Efficient L-Shape Fitting for Vehicle Detection Using Laser Scanners

Xiao Zhang[†], Wenda Xu[†], Chiyu Dong[†], John M. Dolan[†,‡]

[†]Electrical and Computer Engineering, Carnegie Mellon University
[‡]Robotics Institute, Carnegie Mellon University

June, 2017

Outline

Introduction

- Detection of surrounding objects is an essential task in autonomous driving.
- LIDAR, laser scanner, widely used for collecting range data
- Segmentation
  - segment range data into meaningful cluster of points
- **Feature Extraction**
  - line segments, chunks, rectangles, L-shape, ...
  - walls, bicycles, woods, bushes, vehicles, pedestrians, ...
- Tracking
  - feature association: static map, moving targets
  - tracking: Extended Kalman Filter(EKF), Rao-Blackwellized Particle Filter (RBPF)

Related Work

- CMU's "Boss", won DARPA Urban Challenge in 2007
  - urban environment, low-density and low-speed traffic
  - merging, passing, interacting with manned/unmanned vehicle
  - 3D LIDAR sensors sitting on top, e.g. Velodyne HDL-64
  - high-definition, but expensive
- CMU's new Cadillac SRX research platform
  - production-grade sensors, e.g. IBEOs
  - reduce equipment expenditure, enable a neat appearance

Figure: CMU's new autonomous vehicle research platform "SRX"

Related Work

- Challenges
  - giving up high-definition dense range points in 3D
  - detect only object's contour that face towards sensor in 2D
- Relevant Work
  - Principal Component Analysis (PCA)[1]
  - weighted least squares: line fitting + corner fitting[2]
  - utilize scanning order info to split cluster into two edges[3]
- L-Shape based Vehicle Detection
  - no need for laser scanning sequence information
  - robust to various range point density
  - flexible to accommodate specified fitting criterion
  - effectiveness demonstrated by experiments

---

[1] Huijing Zhao, Quanshi Zhang, Masaki Chiba, et al. "Moving object classification using horizontal laser scan data". In: *IEEE International Conference on Robotics and Automation*. 2009, pp. 2424–2430.

[2] Robert MacLachlan and Christoph Mertz. "Tracking of moving objects from a moving vehicle using a scanning laser rangefinder". In: *IEEE Intelligent Transportation Systems Conference*. 2006, pp. 301–306.

[3] Xiaotong Shen, Scott Pendleton, and Marcelo H Ang. "Efficient L-shape fitting of laser scanner data for vehicle pose estimation". In: *IEEE Conference on Robotics, Automation and Mechatronics*. 2015, pp. 173–178.

Outline

Segmentation

- divide the range points into clusters according to an adapting threshold
- K-D tree data structure for finding neighboring points within distance threshold
- further speedup if scanning order available

Algorithm 1 Adaptive Segmentation Algorithm

Input: range data points $X \in R^{n \times 2}$
Output: set of point clusters S

```
for all x ∈ X do
    if x has not been checked then
        C ← ∅
        Q.push(x)
        while Q ≠ ∅ do
            x' ← Q.pop()
            if x' has not been checked then
                r ← α_0||X||
                find all x̄ ∈ X that are within r for x'
                insert all x̄ into C
                mark x' as checked
            end if
        end while
        insert C into S as a new cluster
    end if
end for
```

Minimize Least Squares in L-Shape Fitting

- optimization problem
  - L-Shape rectangle model assumption
  - least squares - classical fitting criterion

$$\begin{aligned} \underset{P,\theta,c_1,c_2}{\text{minimize}} \quad & \sum_{i\in P}(x_i\cos\theta + y_i\sin\theta - c_1)^2 \\ & + \sum_{i\in Q}(-x_i\sin\theta + y_i\cos\theta - c_2)^2 \\ \text{subject to} \quad & P \cup Q = \{1,2,...,m\} \\ & c_1, c_2 \in R \quad 0^\circ \leq \theta < 90^\circ \end{aligned} \tag{1}$$

- decision variables
  - optimal disjunction (P, Q) split the m points into two sets
  - optimal parameters (θ, c_1, c_2) for two perpendicular lines
- the two line expressions
  - $x\cos\theta + y\sin\theta = c_1$ and $-x\sin\theta + y\cos\theta = c_2$
- difficult optimization problem
  - combinatorial complexities due to partition

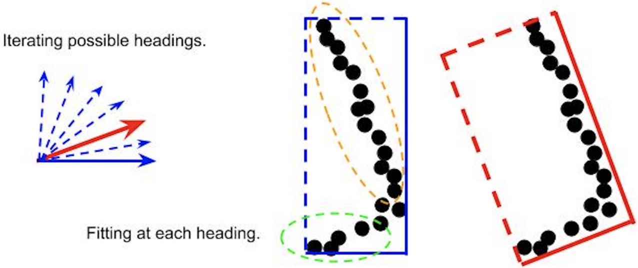
Search-Based Rectangle Fitting

Algorithm 2 Search-Based Rectangle Fitting

Input: range data points $X \in R^{n \times 2}$
Output: rectangle edges $\{a_i x + b_i x = c_i | i = 1, 2, 3, 4\}$

$Q \leftarrow \emptyset$
for $\theta = 0$ **to** $\pi/2 - \delta$ **step** δ **do**
    $\hat{e}_1 \leftarrow (\cos\theta, \sin\theta)$ ▷ rectangle edge direction vector
    $\hat{e}_2 \leftarrow (-\sin\theta, \cos\theta)$
    $C_1 \leftarrow X \cdot \hat{e}_1^T$ ▷ projection on to the edge
    $C_2 \leftarrow X \cdot \hat{e}_2^T$
    $q \leftarrow \text{CalculatecriterionX}(C_1, C_2)$
    insert q into Q with key (θ)
end for
select key (θ^*) from Q with maximum value
$C_1^* \leftarrow X \cdot (\cos\theta^*, \sin\theta^*)^T, C_2^* \leftarrow X \cdot (-\sin\theta^*, \cos\theta^*)^T$
$a_1 \leftarrow \cos\theta^*$, $b_1 \leftarrow \sin\theta^*$, $c_1 \leftarrow \min\{C_1^*\}$
$a_2 \leftarrow -\sin\theta^*$, $b_2 \leftarrow \cos\theta^*$, $c_2 \leftarrow \min\{C_2^*\}$
$a_3 \leftarrow \cos\theta^*$, $b_3 \leftarrow \sin\theta^*$, $c_3 \leftarrow \max\{C_1^*\}$
$a_4 \leftarrow -\sin\theta^*$, $b_4 \leftarrow \cos\theta^*$, $c_4 \leftarrow \max\{C_2^*\}$

Search-Based Rectangle Fitting



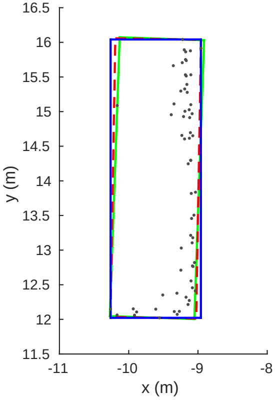
- iterate through all possible headings (θ) of the rectangle
- at each heading θ
  - find the smallest rectangle oriented at θ which covers this cluster of points
  - obtain projections to rectangle edges for all points
  - split points into P and Q according to these distances
  - obtain the fitting criterion
- select optimal heading which achieves the best fitting criterion

Fitting Criterion

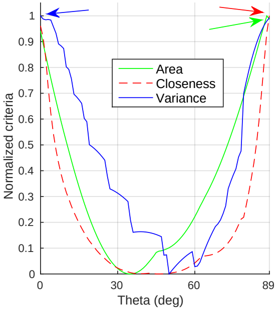
- Area Minimization
  - minimize rectangle area
  - looking for the smallest rectangle that covers all the points
- Closeness Maximization
  - maximize points-to-edges closeness
  - emphasize how close these range points are to the 2-D contour facing towards the sensor
- Variance Minimization
  - minimize points-to-edges squared error
  - emphasize the squared error of the two orthogonal edges fitted by the two disjoint groups of points
  - actually looking for an approximated solution to the above optimization problem

Outline

Typical Rectangle Fitting Example



a Fitted rectangle.



b Fitting criterion.

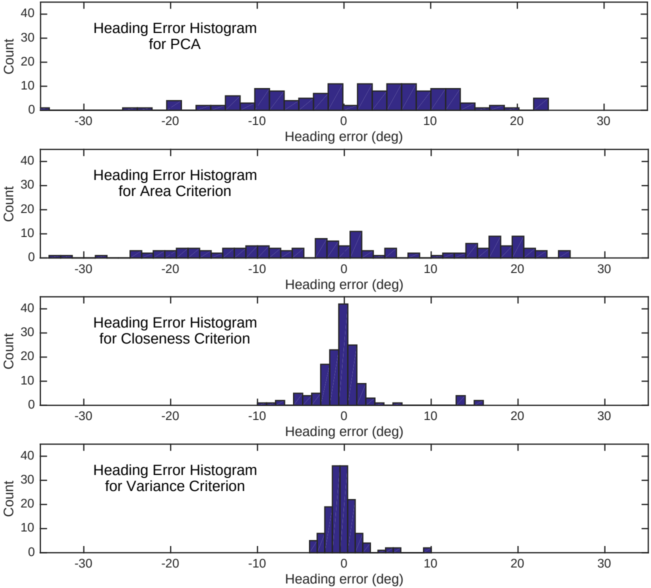
Figure: In example (a), the fitting results from the three criteria are very similar, and the maxima of the three curves in (b) are very close (marked by arrows and achieved at 88°, 89°, and 0°, respectively).

Heading Accuracy in Rectangle Fitting

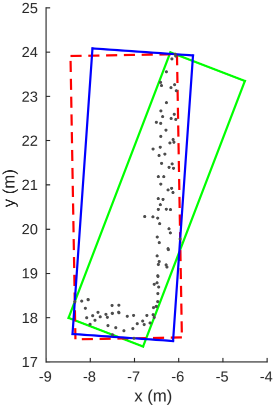
- Observations
  - dataset (145), headings manually labeled at resolution 1°
  - closeness maximization and variance minimization have very high correctness, better than PCA
  - area minimization is only guaranteed with dense range points, e.g. small object or more powerful LIDAR

	Real Error ($\theta - \theta_g$)		Absolute Error ($\lvert\theta - \theta_g\rvert$)	
Method	Mean (deg)	STD (deg)	Mean (deg)	STD (deg)
PCA	-5.60	10.68	10.09	6.57
Area	0.65	14.80	11.78	8.46
Closeness	0.01	3.65	2.47	3.36
Variance	-0.15	2.19	1.55	1.66

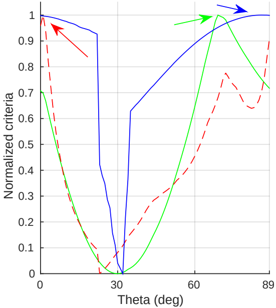
Heading Error Histogram



Example by Minimize Area Criteria Fitting



a Fitted rectangle.

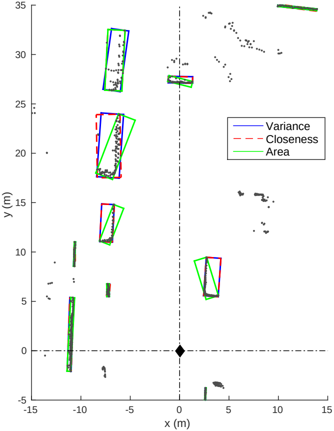


b Fitting criterion.

Figure: In example (a), the fitting result from the area criteria is different from the other two, and its maximum in (b) is away from the other two (achieved at 69°, 1°, and 86°, respectively).

Fitting Results for Typical Cycles

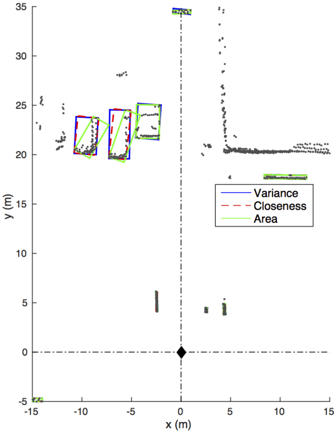
a Camera view.



b Vehicle fitting results.

Fitting Results for Typical Cycles

a Camera view.



b Vehicle fitting results.

Computation Efficiency

- Observations
  - dataset: 10k laser scans collected on local roads
  - MATLAB, Linux, Intel Core i7 CPU
  - variance minimization criterion is the most time-consuming, due to heavy computation in calculating the variance

Criterion	Mean (ms)	STD (ms)
Area Minimization	3.56	0.19
Closeness Maximization	4.00	0.23
Variance Minimization	8.37	0.32

Conclusions

- A search-based L-Shape fitting approach for vehicle detection
  - no need for the scan ordering information, enabling fusion of raw laser data from multiple laser scanners
  - computationally efficient and easy to implement, involving very few parameters and no need for hands-on experience or parameter tuning
  - accommodate any specified criterion, flexible for different fitting demands
  - effective and robust (criterion Closeness and Variance), demonstrated by on-road experiments with production-grade sensors
- Future work
  - improve the algorithms to be more robust with outliers, e.g. SUV side mirrors
  - compare headings through successive cycles