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)

- [23] J. Kibbel, W. Justus, and K. Furstenberg.
  - Uses Ibeo, Large ROI 10-30m and ±12m, and uses histogram for detection. No truth metric provided, but provides detection rates varying from 16-100%, Averaging at 87%.
- [13] K. Dietmayer, N. Kämpchen, K. Fürstenberg, J. Kibbel, W. Justus, and R. Schulz.
  - Once again uses a large ROI 0-30m and ±12m. Truth metric was driving straight for short periods of time and estimating lane width, accurate to 0.25m
- [24] P. Lindner, E. Richter, G. Wanielik, K. Takagi, and A. Isogai.
  - 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)

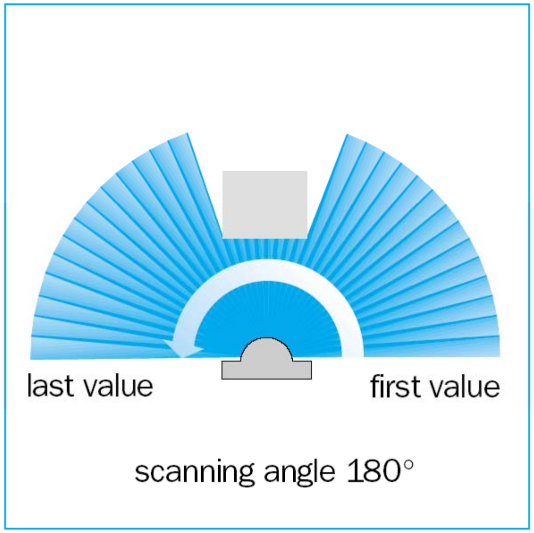
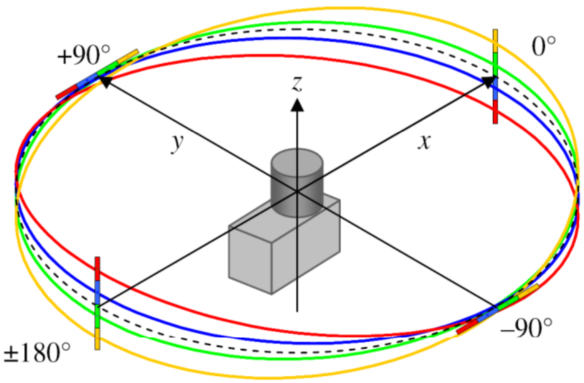
- [37] Toshihiro Tsumura, Hiroshi Okubo, and Nobuo Komatsu.
  - Calibrate uses prior surveyed points
- [5] Matthew Antone and Yuli Friedman.
- [7] Frank S. Barickman.
  - Calibrate using known geometric structures
- [38] Zhenqi Zhu, Qing Tang, Jinsong Li, and Zhongxue Gan.
  - Calibrates using known 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.

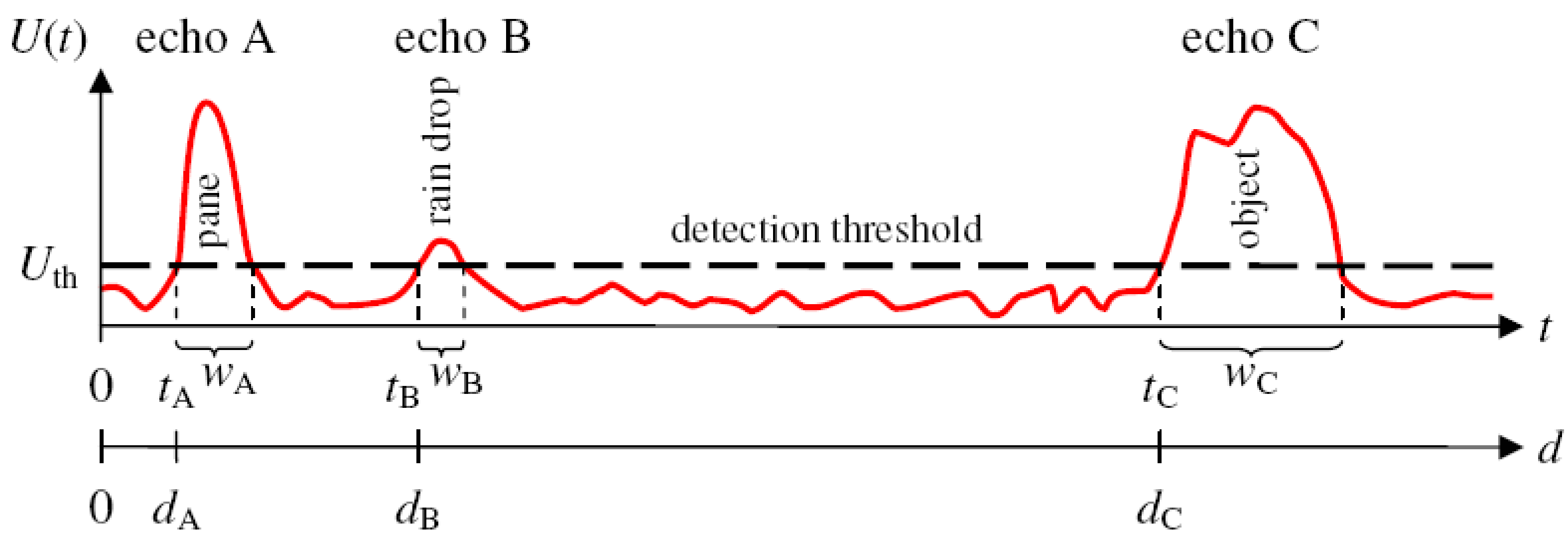
Background : What is a LiDAR ?

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

1D	2D	3D
		

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

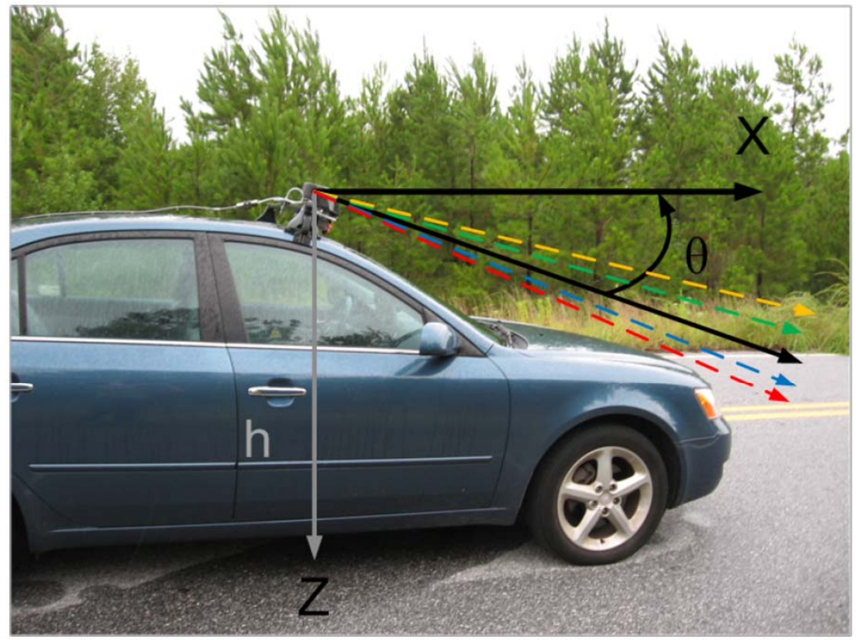


Hardware Overview

- 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

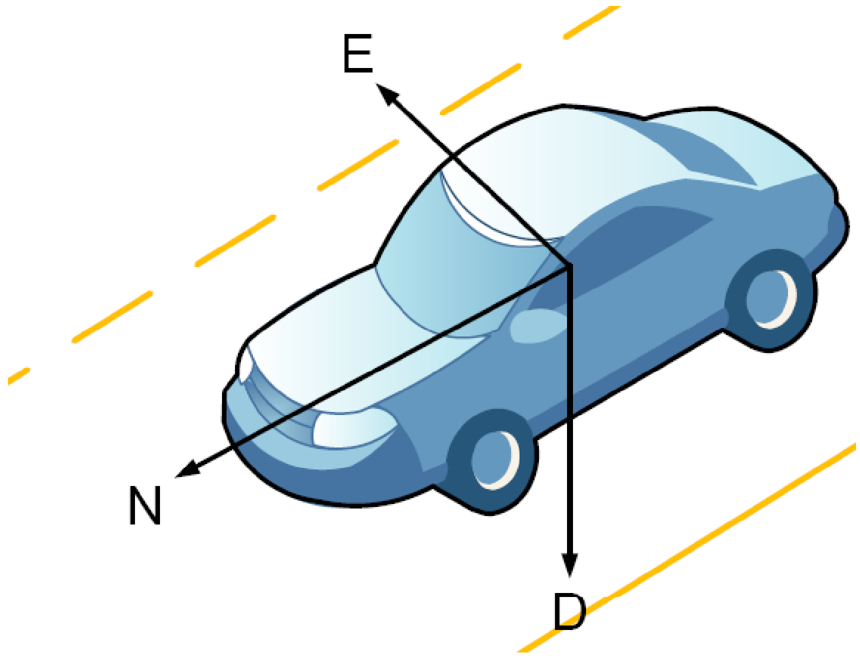


Assumptions of Calibration

- 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

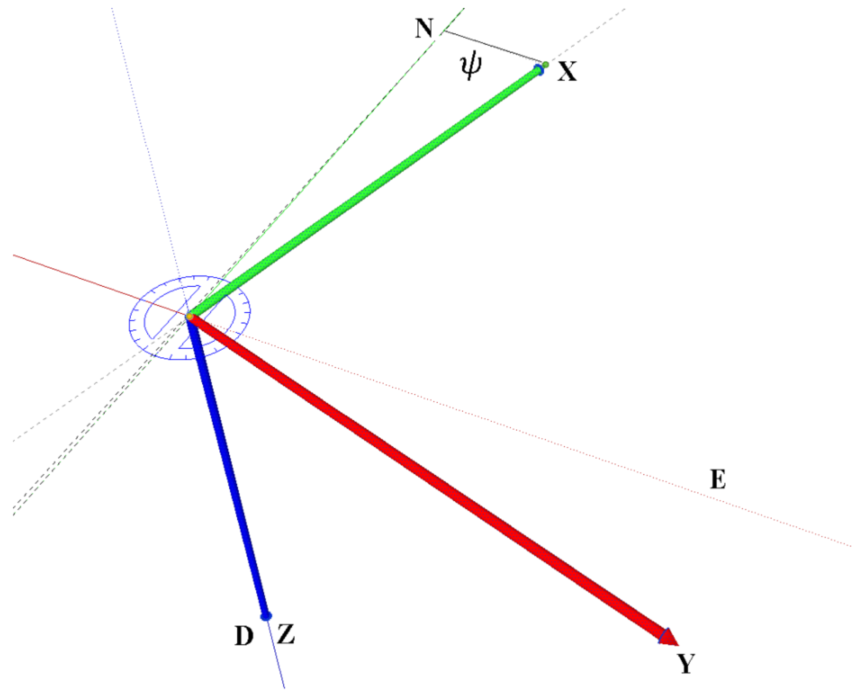


Algorithm Overview

- 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

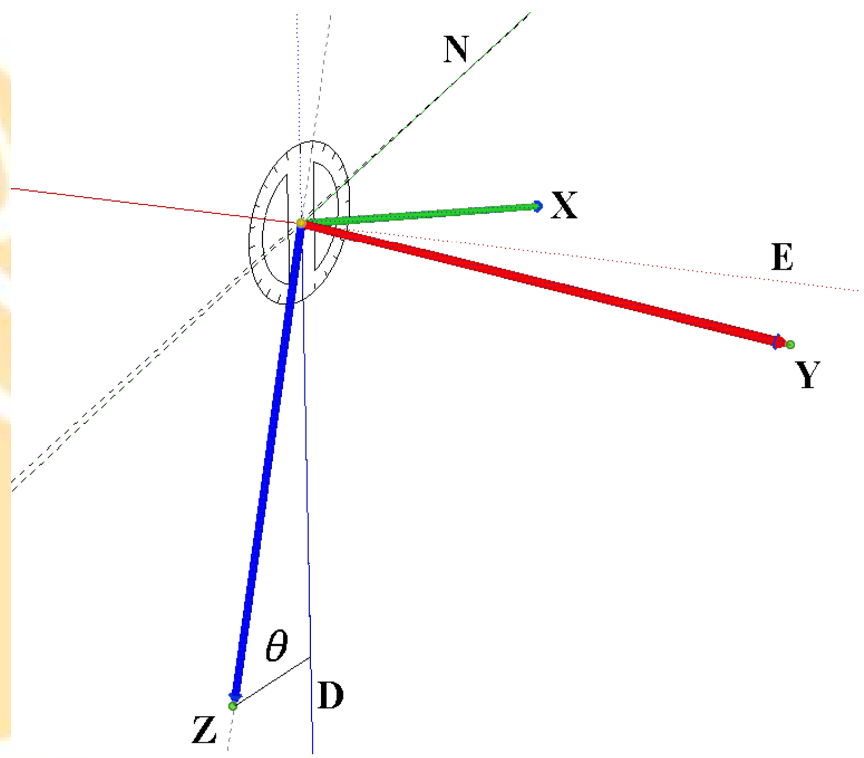
Determination of Yaw

- Rotation about Z-axis
- Yaw cannot be determined directly
- Must have additional dynamic



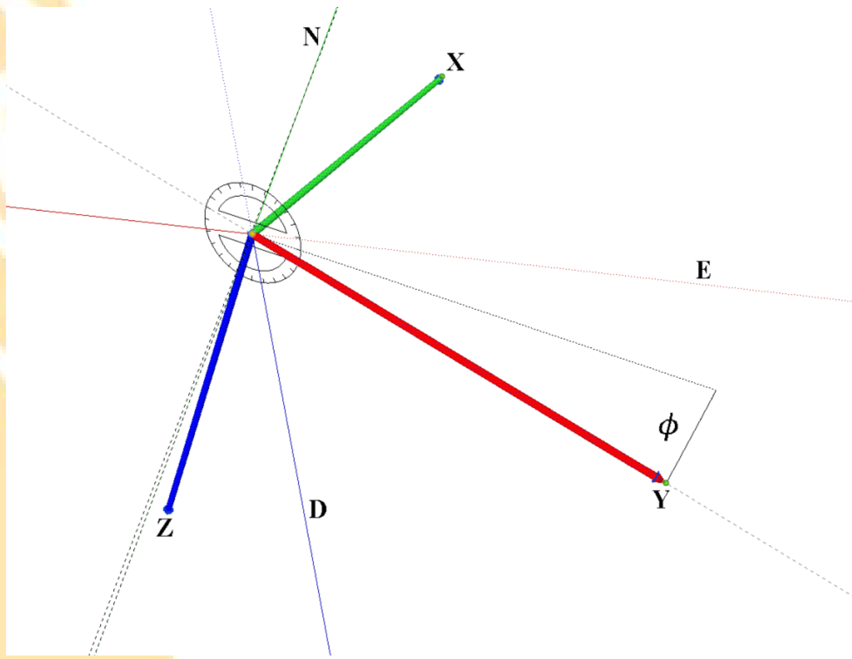
Determination of LiDAR Pitch

- Rotation about Y-axis



Determination of LiDAR Roll

- Rotation about X-axis



Determination of LiDAR Pitch & Roll :: Calibration Phase

- Because all points originate at the same location, we have an over determined system.
  - Note: pitch and roll are not a function of yaw.

$$NED_{lidar\_frame} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\psi) & \sin(\psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}$$

$$D_{\mathrm{nlidar}} = -\sin(\theta)\, x_{\mathrm{n}} + \sin(\phi)\cos(\theta)\, y_{\mathrm{n}} + \cos(\phi)\cos(\theta)\, z_{\mathrm{n}}$$

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

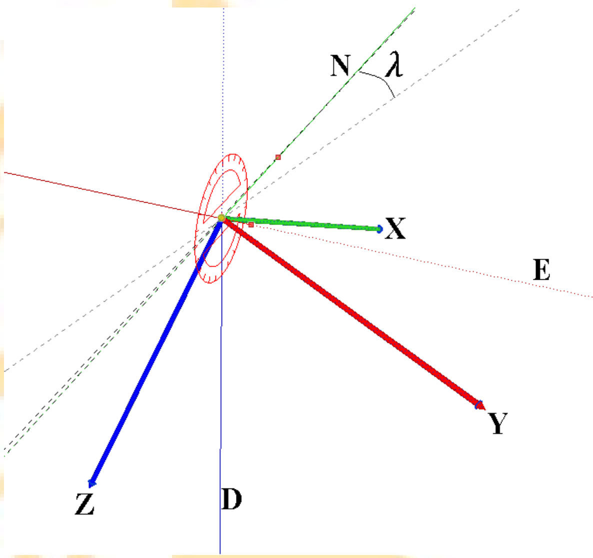
$$\theta_{13} = \tan^{-1}\left(\frac{\sin(\phi)\, y_3 + \cos(\phi)\, z_3 - \sin(\phi)\, y_1 - \cos(\phi)\, z_1}{x_3 - x_1}\right)$$

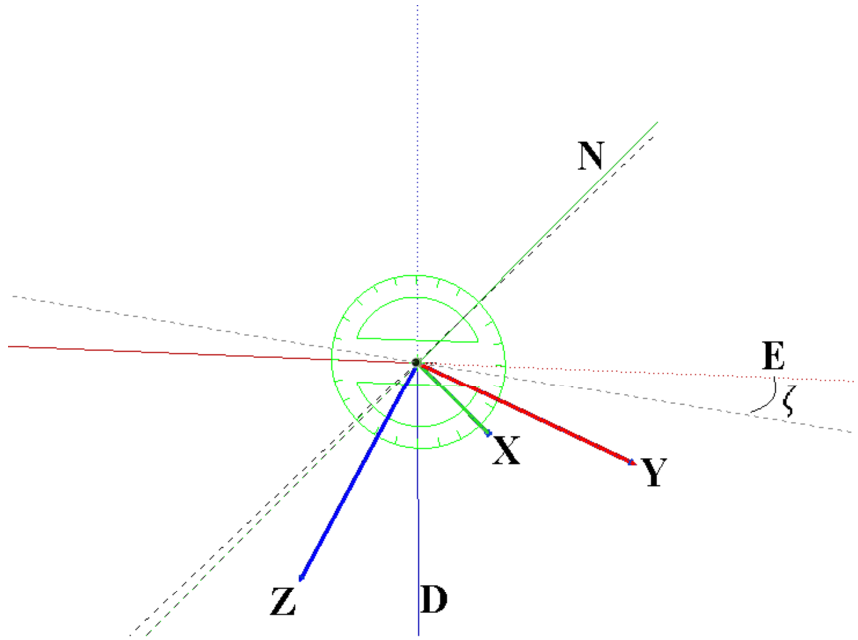
$$\phi_{1213} = \tan^{-1}\left(\frac{(z_3 - z_1)(x_2 - x_1) + (z_1 - z_2)(x_3 - x_1)}{(y_1 - y_2)(x_3 - x_1) + (y_1 - y_3)(x_2 - x_1)}\right)$$

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

$$\begin{bmatrix} N_n \\ E_n \\ D_n \end{bmatrix} = \begin{bmatrix} \cos(\lambda) & 0 & -\sin(\lambda) \\ 0 & 1 & 0 \\ \sin(\lambda) & 0 & \cos(\lambda) \end{bmatrix}^T \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\zeta) & \sin(\zeta) \\ 0 & -\sin(\zeta) & \cos(\zeta) \end{bmatrix}^T$$

$$* \left(\begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\phi) & \sin(\phi) \\ 0 & -\sin(\phi) & \cos(\phi) \end{bmatrix} \begin{bmatrix} \cos(\theta) & 0 & -\sin(\theta) \\ 0 & 1 & 0 \\ \sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \begin{bmatrix} \cos(\psi) & \sin(psi) & 0 \\ -\sin(\psi) & \cos(\psi) & 0 \\ 0 & 0 & 1 \end{bmatrix} \right)^T \begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}$$

$$\begin{aligned} D_n = \sin(\lambda)\ &(\sin(\psi)\,(-z_n \sin(\phi) + y_n \cos(\phi)) \\ &+ \cos(\psi)\,(-x_n \cos(\theta) - y_n \sin(\phi)\sin(\theta) - z_n \cos(\phi)\sin(\theta))) \\ &+ \cos(\lambda)\,(\sin(\zeta)\,(y_n \sin(\phi)\sin(\theta)\sin(\psi) + x_n \cos(\theta)\sin(\psi) \\ &+ y_n \cos(\phi)\cos(\psi) + z_n \cos(\phi)\sin(\theta)\sin(\psi) - z_n \sin(\phi)\cos(\psi)) \\ &+ \cos(\zeta)\,(y_n \sin(\phi)\cos(\theta) - x_n \sin(\theta) + z_n \cos(\phi)\cos(\theta))) \end{aligned}$$

$$D_2 = -z_{22}\sin(\phi) + y_{22}\cos(\phi) + z_{11}\sin(\phi) - y_{11}\cos(\phi)$$

$$E_{11} = -z_{33}\sin(\phi) + z_{11}\sin(\phi) + y_{33}\cos(\phi) - y_{11}\cos(\phi)$$

$$\begin{aligned} A_1 = &-y_1 \sin(\phi)\cos(\theta) + x_1 \sin(\theta) - z_1 * \cos(\phi) * \cos(theta) + z_2 \cos(\phi)\cos(\theta) \\ &+ y_2 \sin(\phi)\cos(\theta) - x_2 \sin(\theta) \end{aligned}$$

$$\begin{aligned} B_1 = &\ y_3 \sin(\phi)\cos(\theta) - x_3 \sin(\theta) + z_3 \cos(\phi) * \cos(\theta) - y_1 \sin(\phi)\cos(\theta) + x_1 \sin(\theta) \\ &- z_1 \cos(\phi)\cos(\theta) \end{aligned}$$

$$\begin{aligned} G_2 = &-x_{11}\cos(\theta) + z_{22}\cos(\phi)\sin(\theta) - y_{11}\sin(\phi)\sin(\theta) + y_{22}\sin(\phi)\sin(\theta) + x_{22}\cos(\theta \\ &- z_{11}\cos(\phi)\sin(\theta) \end{aligned}$$

$$D_1 = -z_2 \sin(\phi) + y_2 \cos(\phi) + z_1 \sin(\phi) - y_1 \cos(\phi)$$

$$E_1 = -z_3 \sin(\phi) + z_1 \sin(\phi) + y_3 \cos(\phi) - y_1 \cos(\phi)$$

$$\begin{aligned} H_2 = &\ z_{33}\cos(\phi)\sin(\theta) + y_{33}\sin(\phi)\sin(\theta) + x_{33}\cos(\theta) - z_{11}\cos(\phi)\sin(\theta) \\ &- y_{11}\sin(\phi)\sin(\theta) - x_{11}\cos(\theta) \end{aligned}$$

$$\begin{aligned} G_1 = &-x_1 \cos(\theta) + z_2 \cos(\phi)\sin(\theta) - y_1 \sin(\phi)\sin(\theta) + y_2 \sin(\phi)\sin(\theta) + x_2 \cos(\theta) \\ &- z_1 \cos(\phi)\sin(\theta) \end{aligned}$$

$$\begin{aligned} A_2 = &-y_{11}\sin(\phi)\cos(\theta) + x_{11}\sin(\theta) - z_{11} * \cos(\phi) * \cos(theta) + z_{22}\cos(\phi)\cos(\theta) \\ &+ y_{22}\sin(\phi)\cos(\theta) - x_{22}\sin(\theta) \end{aligned}$$

$$\begin{aligned} B_2 = &\ y_{33}\sin(\phi)\cos(\theta) - x_{33}\sin(\theta) + z_{33}\cos(\phi) * \cos(\theta) - y_{11}\sin(\phi)\cos(\theta) + x_{11}\sin(\theta) \\ &- z_{11}\cos(\phi)\cos(\theta) \end{aligned}$$

Determination of Vehicle Pitch & Roll

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

$$\lambda_{1122} = \tan^{-1}\left(\frac{\cos(\zeta)A_{11} + \sin(\zeta)\left(\cos(\psi)D_{11} + \sin(\psi)G_{11}\right)}{\cos(\psi)G_{11} - \sin(\psi)D_{11}}\right)$$

$$\lambda_{1133} = \tan^{-1}\left(\frac{\cos(\zeta)B_{11} + \sin(\zeta)\left(\cos(\psi)E_{11} + \sin(\psi)H_{11}\right)}{\cos(\psi)H_{11} - \sin(\psi)E_{11}}\right)$$

$$\zeta_{11221133} = \tan^{-1}\left(\frac{\cos(\psi)\left(B_2G_2 - A_2H_2\right) + \sin(\psi)\left(-B_2D_2 + A_2E_2\right)}{\cos(\psi)^2\left(D_2H_2 - E_2G_2\right) + \sin(\psi)^2\left(-G_2E_2 + H_2D_2\right)}\right)$$

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:

$$\psi = \tan^{-1}\left(\frac{(B_2G_2 - A_2H_2)(D_1H_1 - E_1G_1) - (B_1G_1 - A_1H_1)(D_2H_2 - E_2G_2)}{(-B_1D_1 + A_1E_1)(D_2H_2 - E_2G_2) - (-B_2D_2 + A_2E_2)(D_1H_1 - E_1G_1)}\right)$$

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:

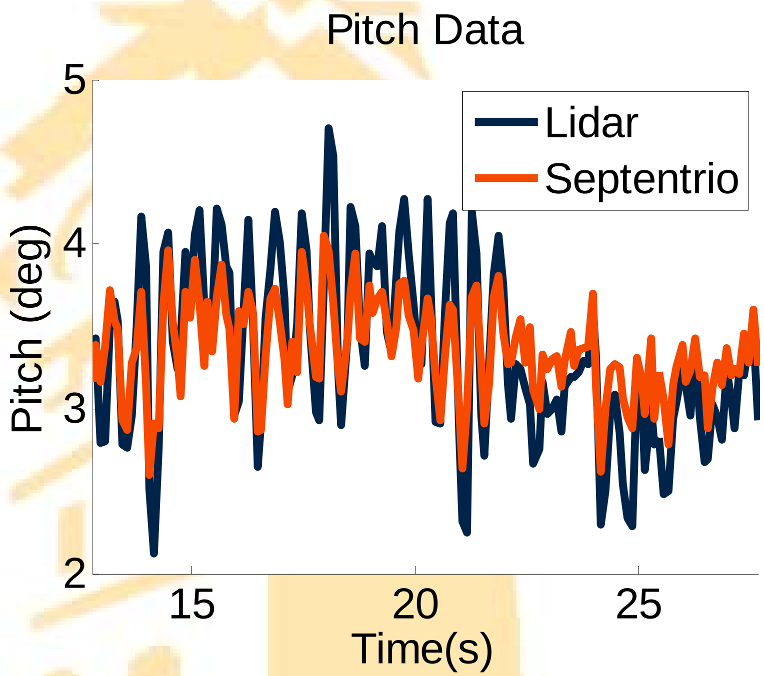
- Vehicle Position on flat level ground
- Vehicle underwent induced pitch and roll maneuvers.
  - Vehicle change in pitch = 1.46 °
  - Vehicle change in roll = 2.75 °

Truth & Comparative system :: Septentrio

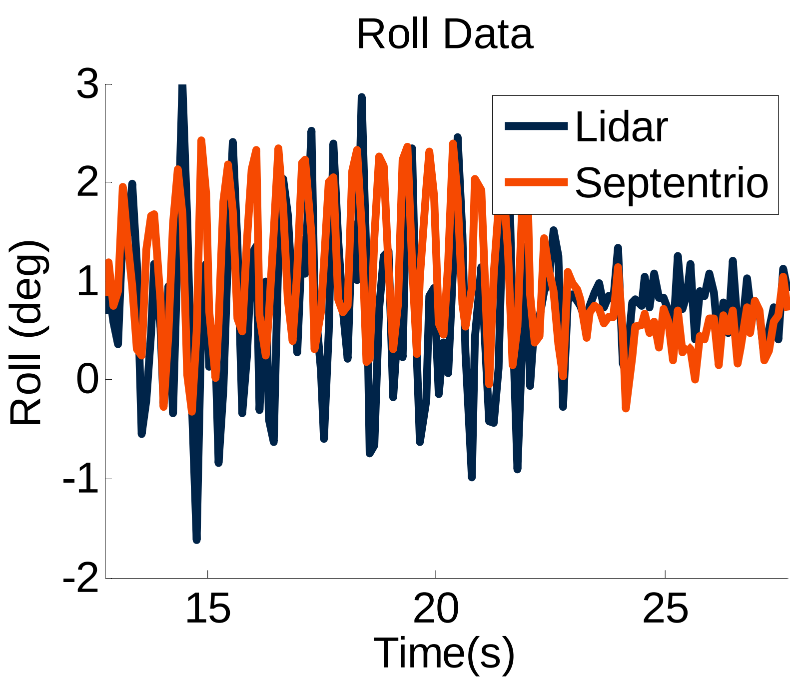
- 3-antenna GPS system
- Provides vehicle pitch, roll, and yaw in Euler angle form.
- Accurate to ~0.6 ° for our given baseline

Comparison to Septentrio: Static

Pitch:



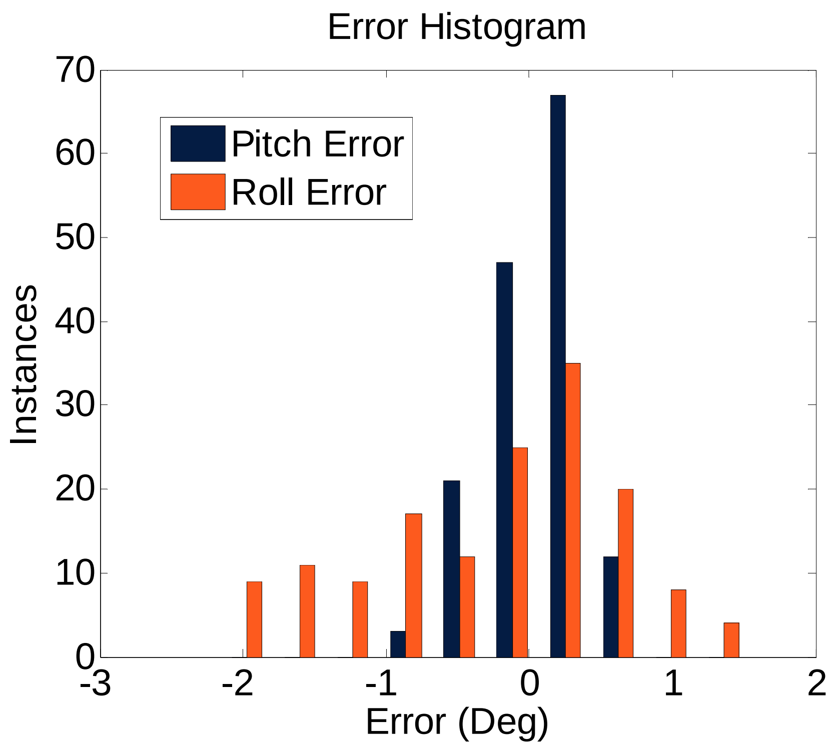
Roll:



Results Vehicle: Static

– MSE Pitch = 0.1129°
– MSE Roll = 0.7855°

– Avg Error Pitch =0.28 °
– Avg Error Roll = 0.68 °



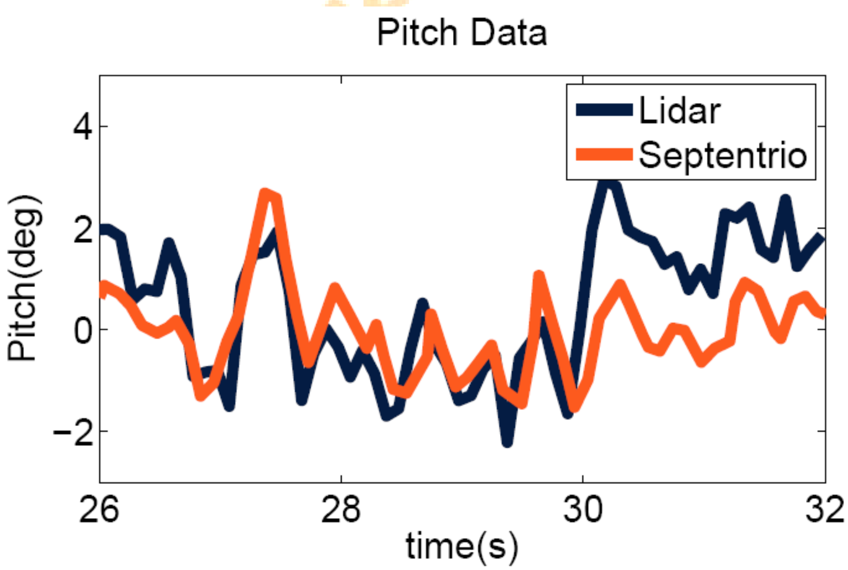
Test Procedure: Dynamic

Attitude Testing:

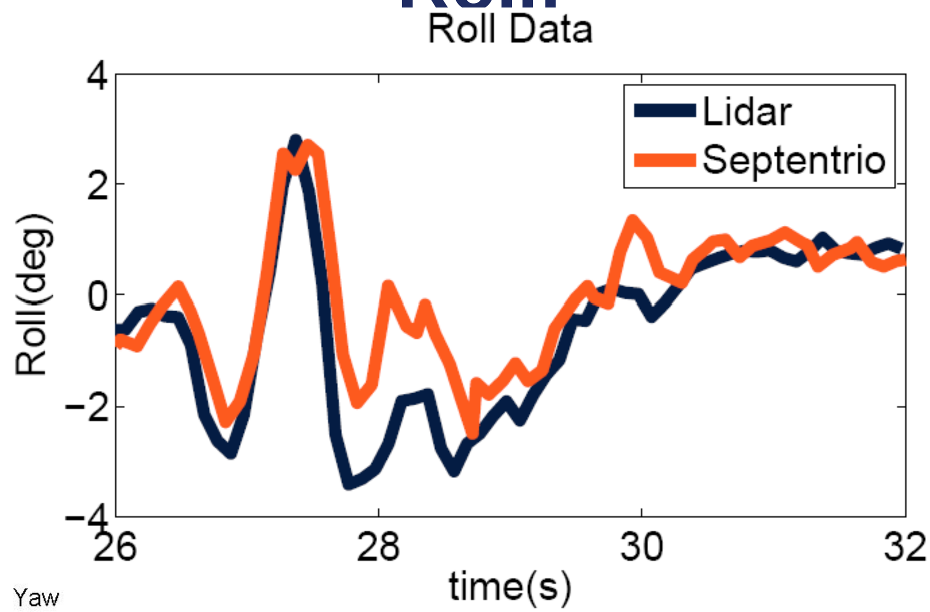
- Vehicle put through a series of dynamic maneuvers to induce vehicle pitch and roll
- Data analyzed only when in the maneuver

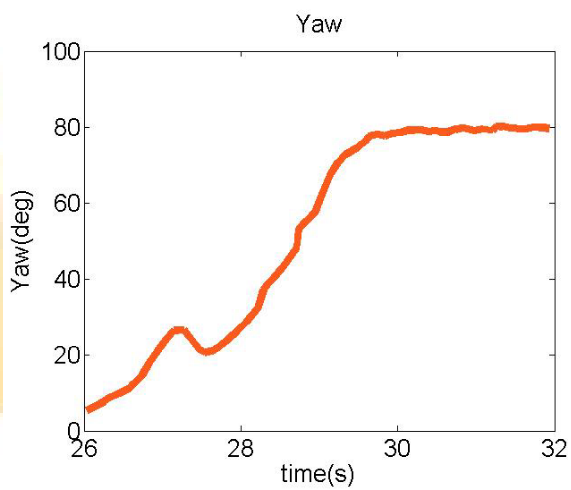
Comparison to Septentrio: Dynamic

Pitch:



Roll:



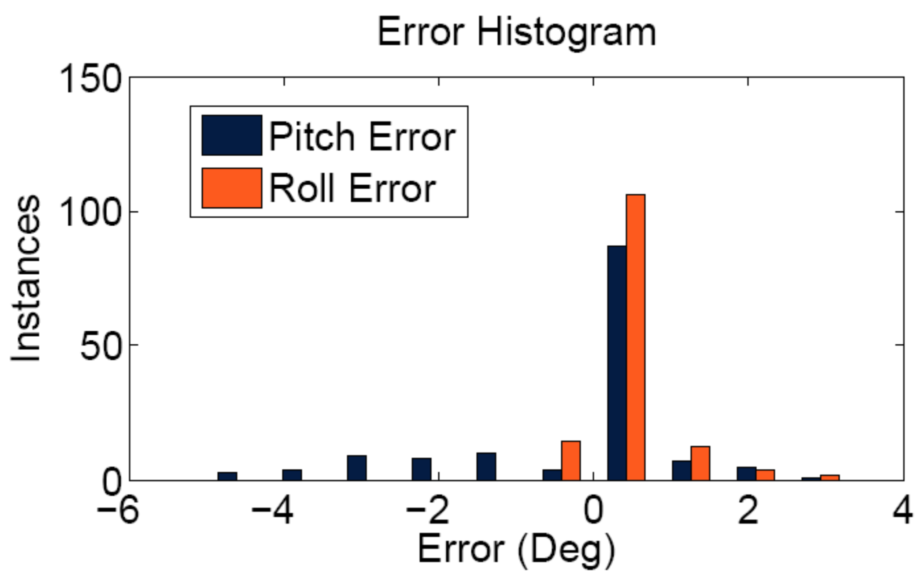


Results Vehicle: Dynamic

- 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

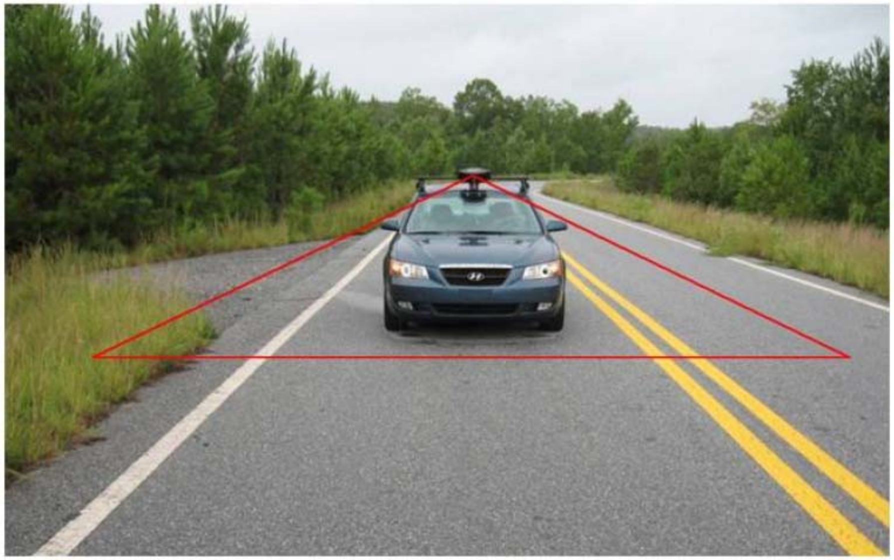


Results – Considerations

- 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

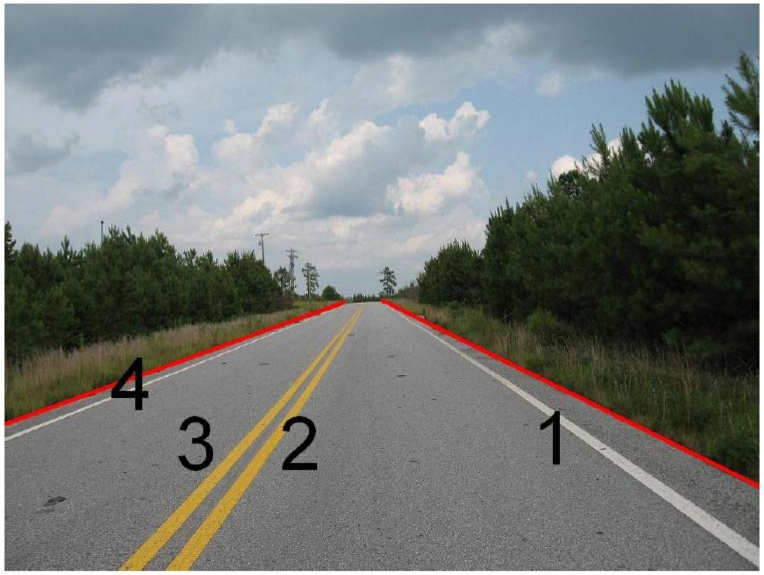
Detection Overview

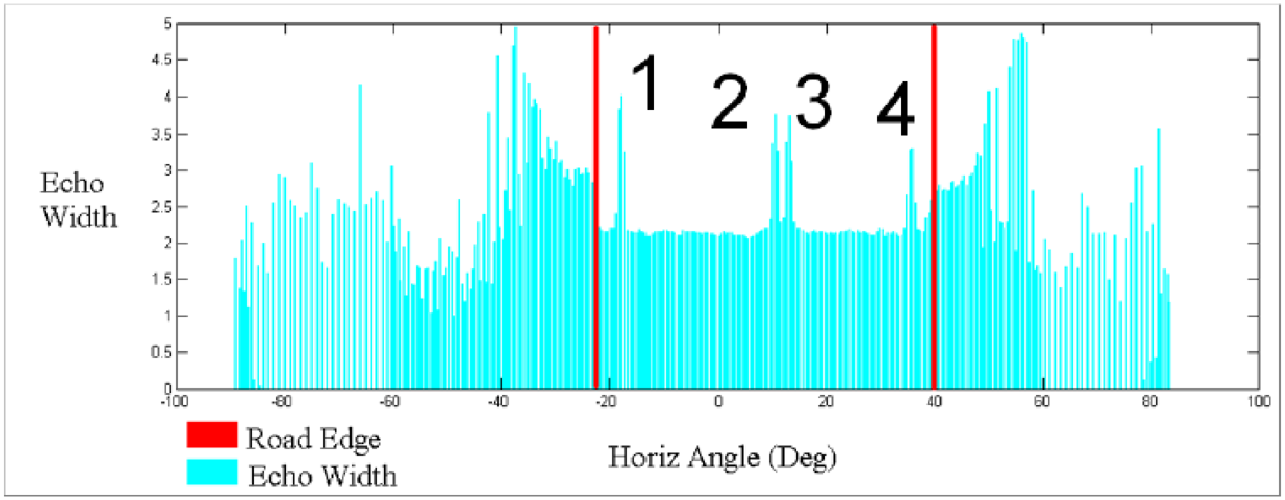
- Bound the Search Area
- Generate an ideal scan to match actual lane markings
- Find the MMSE between the ideal scan and an actual scan
- Window the data
- Filter the data



LiDAR Data Overview

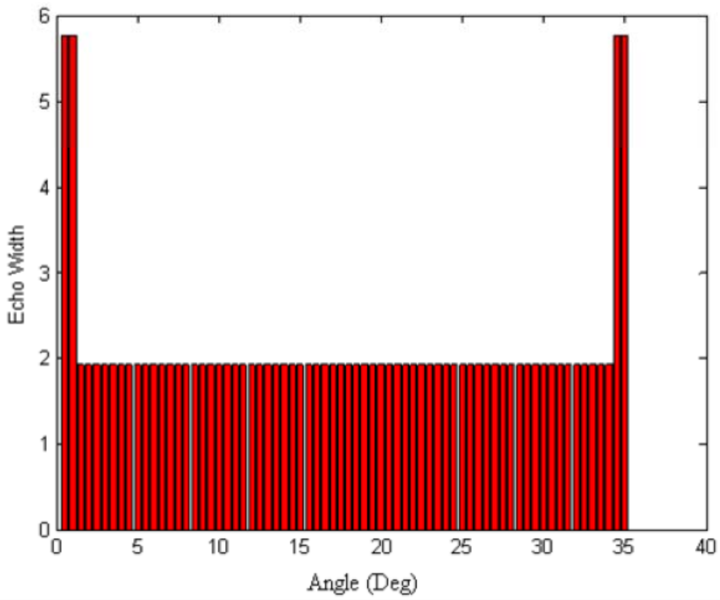
- Ideal scan has distinct peaks, and consistent road surface
- Data to side of road noisy, but resembles lane markings

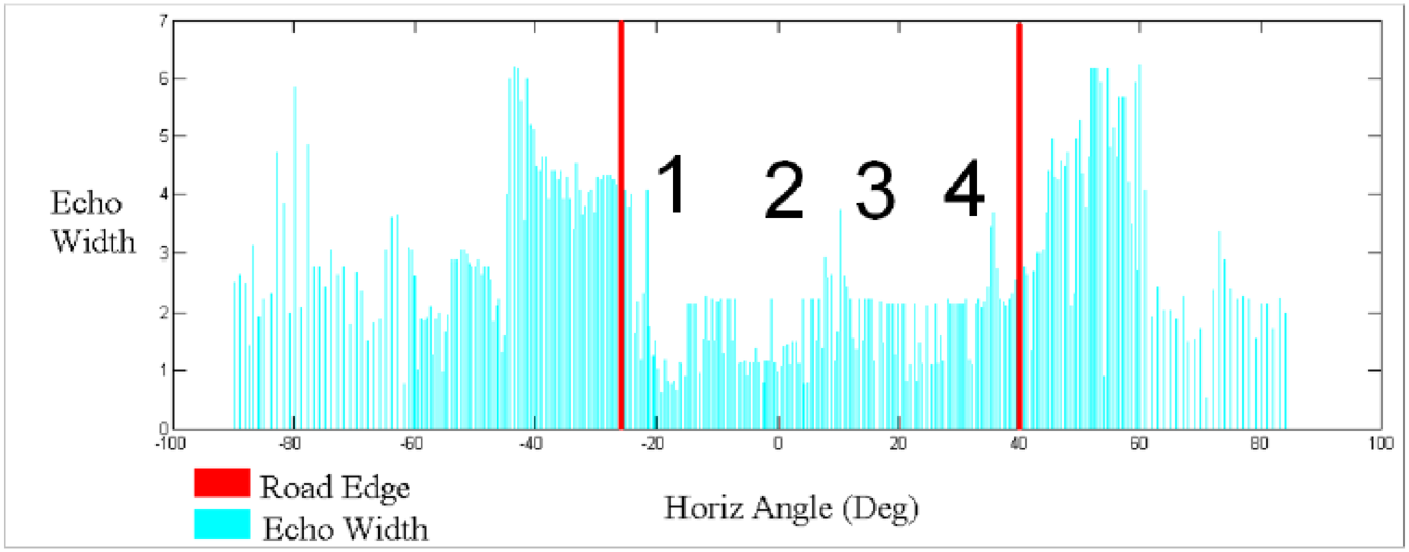




Creating an Ideal Scan

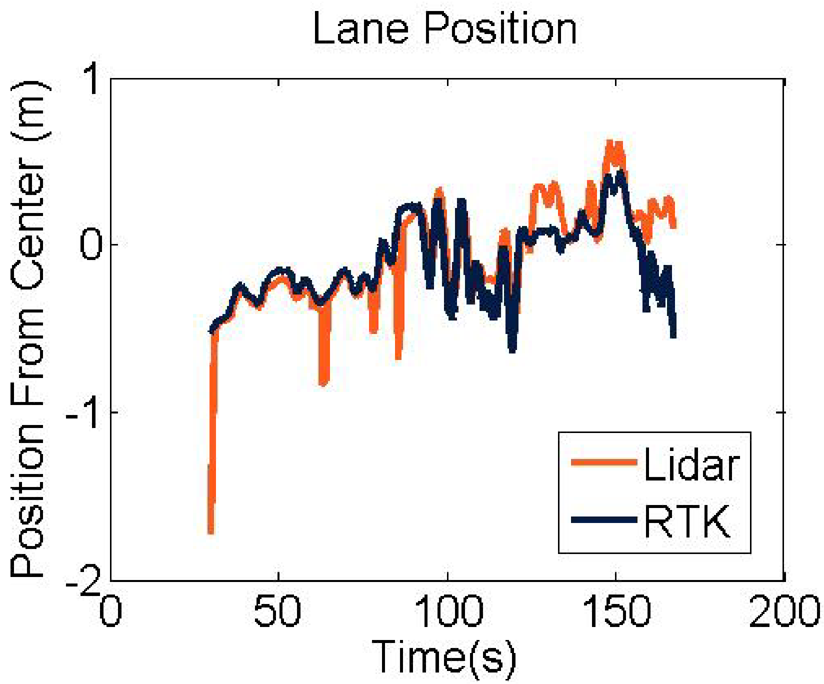
- Spikes represent the increase in reflectivity of the lane markings
- Flat area represents road's surface
- Window found lanes





NCAT Testing

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



	Avg. Lane Width Error (m)	Std of Error (m)	Detection (%)
Highway	0.075	0.233	94.7
Yellow & White	0.042	0.272	81.7
Gravel on Surface	0.129	0.215	97.4
Grass Bordering	0.169	0.329	76.86

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

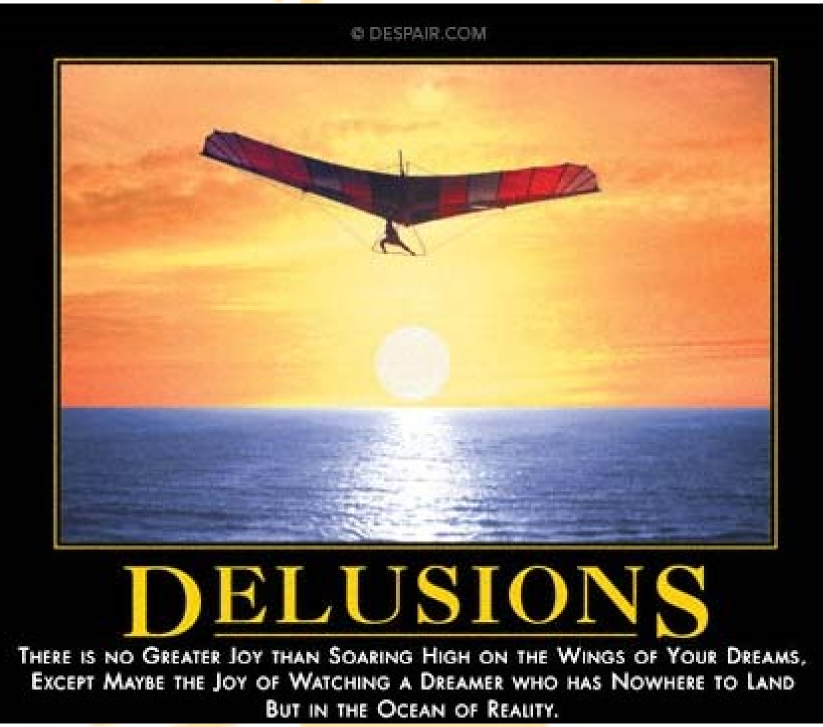
Conclusions - Calibration

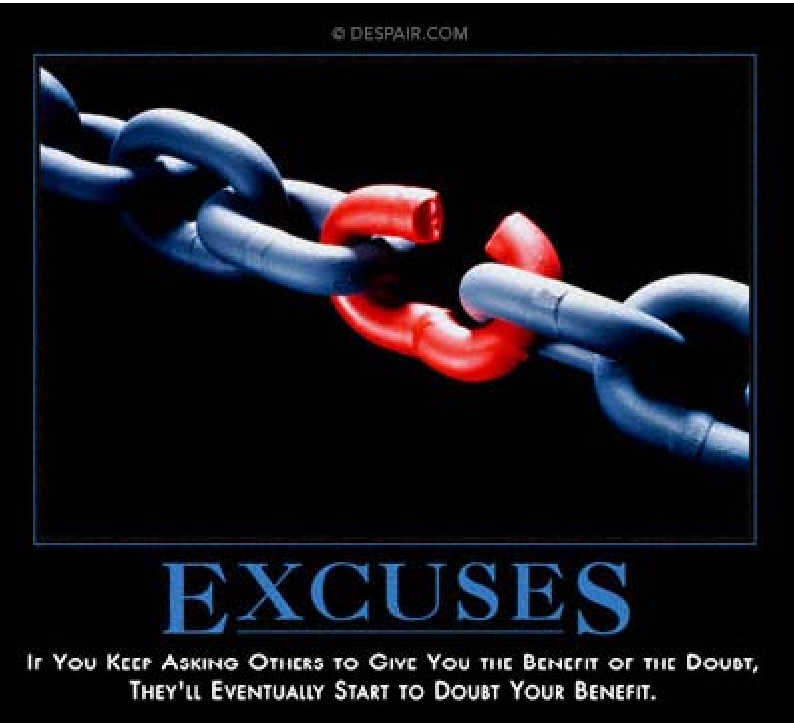
- Capable of determining vehicle pitch and roll to within sub-degree accuracy
- For meaningful calibration : vehicle's axes must be aligned with plane
- Highly non-linear problem
- Computationally complex
- Larger change in pitch dynamics the better for calibration

Future Work

- Determine how non uniform plane can be to yield accurate results

Questions or Comments?





Images Courtesy of Despair.com