Lane Detection, Calibration, and Attitude Determination with a Multi-Layer Lidar for Vehicle Safety Systems

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Overview

- Problem Introduction
- Motivation
- Background
- Calibration and Attitude determination
- Lane Detection
- Testing
- Results
- Conclusions
Problem Introduction

- Attempt to detect lane markings using a 3D lidar to prevent unintended lane departures
- Should be capable of adapting to changing road conditions
- This requires a calibrated lidar
  - Often requires known excitation, surveyed points, or precise structures
Motivation

• We can save lives.
  • In 2008 52% of all highway fatalities occurred from unintended lane departure
  • Nearly 20,000 deaths
  • In 2006 it was 58%, comprising nearly 25,000 deaths
  • In short: more fatalities than any other crash type occur due to single vehicle road departures
Background: Previous Work (LDW)

  - Uses Ibeo, Large ROI 10-30m and \( \pm 12m \), and uses histogram for detection. No truth metric provided, but provides detection rates varying from 16-100%, averaging at 87%.
  - Once again uses a large ROI 0-30m and \( \pm 12m \). Truth metric was driving straight for short periods of time and estimating lane width, accurate to 0.25m.
  - 6-layer lidar, uses a polar histogram. No truth data, but notes it works best on asphalt, and worst on concrete. Rain has an adverse affect on detection.
Contributions

• Development of a novel lane extraction method, that is based on a MMSE to an ideal lane

• Measure of LiDAR position compared to RTK GPS and surveyed lane markings
Background: Previous Work (Att)

- [37] Toshihiro Tsumura, Hiroshi Okubo, and Nobuo Komatsu.
  - Calibrate uses prior surveyed points
  - Calibrate using known geometric structures
- [38] Zhenqi Zhu, Qing Tang, Jinsong Li, and Zhongxue Gan.
  - Calibrates using known motion of robotic arm
Contributions

• Development of a 3D LiDAR calibration and attitude determination scheme.
• Capable of calibrating “quickly”
• Capable of determining attitude with sub-degree accuracy.
Background: What is a LiDAR?

- **LiDAR**: Light Detection and Ranging
- Similar in concept to sonar or radar, but uses light instead of sound or electromagnetic waves

<table>
<thead>
<tr>
<th>1D</th>
<th>2D</th>
<th>3D</th>
</tr>
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<tbody>
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LiDAR: Reflectivity

- LiDAR provides distance as well as reflectivity, known as echo width.
- Lines are detected on the premise that they are of high reflectivity than the road’s surface.
Hardware Overview

• 3D LiDAR
  – 4 layers
  – 3.2° vertical field of view

• Mounted on roof rack of vehicle
  – Resolution of 1.6 inches at lane markings

• Operates at 10Hz with 0.25° resolution
Calibrating the Lidar

- Calibrate the height, yaw, pitch, and roll of the LiDAR.
- Allows us to compensate for LiDAR mounting
- Determine resolution at lane markings
Assumptions of Calibration

- Vehicle is on a planar surface
  - Road, Garage, Hanger, Factory Floor
- Vehicle is capable of performing a pure pitch maneuver
- Vehicle is equipped with forward looking 3D LiDAR that can measure the planar surface
- LiDAR remains fixed on the vehicle once calibrated
Assumptions Continued

- All LiDAR measurements originate at the same physical location
- Operating in the NED frame
- Standard SAE YPR rotation order
Algorithm Overview

• Develop an equation to describe the Euler angles relating the LiDAR measurements to a vehicle on a level plane.

• LiDAR data will be collected on a static vehicle in steady state.

• LiDAR data will then be taken on a dynamic vehicle and compared to the steady state data to estimate vehicle motion and/or calibration parameters.
Determination of Yaw

- Rotation about Z-axis
- Yaw cannot be determined directly
- Must have additional dynamic
Determination of LiDAR Pitch

- Rotation about Y-axis
Determination of LiDAR Roll

• Rotation about X-axis
Because all points originate at the same location, we have an over determined system.

- Note: pitch and roll are not a function of yaw.

\[ D_{\text{lidar}} = -\sin(\theta)x_n + \sin(\phi)\cos(\theta)y_n + \cos(\phi)\cos(\theta)z_n \]

\[ \theta_{12} = \tan^{-1}\left( \frac{\sin(\phi)y_2 + \cos(\phi)z_2 - \sin(\phi)y_1 - \cos(\phi)z_1}{x_2 - x_1} \right) \]

\[ \theta_{13} = \tan^{-1}\left( \frac{\sin(\phi)y_2 + \cos(\phi)z_2 - \sin(\phi)y_1 - \cos(\phi)z_1}{x_2 - x_1} \right) \]

\[ \phi_{1213} = \tan^{-1}\left( \frac{(x_3 - x_1)(x_2 - x_1) + (x_1 - x_2)(x_3 - x_2)}{(y_2 - y_1)(x_3 - x_1) + (y_1 - y_2)(x_3 - x_2)} \right) \]
Determining LiDAR yaw

• The yaw is the relative yaw between the vehicle and LiDAR not global yaw.

• Vehicle must undergo a pure pitch dynamic.
  – Hence if the LiDAR and vehicle’s axes are aligned with the vehicle’s there should be no change in roll during this maneuver.

• We compare a pitched scan and static scan to determine this relative yaw
Determination of Vehicle Pitch & Roll
Perform some math
Determination of Vehicle Pitch & Roll

- Note: Function of LiDAR yaw
- Use similar procedure.

\[
\lambda_{122} = \tan^{-1}\left(\frac{\cos(\xi) A_{11} + \sin(\xi) (\cos(\psi) D_{11} + \sin(\psi) G_{11})}{\cos(\psi) G_{11} - \sin(\psi) D_{11}}\right)
\]

\[
\lambda_{133} = \tan^{-1}\left(\frac{\cos(\xi) B_{11} + \sin(\xi) (\cos(\psi) E_{11} + \sin(\psi) H_{11})}{\cos(\psi) H_{11} - \sin(\psi) E_{11}}\right)
\]

\[
\xi_{1221333} = \tan^{-1}\left(\frac{\cos(\psi) (B_2 G_2 - A_2 H_2) + \sin(\psi) (-B_2 D_2 + A_2 E_2)}{\cos(\psi)^2 (D_2 H_2 - E_2 G_2) + \sin(\psi)^2 (-G_2 E_2 + H_2 D_2)}\right)
\]
Determination of relative yaw

• Note: yaw is now reduced to LiDAR pitch and roll measurements.

• Setting the static vehicle roll calculation and the pitched vehicle roll calculation equal to one another, yields:

\[ \psi = \tan^{-1}\left( \frac{(B_1 G_1 - A_1 H_2)(D_1 H_1 - E_1 G_1) - (B_1 G_1 - A_1 H_1)(D_2 H_2 - E_2 G_2)}{(-B_1 D_1 + A_1 E_1)(D_2 H_2 - E_2 G_2) - (-B_2 D_2 + A_2 E_2)(D_1 H_1 - E_1 G_1)} \right) \]
Considerations

• Singularities
  – Cannot report meaningful data if pointed straight down

• Larger separation the better
  – Due to numerical issues and noise, the LiDAR measurements should have a large separation to guarantee the best results
Computing a Solution

- Unscented Transform used for error propagation estimation and propagation.
  - See thesis for details
- Kalman filter used for determining the final result.
Test Procedure: Static

Calibration:
(same for static and dynamic)
- 50 Static Scans taken
- Vehicle was then driven and the brakes applied to induce vehicle pitch
- 50 static and one pitched scan of the brake test compared

Attitude Testing:
- Vehicle Position on flat level ground
- Vehicle underwent induced pitch and roll maneuvers.
  - Vehicle change in pitch = 1.46°
  - Vehicle change in roll = 2.75°
Truth & Comparative system :: Septentrio

- 3-antenna GPS system
- Provides vehicle pitch, roll, and yaw in Euler angle form.
- Accurate to ~0.6 ° for our given baseline
Comparison to Septentrio: Static

Pitch:

Roll:

Pitch Data

Roll Data

Pitch (deg)

Roll (deg)

Lidar

Septentrio

Time (s)
Results Vehicle: Static

- MSE Pitch = 0.1129°
- MSE Roll = 0.7855°
- Avg Error Pitch = 0.28°
- Avg Error Roll = 0.68°
Test Procedure: Dynamic

Attitude Testing:

• Vehicle put through a series of dynamic maneuvers to induce vehicle pitch and roll
• Data analyzed only when in the maneuver
Comparison to Septentrio: Dynamic

**Pitch:**

- **Pitch Data**
- **Lidar** (black) vs. **Septentrio** (orange)

**Roll:**

- **Roll Data**
- **Lidar** (black) vs. **Septentrio** (orange)

- **Yaw**

Samuel Ginn College of Engineering
Results Vehicle: Dynamic

- MSE Pitch = 2.054°
- MSE Roll = 0.4617°
- Avg Error Pitch = 0.78°
- Avg Error Roll = 0.31°
- Average Processing time per scan = 0.06s
- Average Calibration time = 2.26s
Results – Considerations

• Data was post processed
• No truth method used for determination of calibration success
• Error is merely comparative not absolute
  – Septentrio only accurate to ~0.6°
  – No test performed to determine the accuracy of the Septentrio's mounting on the vehicle
Detection Overview

- Bound the Search Area
- Generate an ideal scan to match actual lane markings
- Find the MMSE between the ideal scan and an actual scan
- Window the data
- Filter the data
LiDAR Data Overview

• Ideal scan has distinct peaks, and consistent road surface
• Data to side of road noisy, but resembles lane markings
Creating an Ideal Scan

- Spikes represent the increase in reflectivity of the lane markings
- Flat area represents road’s surface
- Window found lanes
NCAT Testing

- Mean error: 0.1252m
- Var of error: 0.0362m

<table>
<thead>
<tr>
<th>Condition</th>
<th>Avg. Lane Width Error (m)</th>
<th>Std of Error (m)</th>
<th>Detection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway</td>
<td>0.075</td>
<td>0.233</td>
<td>94.7</td>
</tr>
<tr>
<td>Yellow &amp; White</td>
<td>0.042</td>
<td>0.272</td>
<td>81.7</td>
</tr>
<tr>
<td>Gravel on Surface</td>
<td>0.129</td>
<td>0.215</td>
<td>97.4</td>
</tr>
<tr>
<td>Grass Bordering</td>
<td>0.169</td>
<td>0.329</td>
<td>76.86</td>
</tr>
</tbody>
</table>
Conclusions - LDW

- Lane extraction algorithm does not appear to be effected by changes in lighting.
- Error prone to grass and rain.
- Accurate to within the width of a lane marking.
Conclusions - Calibration

• Capable of determining vehicle pitch and roll to within sub-degree accuracy
• For meaningful calibration: vehicle’s axes must be aligned with plane
• Highly non-linear problem
• Computationally complex
• Larger change in pitch dynamics the better for calibration
Future Work

• Determine how non uniform plane can be to yield accurate results
Questions or Comments?

Images Courtesy of Despair.com