Robot Exploration with Fast Frontier Detection: Theory and Experiments

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Thesis Defense

Exploration

- Robot Exploration: a fundmental problem in mobile robotics
- Variety of applications:
  - Search and Rescue [Kitano et al., 1999]
  - Planetary Exploration [Apostolopoulos et al., 2001]
  - Surveillance [Hougen et al., 2000]

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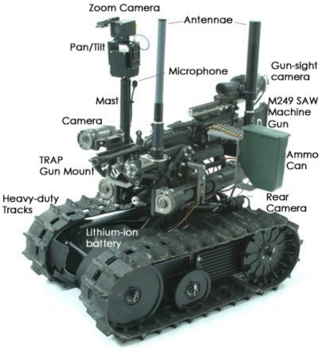

Frontier-Based Exploration

- 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, 2003, Sawhney et al., 2009]

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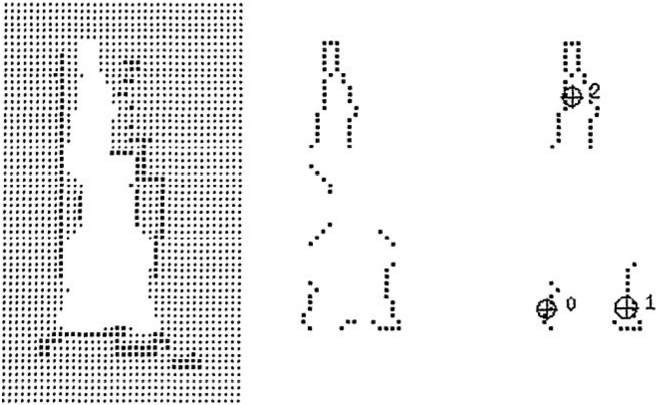

Figure: Image taken from [Yamauchi, 1998]: evidence grid, frontier points, extraction of different frontiers (from left to right).

Outline

- Previous methods for computing frontiers: Slow!
  - searches the entire map with every call
- Two approaches for frontier detection: *WFD*, *FFD*
  - *WFD*: explores only known regions
  - *FFD*: explores only border of known regions
- Theoretical analysis (correctness, complexity)
- Incremental versions of *WFD*: *WFD-INC*, *WFD-IP*
- Results: improvement of 1-2 orders of magnitude over *SOTA*

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

Efficient frontier detection can shorten the exploration time

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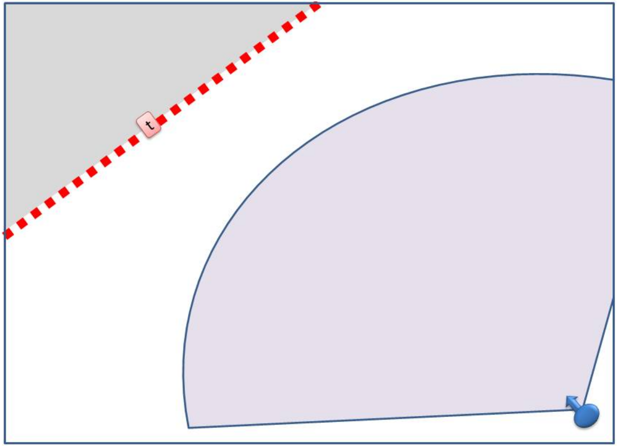
Single-Robot Example



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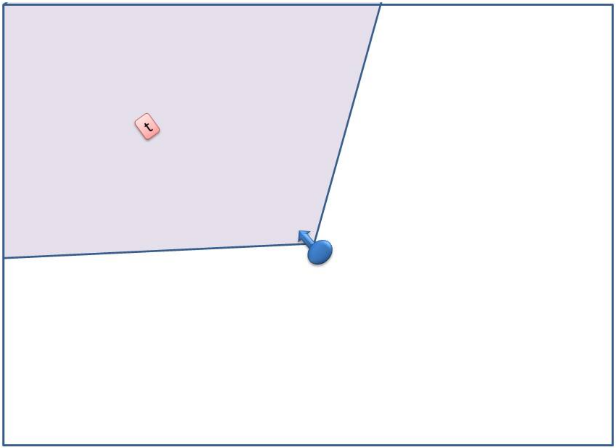

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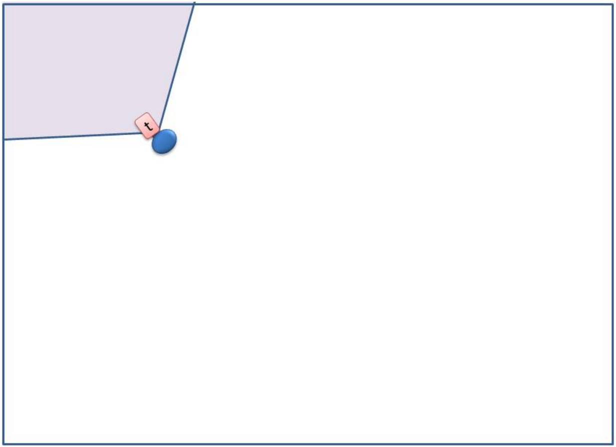
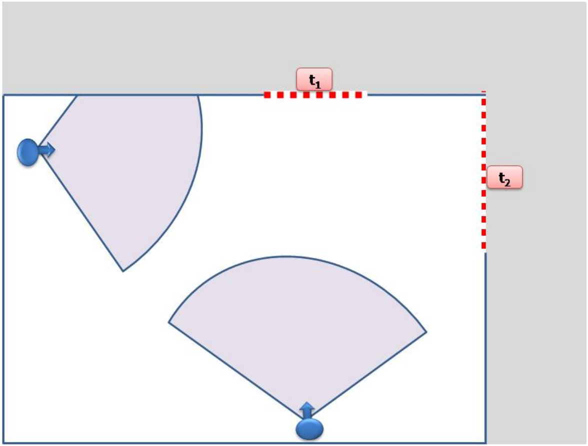


Multi-Robot Example



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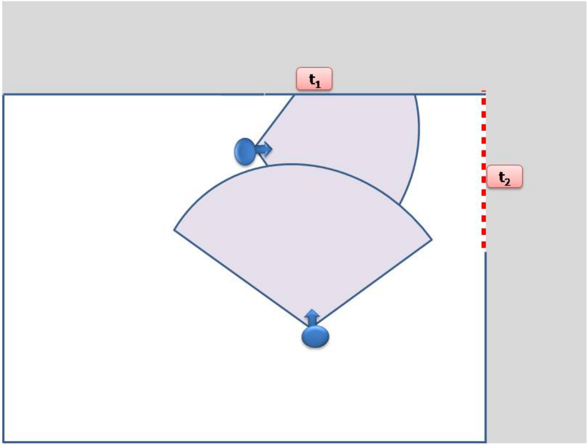

Simulaneous Localization and Mapping Methods

- Builds a map of an unknown environment while navigating
- Robots do not utilize any *a priori* knowledge of the environment
- *SLAM* is a concept, not an algorithm
- *Extended Kalman Filter*
  - Beliefs are represented by moments
  - Markov assumptions are hold and the posteriors are Gaussian
  - Only one map that is composed from observed landmarks
- *Particle Filter*
  - Also known as *sequential Monte Carlo method*
  - Online version of *Markov Chain Monte Carlo (MCMC)* methods
  - State: set of variables (e.g map of explored area, robot position)
  - Each particle is an instance of the system state at a certain time

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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

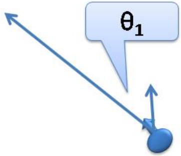
1. Sorting
2. Contour
3. Detecting New Frontiers
4. Maintaining Previously Detected Frontiers

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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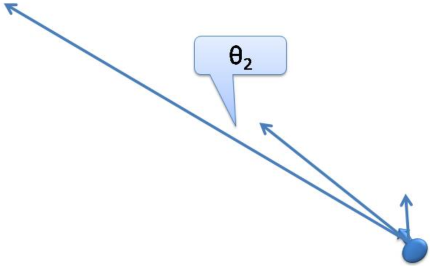

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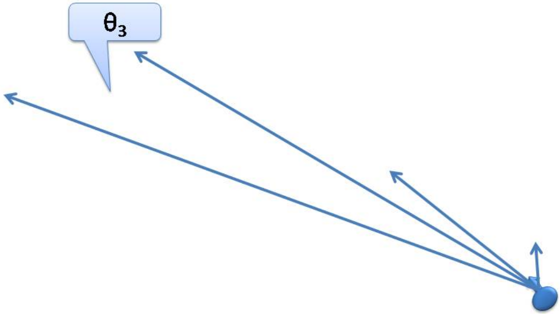

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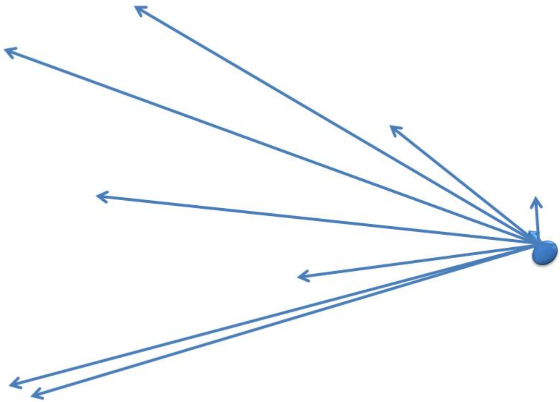

Contour

- **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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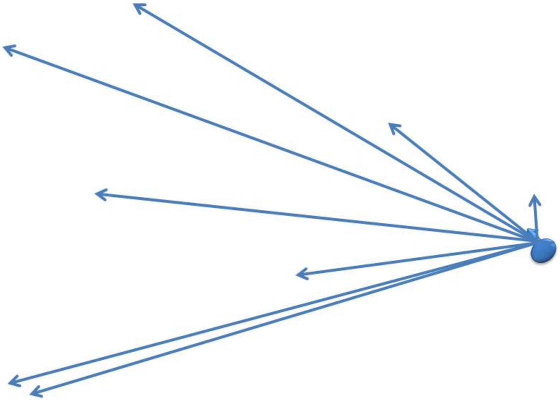

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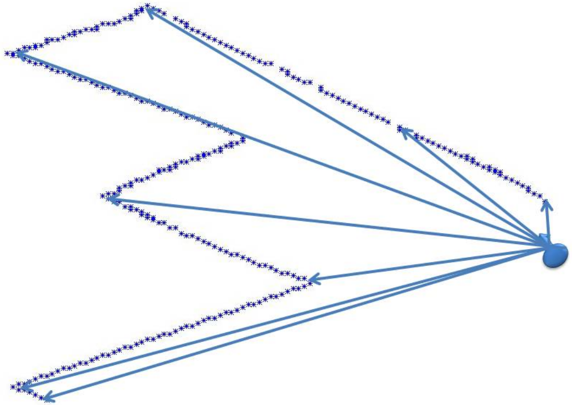

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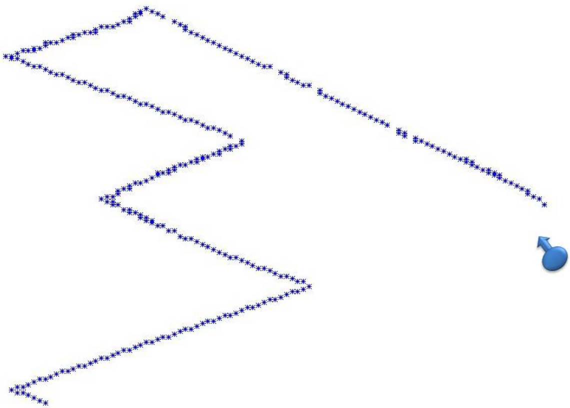

Detecting New Frontiers

- 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
  - Scanned point is not a frontier cell but its predecessor is

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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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Solution

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

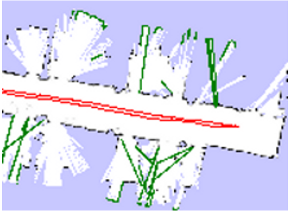
Maintenance 2: Avoiding Re-detection of Same Frontier

Problem

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

Solution

FFD distinguishes between laser readings in different time frames



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

FFD is Complete

Lemma (1)

Suppose f is a frontier point at time t, which was not a frontier point at any time s, where $s < t$.
Then FFD will mark f as a frontier given observation O_t.

FFD is Complete

Proof.

- Towards a contradiction: *FFD* did not recognize *f* as a frontier
- *f* cannot be located wholly within an *unknown* region
  - because it must have at least one *Open Space* neighbor
- *f* cannot be located wholly within a *known*
  - since *f* is a valid frontier point and hence, its value is *Unknown*
- Therefore, *f* must be located on the contour itself.
- Detection Stage: *FFD* scans *all* contour points sequentially
  - and specifically searches for frontier points
- It follows that *f* would be detected, contradicting the assumption

□

FFD is Complete

Theorem (Completeness)

Let f be a valid frontier point at time t.
Then FFD will mark f as a frontier point given the sequence of observations $\langle O_0, \ldots, O_t \rangle$.

FFD is Complete

Proof.

- **Case 1.** f **is a new frontier point at time** t**.**
  Trivially, this case is handled directly by lemma 1.
- **Case 2.** f **was a new frontier point at time** s**, where** $s < t$**.**
    - Let s be the earliest time in which f was a frontier.
    - Based on lemma 1, it follows that it was detected at this time.
    - f must be a frontier point that is maintained by *FFD* at time t.
    - f can be eliminated only by the maintenance stage.
    - f is still a valid frontier and hence, was not covered by the sensors.
    - Therefore, f will not be scanned and eliminated in time t
    - $\Rightarrow$ f remains classified as a frontier by *FFD*.
- In both cases *FFD* will recognize f to be a valid frontier at time t.

□

FFD is Sound

Theorem (Soundness)

Let $\hat{f}$ be an arbitrary point in the occupancy grid, which is not a frontier at time t.
Then FFD will not return $\hat{f}$ as a frontier point, given the sequence of observations $\langle O_0, \ldots, O_t \rangle$.

FFD is Sound

Proof.

- $\hat{f}$ is not *Unknown* or all its neighbors are not *Open Space*
- **Case 1. $\hat{f}$ is marked as a new frontier.**
  - *FFD* detects $\hat{f}$ as a new frontier
  - $\hat{f}$ must be located on the contour *and* detected by Extraction stage
  - *FFD* specificially avoids detecting non-frontier points as frontiers
  - Case 1 is not possible
- **Case 2. $\hat{f}$ is an old frontier but was not eliminated.**
  - $\hat{f}$ is located inside the active area and was not eliminated.
  - $\hat{f}$ is a point that was covered by the robot's sensors
  - Each point in the map keeps a frontier index (or NULL value)
  - *FFD* scans $\hat{f}$ and finds out it has a not NULL frontier index
  - The Maintenance stage will eliminate $\hat{f}$
  - Case 2 is not possible

□

WFD Complexity

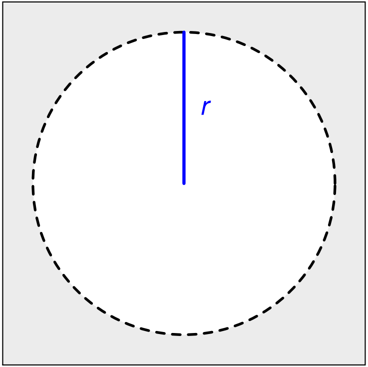
- *WFD* is based on Breadth-First Search (BFS) over the map.
- *WFD* scans all *Open Space* regions for frontier points.
- When a frontier point is found, another BFS is executed
  - in order to extract the frontier.
- BFS time complexity is linear in size of the search space.
- $\Rightarrow$ Linear in size of *area* and *perimeter* of *Open Space* regions

$$\mathcal{O}\left(\underbrace{\mathcal{S}(open - space)}_{area} + \underbrace{\mathcal{P}(open - space)}_{perimeter}\right)$$

WFD Best Case

Best Case

The perimeter of the *open-space* regions is minimal relatively to the area of the *open-space* regions



WFD Best Case

- Notation:
  - $S_{open} :=$ the area of the shape
  - $P_{opt} :=$ the perimeter of the shape
- The best case holds:

$$S_{open} = 4\pi r^2$$

$$P_{opt} = 2\pi r$$

WFD Worst Case

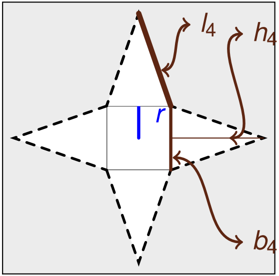
Worst Case

- Maximize the length of the perimeter
  - while keeping the total area of the *open-space* regions.
- Use a polygon as an approximation to a circle.
- The level of accuracy is determined by k, the number of vertices.

WFD Worst Case

Notation (for a given k vertices):

- $S_k :=$ the area of the shape.
  - $S_k = S_{open}$ (area remains the same)
- $P_k :=$ the perimeter of the shape.
- $b_k :=$ the base of the inner *open-space* polygon.
- $h_k :=$ the height of an outer triangle
- $l_k :=$ the length of an outer triangle side.



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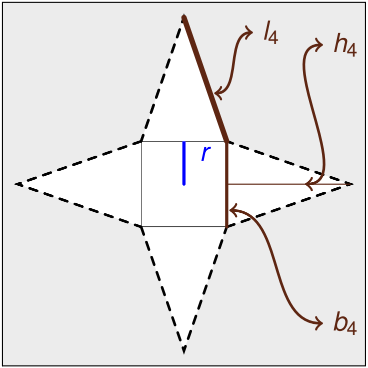


Figure: $k = 4$

WFD Worst Case

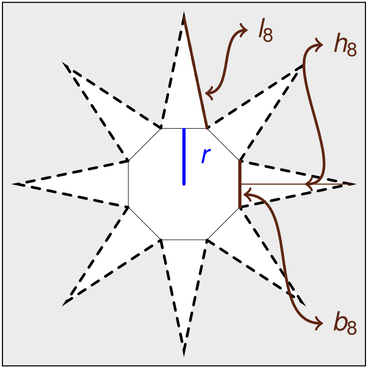


Figure: $k = 8$

WFD Worst Case

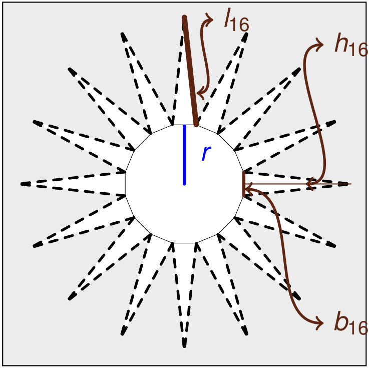


Figure: $k = 16$

WFD Worst Case

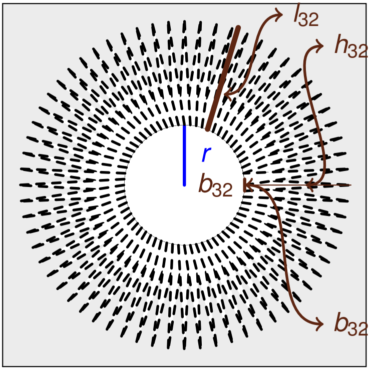


Figure: $k = 32$

WFD Worst Case

- The *open-space* regions are equal:

$$\begin{aligned} S_k &= S_{open} \\ \underbrace{k \cdot \frac{r \cdot b_k}{2}}_{\text{inner polygon}} + \underbrace{k \cdot \frac{h_k \cdot b_k}{2}}_{\text{outer triangles}} &= 4\pi r^2 \end{aligned}$$

- We can express b_k by:

$$b_k = 2r \cdot \tan \frac{\pi}{k}$$

- $\Rightarrow h_k$ can be expressed by:

$$h_k = \frac{8\pi r^2}{k \cdot b_k} - r$$

WFD Worst Case

- Each outside triangle edge can be expressed by:

$$l_k = \sqrt{(h_k)^2 + \left(\frac{b_k}{2}\right)^2}$$

- The length of the polygon perimeter equals to:

$$P_k = 2k \cdot l_k$$

- We would like to express P_k as a function of S_{open}:

$$P_k = \sqrt{\left(\frac{2 \cdot S_{open}}{r \cdot \tan\frac{\pi}{k}}\right)^2 - 8\frac{k \cdot S_{open}}{\tan\frac{\pi}{k}} + 4\frac{k^2 \cdot r^2}{\cos^2\frac{\pi}{k}}}$$

WFD Worst Case

- Since $k \leq S_{open}$, P_k can be bounded by:

$$P_k \leq \sqrt{\left(\frac{2 \cdot S_{open}}{r \cdot \tan\frac{\pi}{S_{open}}}\right)^2 - 8\frac{S_{open}^2}{\tan\frac{\pi}{S_{open}}} + 2 \cdot S_{open}^2 \cdot r^2}$$

- $\Rightarrow$ Run-time complexity of *WFD* in terms of *open-space* area:

$$\mathcal{O}\left(S_{open} + \sqrt{\left(\frac{S_{open}}{r \cdot \tan\frac{\pi}{S_{open}}}\right)^2 - \frac{S_{open}^2}{\tan\frac{\pi}{S_{open}}} + S_{open}^2 \cdot r^2}\right)$$

FFD Complexity

- It may seem that *FFD*'s complexity is contained within *WFD*
  - since *FFD* searches only inside the active area (*open-space*)
- It is not true since *FFD* has to persistently run in the background
- We analyse the complexity of each stage separatly

FFD Complexity - Sorting Stage

- *FFD* performs polar-sorting of laser readings.
- Cross-product instead of actually calculating angle and radius
  - which are relatively very time-consuming calculations
- Cross-product calculation is performed in a constant time
- Sorting is performed in time of $\mathcal{O}(n \log n)$.
- $l_r :=$ the number of laser readings received in each measurement
- Total complexity of this stage is:

$$\mathcal{O}(l_r \log l_r) \cdot \mathcal{O}(1) = \mathcal{O}(l_r \log l_r)$$

FFD Complexity - Contour Stage

- Scans each two adjacent points from the polar-sorted readings.
- *FFD* connects each two adjacent points by a line
  - by calling *Bresenham's line algorithm*, linear time complexity
- d_{p_i,p_j} := euclidean distance between points p_i and p_j
- $c^{(t)}$:= the length of the contour in time t
- Total complexity of this stage is:

$$\mathcal{O}\left(\sum_{p_i \in l_r} d_{p_{i-1},p_i}\right) = \mathcal{O}\left(c^{(t)}\right)$$

FFD Complexity - Detection Stage

- Scans the contour extracts new frontiers (if available any)
- Each found new detected frontier is added into a list
- All actions are performed in a constant time
- Total complexity of this stage is:

$$\underbrace{\mathcal{O}(1)}_{\text{special case}} + \underbrace{\mathcal{O}\left(c^{(t)}\right) \cdot \mathcal{O}(1)}_{\text{general case}} = \mathcal{O}\left(c^{(t)}\right)$$

FFD Complexity - Maintenance Stage (1)

Elimination of previous frontiers:

- Scans each point that lies inside the active area
- Checks if it was previously belonged to a frontier
- $A^{(t)} :=$ the bounding rectangle (the active area) in time t
- $f_{max}^{(t)} :=$ length of the longest frontier the frontier database in time t
- $n_f^{(t)} :=$ number of frontiers in the frontier database in time t
- Total complexity of this stage is:

$$\mathcal{O}\left(\underbrace{A^{(t)}}_{\text{scanning active area}} \cdot \left(\underbrace{f_{max}^{(t)}}_{\text{find frontier point}} + \underbrace{\log n_f^{(t)}}_{\text{get frontier from DB}}\right)\right)$$

FFD Complexity - Maintenance Stage (2)

Adding new frontiers:

- Scans each frontier point within all new detected frontiers
- $n_{new}^{(t)} :=$ number of new frontiers that were found in time t
- Checks if new frontier point belongs to previously detected frontier
- The check is performed in a constant time
- All other actions are performed in a constant time
- Total complexity of this stage is:

$$\mathcal{O}\left(\underbrace{n_{new}^{(t)}}_{\text{scan frontiers}} \cdot \left(\underbrace{f_{max}^{(t)}}_{\text{scan all points in frontier}} + \underbrace{\log n_f^{(t)}}_{\text{get frontier from DB}}\right)\right)$$

FFD Complexity - Combining All Stages

- We join all previous stages and get:

$$\mathcal{O}\left(l_r \log l_r + c^{(t)} + \left(A^{(t)} + n_{new}^{(t)}\right) \cdot \left(f_{max}^{(t)} + \log n_f^{(t)}\right)\right)$$

- The above equation can be bounded to:

$$\mathcal{O}\left(c^{(t)} + \log n_f^{(t)}\right)$$

- *FFD* has to run in the background
  - $l_\omega :=$ frequency of the laser sensor
  - $t_m :=$ worst-case elapsed time between two following map-events
  - $P_n :=$ number of particles in the SLAM implementation

$$\mathcal{O}\left(P_n \cdot (t_m \cdot l_\omega) \cdot \left(c^{(t)} + \log n_f^{(t)}\right)\right)$$

General Maintenance Concepts

- *WFD*: detects old and new frontiers within each execution
- *FFD*: is able to detect new frontiers only
  - and therefore has perform a background maintenance
- The maintenance algorithm can be applied to *WFD*
  - and to other frontier detection algorithms

Incremental Wavefront Frontier Detector

- Abbreviation: *WFD-INC*
- Search domain contains only points that lie inside the active area
  - instead of searching the whole known regions for frontier points
- Key idea: the only region that contains changes is the active area
- If a map orientation was changed, then *WFD-INC* acts as *WFD*
- *WFD-INC* has to call the maintenance routine
  - since it does not search the whole map

Incremental-Parallel Wavefront Frontier Detector

- Abbreviation: *WFD-IP*
- Robust against map orientation changes that happens too often
- Key idea: keep a separate instance of *WFD-INC* for each particle
- Execute *WFD-INC* according to each particle's map data
- Result: all *WFD-INC* instances keep frontier data between calls

Experiment Design

- We have fully implemented *WFD*, *WFD-INC*, *WFD-IP* and *FFD*
- We compare all algorithms 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

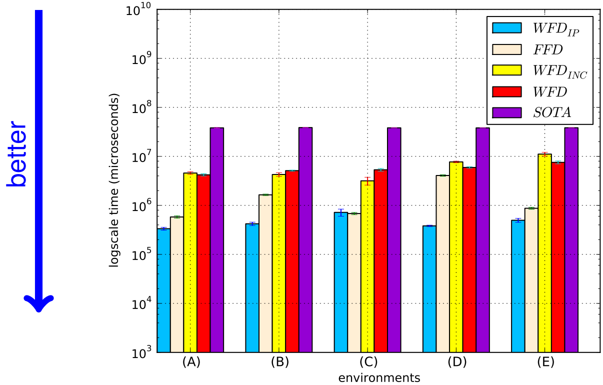
Experiment Design

- 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

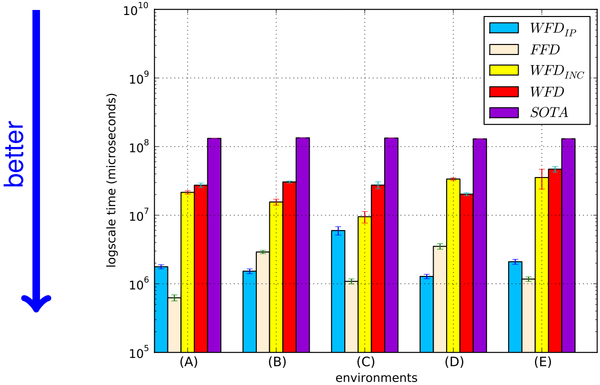
Figure: Example of a testing environment, University of Freiburg. Image was taken from RADISH, Howard and Roy [2003]

Runtime Comparision (Core 2 Duo)



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

Runtime Comparision (Coppermine)



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What Happend in Environment (D)?

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The mean run-time of *WFD* is not relatively slower than *FFD*

Answer

- Environment (D) contains regions that contains small obstacles
- The obstacles enlarge the length of contour scanned by *FFD*
- As shown, the contour length affects the run-time complexity

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Why is *WFD-INC* Sometimes Worse than *WFD*?

What Happend?

- In the worst-case, *WFD-INC* should perform the same as *WFD*
- The run-time means of *WFD* and *WFD-INC* do not have a trend

Hypothesis

- Certain environments have high frequency of particle change
- $\Rightarrow$ *WFD-INC* cleans its previous detected frontiers more often

Map	Changes	Executions	Percent (%)
(A)	56	110	50.91
(B)	52	287	18.12
(C)	25	160	15.62
(D)	193	429	44.99
(E)	73	340	21.47

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What Happend to *WFD-IP* in Environments (A),(C),(E), Weak Machine?

- Strong machine: *WFD-IP* outperforms all other algorithms
- Weak machine: the situation is different in maps (A),(C),(E)
- Hypothesis (1) Memory:
  - Weak machine is equipped with less RAM than strong machine
  - *WFD-IP* holds a separate instance of *WFD-INC* for each particle
  - Hypothesis: strong machine runs each thread on a separate core
  - In our experiment, 30 instances of *WFD-INC*
- Hypothesis (2) CPU:
  - Weak machine is equipped a single CPU
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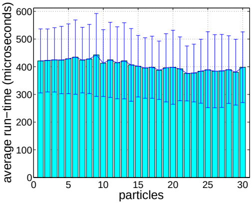
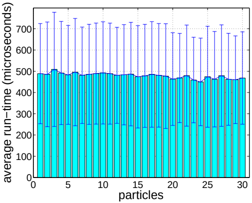
Measuring Run-Time for Individual Particle

- We compare the run-time of individual particles in each map
- Each bar represents a specific particle
- Vertical axis: measures the run-time of *FFD* for the particle
- Error-bars: the standard deviation of each particle's run-time

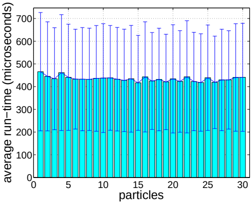
Measuring Run-Time for Individual Particle



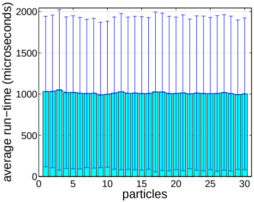
(a)



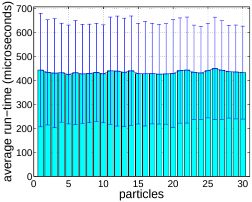
(b)



(c)



(d)



(e)

FFD Performance According to Number of Particles

- *FFD* has to persistently run in the background
- Particle-filter systems: each particle has its own instance of *FFD*
- Hence, the overall run-time is increased
- We change the number of particles in different maps
- Each bar represents a run with a specific number of particles
- Vertical axis: mean run-time of *FFD* for the configuration
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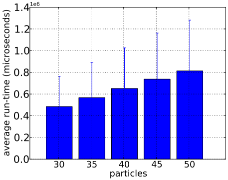

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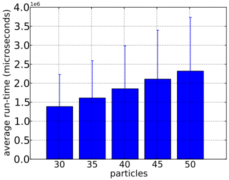

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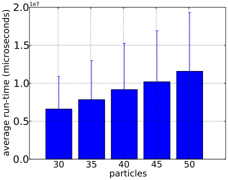

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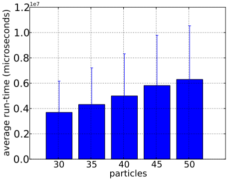

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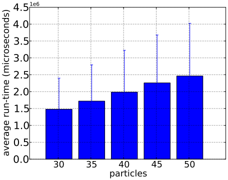

(e)

Summary and Future Work

- Real-Time frontier detection on weak CPU's
- *WFD*, *FFD*, *WFD-INC*, *WFD-IP*: methods for frontier detection
  - significant reduction of calculation time
- Publications:
  - AAMAS 2012
  - ARMS workshop at AAMAS 2011
- Future work:
  - Address efficient methods for maintaining frontiers in *FFD*
  - Novel exploration policies based on real-time frontier-detection

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 $\overrightarrow{P_0P_1}$ is clockwise from $\overrightarrow{P_0P_2}$.
  - 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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Back to *FFD*

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