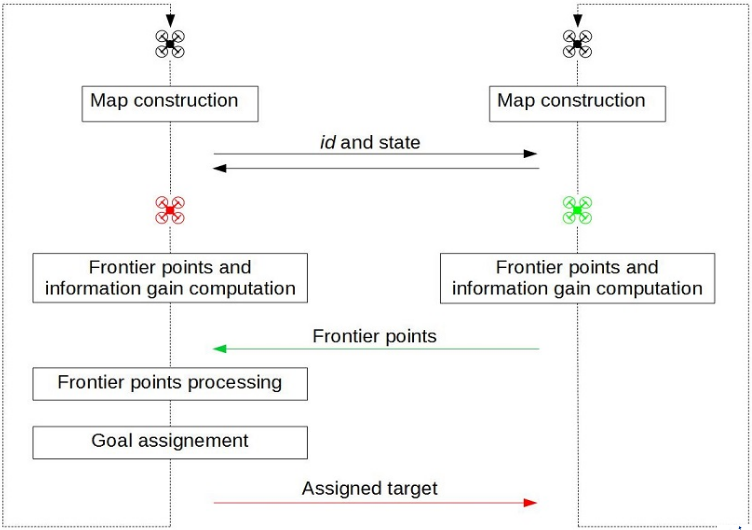
- Frontier points $f_{i,j}$ with their respective information gain $I(f_{i,j})$

Data 3

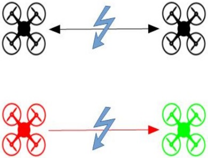
- Assigned target t_k

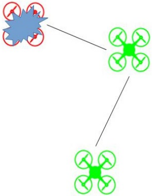
Note: All MAVs' status are initialized to *Leader*.

MAVs interaction



Strategies to face some issues





Communication loss/failure

- If the Explorer does not receive any assigned target from the Leader after a period τ, it selects its own one

MAV getting stuck

- MAVs' status are always updated
- A new Leader is selected at each iteration during the mission

Plan

- Introduction
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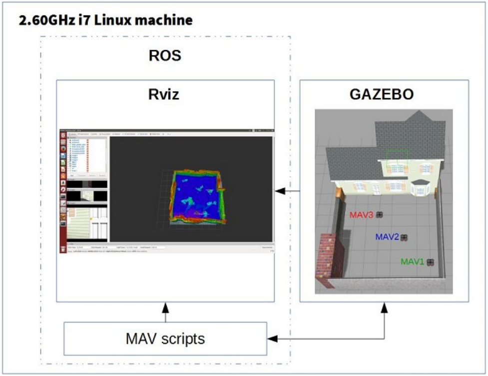
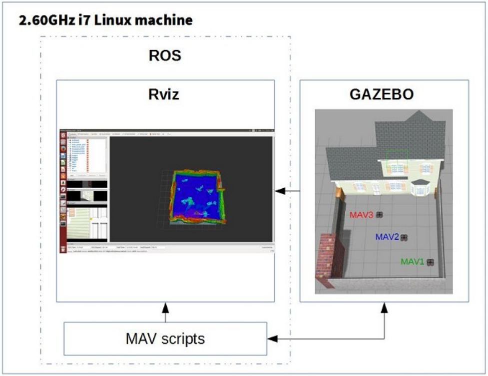
- **Simulation study**
  - Implementation details
  - Exploration evaluation
  - Evaluation with an Ad Hoc network
- Conclusions

Implementation details



http://www.ros.org/
http://gazebosim.org/
http://wiki.ros.org/ardrone_autonomy

Implementation details

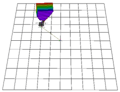


FoV	$\pi/3$	**Trade-off parameter** λ	0.2
Dimension	$8m*8m$	**Min distance between frontiers** d	0.3
Resolution	$0.05m$	**Range to reduce the Ig** $[R_{min}, R_{max}]$	$[1m, 3m]$
Linear velocity	$[0.1, 0.3]$	**Theta velocity**	$[0.1, 0.3]$
Initial position	*One MAV:* $\{MAV1(1,1)\}$; *two MAVs:* $\{MAV1(1,1); MAV2(2,2)\}$ and *Three MAVs:* $\{MAV1(2,2); MAV2(0,0); MAV3(-2,-2)\}$		

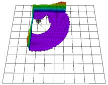
http://www.ros.org/
http://gazebosim.org/
http://wiki.ros.org/ardrone_autonomy

Exploration evaluation

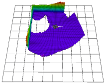
Ratio of explored space during time for one MAV



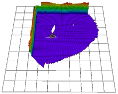
(a) 3% rate (5s)



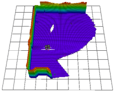
(b) 20% rate (28s)



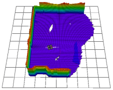
(c) 31% rate (50s)



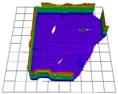
(d) 40% rate (69s)



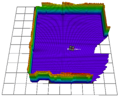
(e) 50% rate (75s)



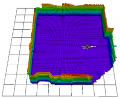
(f) 60% rate (83s)



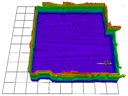
(g) 70% rate (98s)



(h) 81% rate (127s)



(i) 90% rate (133s)

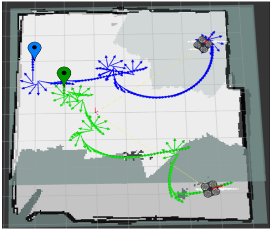


(j) 99% rate (202s)

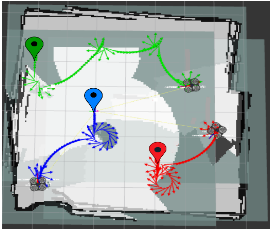
Exploration evaluation

Projected 2D map in a coordinated exploration with a team of one, two and three MAVs

(a) One MAV



(b) Two cooperative MAVs



(c) Three cooperative MAVs

Green, blue and red markers and arrows define the initial position and the trajectory of MAV1, MAV2 and MAV3, respectively.

Exploration evaluation

Total time spent during exploration and total distance traveled by each MAV in the fleet

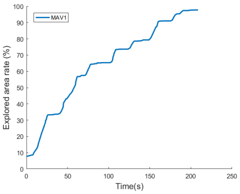
# MAVs		Total traveled distance (m)	Total time exploring (s)
One MAV	MAV1	22.69 ± 2.74	197.85 ± 17.34
Two MAVs	MAV1	15.12 ± 2.35	133.85 ± 7.83
	MAV2	9.35 ± 1.81	
Three MAVs	MAV1	10.91 ± 1.04	126.42 ± 14.08
	MAV2	7.75 ± 1.9	
	MAV3	8.30 ± 1.71	

Frontier points processing

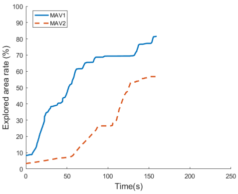
Explored area space and frontier points evolution

A:

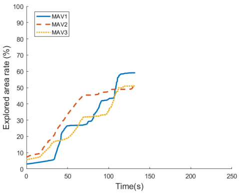
One MAV



Two cooperative MAVs

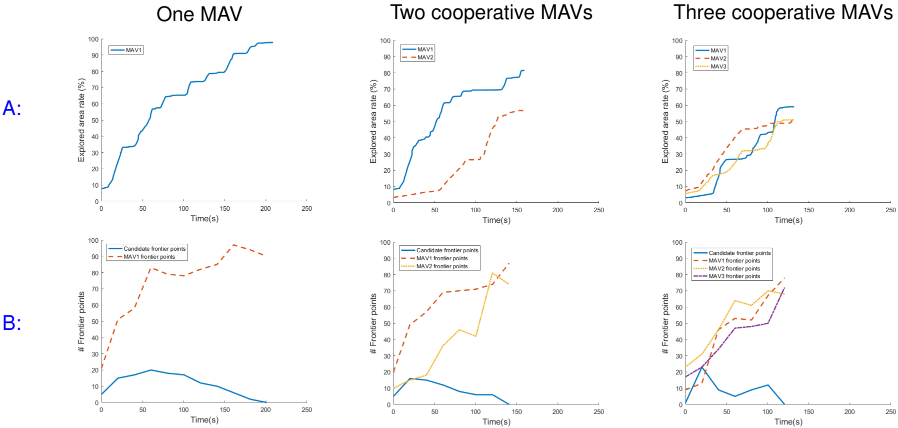


Three cooperative MAVs



A: Explored space rate with one, two and three MAVs

Frontier points processing
Explored area space and frontier points evolution



A: Explored space rate with one, two and three MAVs

B: The evolution of frontier points and candidate targets number during cooperative exploration

Evaluation with an Ad Hoc network
Implementation details

One ROS core on multiple machines:

+ Easy to implement
– Vulnerable regarding the ROS core
– Reliable network required

Multiple ROS cores on multiple machines (multi-master):

+ Independent ROS cores
+ Robust to network failure
– Cores synchronization required

Evaluation with an Ad Hoc network
Implementation details

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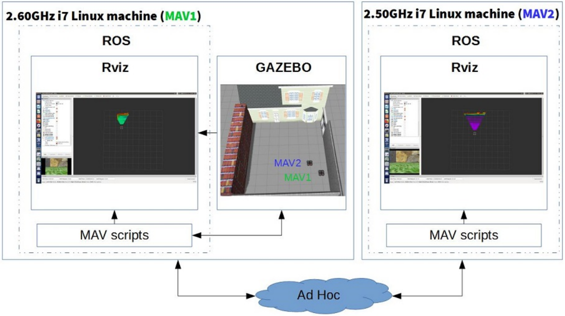
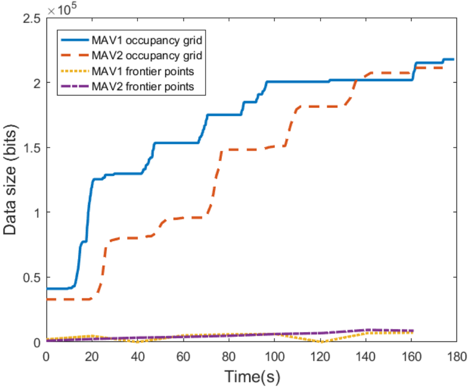


http://wiki.ros.org/multimaster_fkie
Network Time Protocol (NTP)

Evaluation with an Ad Hoc network

Comparison of exchanged data size of 2D occupancy grid versus frontier points



Result

The data exchanged using the proposed strategy are **10 times less** than those of a strategy that makes MAVs exchange the whole local map

Demo

`video/Final_with_com_two_t.mp4`

Plan

Conclusions

- Frontier-based strategy

→ Exploration time

Conclusions

- Frontier-based strategy

→ Exploration time

- Novel utility function

→ traveled distance

Conclusions

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- Leader-based approach

→ Communication issues

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→ Exchanged data size

Conclusions

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→ Communication issues

- Frontier points exchange

→ Exchanged data size

Future work

- Large scale evaluation
- Relative localization estimation

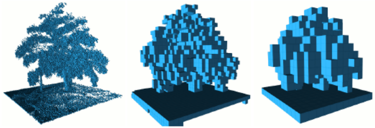
Thank you for your attention.

Mapping process

Octomap

The octomap is a 3D mapping framework based on a hierarchical data structure (Octree).
The 3D space is recursively subdivided until attending minimum voxel size (resolution).

- Compact memory representation
- Fast data access
- Obstacle avoidance



Hornung, A.; Wurm, K. M.; Bennewitz, M.; Stachniss, C. & Burgard, W. OctoMap: An efficient probabilistic 3D mapping framework based on octrees Autonomous Robots, Springer, 2013, 34, 189-206

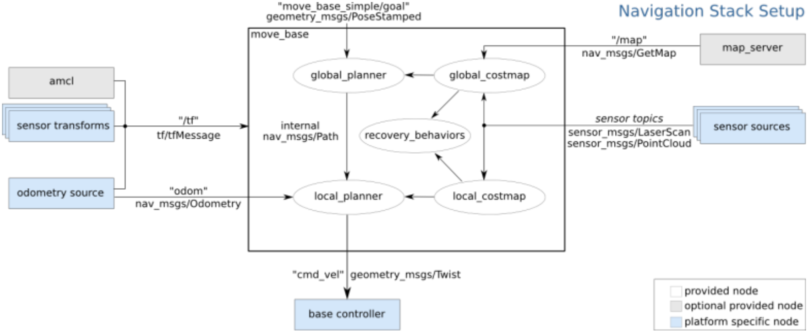
The utility function

Utility function

$$U(t_j) = I(t_j)\exp(-\lambda.(dmin(s_i,t_j) + n_C/\sum_{k=1,k\neq i}^{n_C}(dmin(s_k,t_j))))$$

where:
$I(t_j)$: information gain of the target goal t_j
λ: tuning parameter for trade-off between rapid exploration and filling in details
n_C: number of neighbors in the cluster C
$dmin(si,t_j)$: shortest distance from robot i's state to the candidate target goal

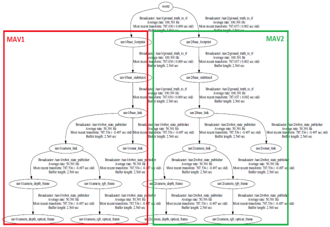
Path planning and control



move_base package

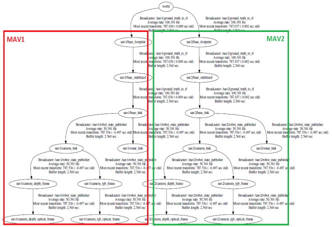
- Velocity commands
- Global and local planner
- Dijkstra algorithm

ROS data exchange



ROS frames for two MAVs.

ROS data exchange



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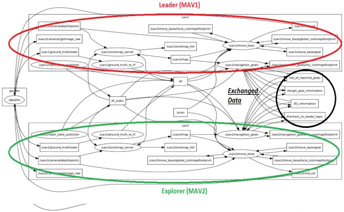
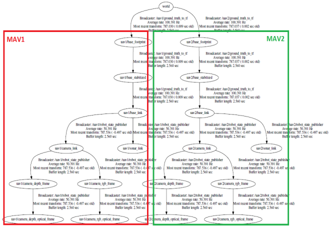


ROS topics for two MAVs.

ROS data exchange



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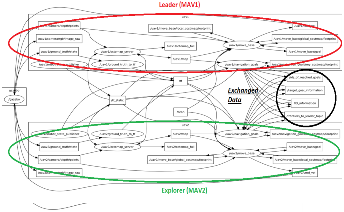

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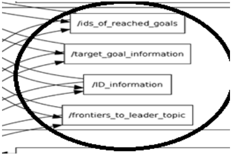

Topics for data exchange

- **ID_informtion :** Robot ID (int) and its state (geometry_msgs/PoseStamped)
- **Frontiers_to_leader_topic:** frontiers (geometry_msgs/Point) and their corresponding information gain(int)
- **Target_goal_information :** state of the future target (geometry_msgs/Pose)
- **Ids_of_reached_goals:** information for acknowledgment(int)