Robot Exploration with Fast Frontier Detection: Theory and Experiments

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Outline

- Frontier-Based Exploration: a fundmental problem in robotics
- Variety of applications:
  - Search and Rescue [Kitano et al., 1999]
  - Planetary Exploration [Apostolopoulos et al., 2001]
  - Surveillance [Hougen et al., 2000]
- Previous methods for computing frontiers: Slow!
- Wavefront Frontier Detector (*WFD*)
- Fast Frontier Detector (*FFD*)
- Results: improvement of 1-2 orders of magnitude over *SOTA*

Frontier-Based Exploration

- The most common approach to exploration is based on *frontiers*
- *Frontier*: separates known regions from unknown regions
  - Set of *unknown* points
  - Each has at least one *open-space* neighbor
- By moving towards frontiers, robots keep discovering new regions
- Yamauchi was the first to show a frontier-based strategy
  - [Yamauchi, 1997, 1998]
- His work preceeded many others
  - [Burgard et al., 2005, Lau and NSW, 2003, Sawhney et al., 2009]

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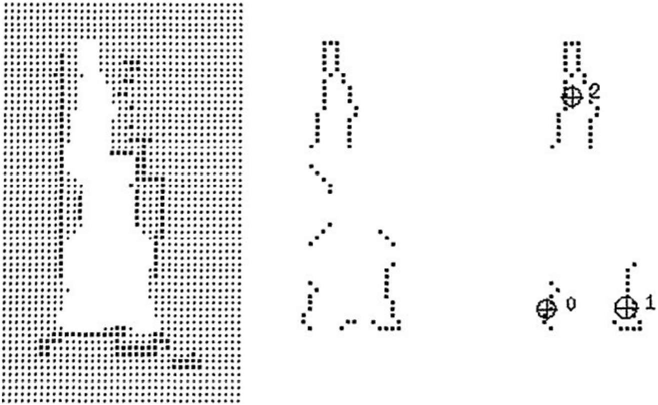

Figure: Image taken from [Yamauchi, 1998]: evidence grid, frontier points, extraction of different frontiers (from left to right).

Existing Frontier Detection is Slow

- Frontier detection algorithms rely on computer vision methods
  - e.g. edge detection and region extraction
- They have to process the entire map data with every execution
- Existing frontier detection methods take ~10–30 seconds to run
  - Even on powerful computers
  - Exploring a large area forces the robot to wait in its spot
  - Frontier detection is called only when the robot arrives at its target

Result

Real-time frontier detection can shorten the exploration time

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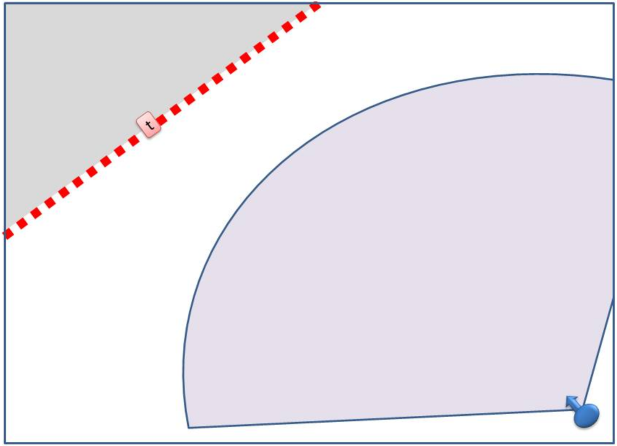
Single-Robot Example



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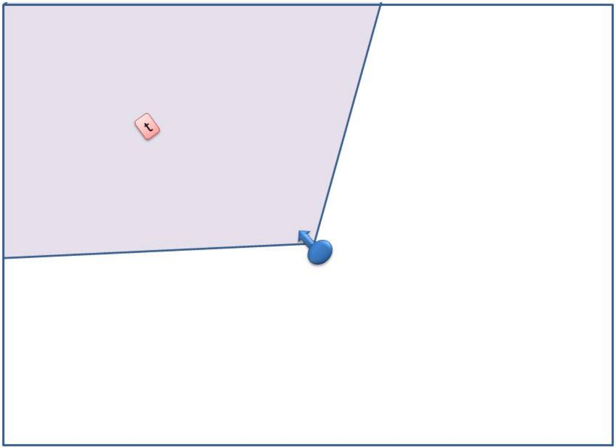

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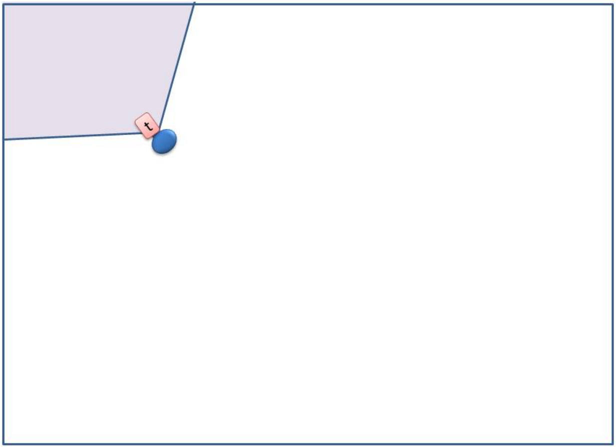

WFD: Wavefront Frontier Detector

- Breadth-first search approach for frontier detection
- *WFD* avoids searching unknown regions
- *WFD* scans only known regions

WFD Outline

1. Enqueue current robot position
2. Perform Breadth-First Search
   - scan only open-space points that were not previously scanned
3. For every dequeued point, check if it is a frontier point
   - If True: extract the frontier by using another Breadth-First Search

WFD Conclusions

- Ensures that only known regions are actually scanned
- Frontier points are adjacent to open space points
  - All relevant frontiers will be found when *WFD* finishes
  - Connectivity of frontier points ensures complete frontier extraction
  - The algorithm does not have to scan the entire grid each time
- *WFD* still searches frontiers in all known space

FFD: Fast Frontier Detector

- Insights:
  - New frontiers are never contained within known regions
  - New frontiers are never wholly within unknown regions
- Hence, scanning all known regions is definitely unnecessary
  - and not time-efficient
- *FFD* avoids searching both known and unknown regions
  - Only processes new laser readings

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FFD Outline

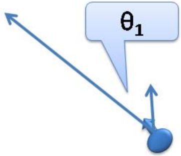
1. Sorting
2. Contour
3. Detecting New Frontiers
4. Maintaining Previously Detected Frontiers

Sorting

- Most laser sensors return readings that are already sorted
  - Points that are sorted according to polar angle
  - The robot as center
- However, if this is not the case, we can sort them efficiently

Sorting in details

Sorting



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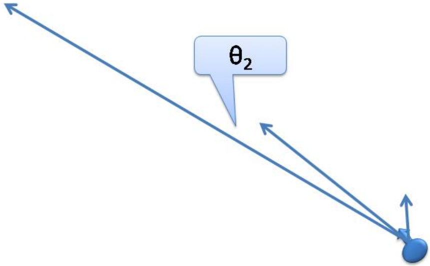

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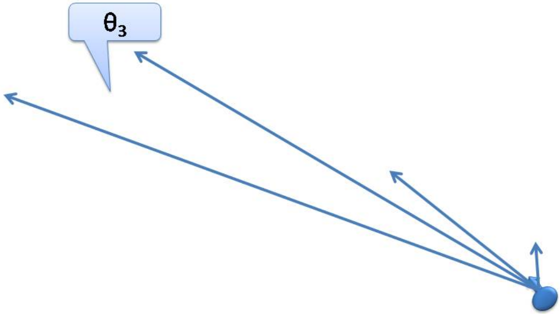

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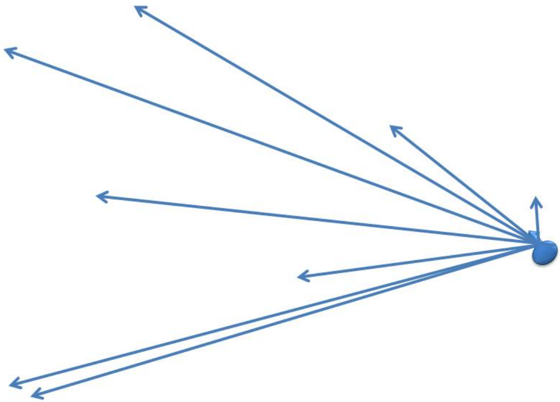

Contour

- **Input**: sorted set of points
- **Output**: a contour that is built from the laser readings set
    - The line that connects each two adjacent points from the set
- Calculate the points that lie between each adjacent laser readings
- The desired contour contains all the points mentioned above

Contour

Problem

We need the algorithm to be fast and robust against rounding errors

Solution

We use *Bresenham's line algorithm* [Bresenham, 1965]

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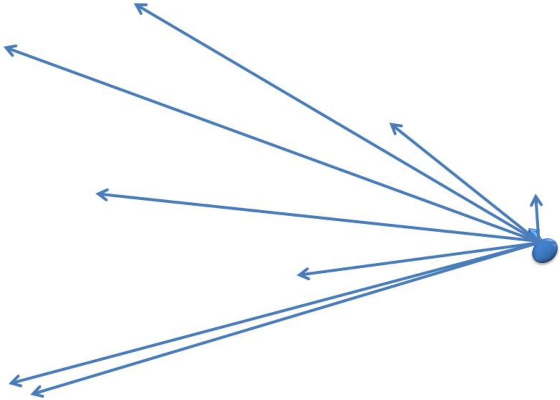

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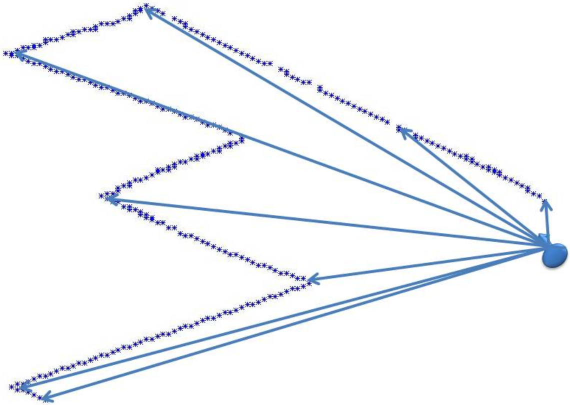

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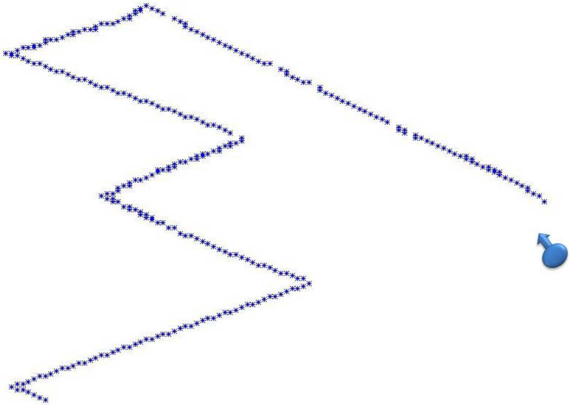

Detecting New Frontiers

- We scan the calculated contour from previous step
- Each point is compared with its (already scanned) predecessor
- Four possible cases:
  - Scanned point is not a frontier cell
  - Scanned point is a frontier cell but its predecessor is not
  - Both scanned point and its predecessor are frontier points
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- Full details can be found in the paper

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Maintenance: Motivation

- *FFD* gains its speed by only processing the laser readings
  - rather than entire regions of the map
- Previously detected frontiers are not updated during navigation
- Only the frontier that the robot is headed to

Problem

FFD is able to detect only *new* frontiers in each execution

Solution

Maintenance of frontiers which are not covered in the sensors range

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Maintenance of frontiers which are not covered in the sensors range

Maintenance 1: Eliminating Previously Detected Frontiers

- Points which are no longer in frontiers have to be eliminated
- *Active Area*: blocking rectangle constructed from laser readings
- If a frontier is to be eliminated, it must lie inside the active area
  - it contains regions that are covered by the robot's sensors
- *FFD* scans each point that lies inside the *Active Area*
  - Checking if a point is previously belonged to a frontier is fast
  - Full details can be found in the paper

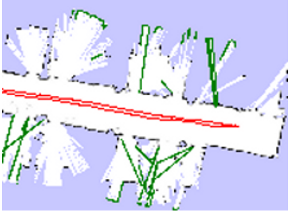
Maintenance 2: Avoiding Re-detection of Same Frontier

Problem

FFD might wrongly detect a new frontier in an already scanned area

Solution

FFD distinguishes between laser readings in different time frames



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Maintenance: Summary

- *FFD* has to run in the background
    - In contrast to other approaches that are executed in a certain time
- *FFD* requires robustness against map orientation changes
    - caused by loop-closures

Experiment Design

- We have fully implemented *WFD* and *FFD*
- We compare *WFD* and *FFD* with a State-of-the-Art algorithm[1]
- Our system is based on *GMapping* SLAM implementation
  - [Grisetti et al., 2005, 2007]
- Two machines:
  - Intel Core 2 Duo T6600 CPU, 2.20GHz, 4GB RAM
  - Intel Pentium III Coppermine CPU, 800MHz, 1GB RAM
- We measured CPU-process time

[1] We thank Kai M. Wurm and Wolfram Burgard for providing us their own implementation

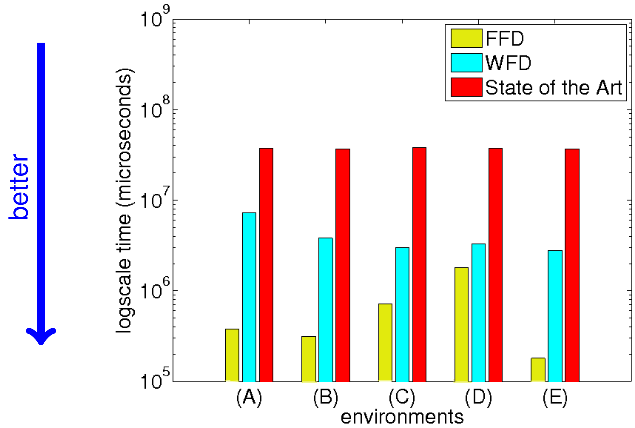
Experiment Design

- All detection algorithms are executed when a map update occurs
- *FFD* is executed when a new laser reading is received
- We accumulate *FFD*'s time between calls to other algorithms
- Tested on data obtained from RADISH [Howard and Roy, 2003]

Experiment Design

Figure: Example of a testing environment, University of Freiburg. Image was taken from RADISH, Howard and Roy [2003]

Results



- Y axis: mean execution time (microseconds) on a *logaritmic scale*
- *WFD* is faster than *SOTA* by two orders of magnitude
- *FFD* is faster than *WFD* by an order of magnitude

Summary and Future Work

- Real-Time frontier detection on weak CPU's
- *WFD*, *FFD*: two methods for frontier detection
  - significant reduction of calculation time
- Future work:
  - Address efficient methods for maintaining frontiers in *FFD*
  - Novel exploration policies based on real-time frontier-detection
- For more information:
  - `matankdr@gmail.com`
  - `galk@cs.biu.ac.il`

Sorting

- The first step sorts laser readings based on their angle
  - i.e based on the polar coordinates with the robot as the origin
- The naive method for converting Cartesian coordinates to polar coordintates is time-consuming
  - calling *atan2* and *sqrt*
- By using *Cross-Product* we can perform sorting much faster
  - $(p_1 - p_0) \times (p_2 - p_0) = (x_1 - x_0) \cdot (y_2 - y_0) - (x_2 - x_0) \cdot (y_1 - y_0)$
  - If the result is positive, then $\overrightarrow{P_0 P_1}$ is clockwise from $\overrightarrow{P_0 P_2}$.
  - Else, it is counter-clockwise.
  - If result is 0, then the two vectors lie on the same line in the plane

Back to *FFD*

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