Sensor Fusion for Navigation in Degraded Environments

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GPS and Vehicle Dynamics Lab
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Control of Vehicles

• Need to know vehicle:
  – Position (lane level), Velocity, Direction of travel, Orientation
• Above measurements can be made using GPS to:
  – Improve vehicle state estimation for Electronic Stability Control (ESC)
  – Provide lane keeping control technologies
  – Create other driver assistance systems
• Issues associated with positioning for vehicle safety systems:
  – Integrity and Security (when communicating and sharing data)
  – Reliability and Robustness (due in part to ubiquitous nature)
• Integration with other sensors
  – Used to overcome some of the limitations
  – Increase flexibility through software defined radios
    • Bring in new sensor measurements easily
      – including wireless signals (signals of opportunity)
    • Fully reprogrammable
    • Allows any integration scheme
      – Loosely, tightly, ultra-tight/deep integration
    • FPGA -> ASIC
Vehicle Control Using of GPS
UNIFIED GPS/INS KALMAN FILTER BASED STATE ESTIMATION
Loosely Coupled Algorithm

\[ [\dot{V}, \dot{\Psi}] \]

INS

\[ [\dot{V}, \dot{\Psi}] \]

GPS

\[ \dot{V} \]

\[ \delta V \]

\[ \dot{V} \]

\[ \delta V \]

Error State EKF

+\[ \delta V, \delta \Psi \]

Doesn’t currently exist because of lack of communication between various suppliers
What to Expect (from Literature)

• Loosely Coupled filter is not fully observable during steady driving.
  – P,V observable \((V \text{ in the NED frame, not } XYZ)\)
  – Combination of biases and attitudes observable
  – Biases and attitudes are not independently observable \((\text{can’t separate})\)
    • Exception: the vertical accelerometer bias is always observable.

• Acceleration changes make the filter observable.

• Constant axial acceleration or steady turning improves the observability, but not fully.

• These conclusions also apply to the AUNAV estimator!
Sideslip Definitions

\[ \nu = \beta + \psi \]

\[ \beta = \tan^{-1} \frac{V_y}{V_x} \]

\( \beta = \text{Sideslip} \)

\( \nu = \text{Course} \)

\( \psi = \text{Heading} \)
Loosely Coupled Integration

• Components:
  • INS (6DOF)
  • GPS (single antenna)
  • EKF

• EKF states (15):
  • INS solution errors (9)
  • INS sensor biases (6)

\[
\delta \hat{X} = \begin{bmatrix}
\delta \hat{r}, & \delta \hat{V}, & \delta \hat{\psi}, & \delta \hat{f}, & \delta \hat{\omega}
\end{bmatrix}^	op
\]

\[
\beta = \arctan \left( \frac{\hat{V}_{east}}{\hat{V}_{north}} \right) - \hat{\psi}_{yaw}
\]

- \( \hat{r} \) – position
- \( \hat{V} \) – velocity
- \( \hat{\psi} \) – attitude
- \( \delta \hat{f} \) – accelerometer biases
- \( \delta \hat{\omega} \) – gyroscope biases
Automotive Navigation Estimator

- Pitch rate gyroscope is removed.
- Yaw constraint added during periods of straight driving
  - GPS course measurement used as a yaw measurement.
- If yaw rate signal is less than some threshold for some time period, then the constraint is added.
  - Threshold, time window are tuning parameters of the overall estimator.

\[
Y = \begin{bmatrix}
\hat{r} \\
\hat{V} \\
\hat{\psi}_{yaw}
\end{bmatrix} - \begin{bmatrix}
\hat{r} \\
\hat{V} \\
\hat{\psi}_{yaw}
\end{bmatrix}_{GPS}
\]
Lane Change Experiment
Lane Change Results

- Sideslip
- Roll

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Low Rates of Sideslip Buildup

• Slow sideslip buildup is generally difficult to estimate
  – Low signal to noise ratio.
  – Lateral accelerometer bias
  – Lateral acceleration vs. roll

Video courtesy of
Low Rates of Sideslip Buildup

- The AUNAV estimator is able to accurately estimate the sideslip for the duration of the simulation.
- The estimate does begin to drift slowly once the dynamics settle out.

Simulation Slip Rate

Simulation Performance
(Sideslip and Sideslip Error)
Results: Dynamic

• NCAT skid pad

• Maneuver:
  – Straight
  – Turn uphill
  – Straight
  – Aggressive turn
  – Straight
  – Turn downhill
Low Rates of Sideslip Buildup

- Average rate of sideslip for third turn of the dynamic experiment is 1.8 deg/s.
- AUNAV estimator is able to accurately estimate the sideslip during this time.
- Conclusion: The AUNAV estimator can estimate sideslip at rates as low as ≈ 1.8 deg/s.

Experimental Performance
Integrating GPS with other on-board vehicle sensors

VEHICLE LANE POSITIONING
Need for Lane Level Positioning

• Vehicle lane departure – major cause of highway fatalities
  – 42,000 roadway fatalities in 2004
  – 50% resulting from vehicle lane departure

• ITS Research
  – LDW- Lane Departure Warning
    • Send warning to driver if lane is being approached
    • Helps to prevent un-intended lane departure
  – ADAS – Advanced Driver Assistance Systems
    • Keep vehicle in the intended lane
    • Help prevent intersection accidents

http://safety.fhwa.dot.gov
LiDAR and Vision based Lane Detection
Collaborative/Assisted GPS

- Some scenarios provide poor GPS position
- Augment navigation with ranges to known positions
- Share GPS information for improved tracking and TTFF
- Provides more seamless operation
- Combine measurements
  - Visual odometry
  - Road signature
  - Map databases

DSRC -> Dedicated Short Range Communication
  - WiFi like signal (802.11p, 5.9 GHz)
  - Developed for V2V and V2I Communications
The goal of this project is to design a system that can track lateral lane position on a highway.
A Kalman Filter is used to blend measurements from an IMU and 3 other sensors.
- Kalman Filter updates when a GPS, camera, or LiDAR measurement is received
- GPS measurements must be rotated into road frame

3 types of measurement updates to KF
- GPS/Map
- Camera
- (Light Detection and Ranging) LiDAR

Include other available inputs
- DSRC Ranges
- Road Signature
- Visual Odometry
- Vehicle Constraints
Lane Detection and Lateral Distance Estimation

Lateral Distance Estimation
- Sensor fusion with camera and LiDAR for robustness of lateral distance measurement
- Used for lane level localization in multipath environments

Lane Detection Sensors
- Logitech QuickCam Pro 9000
- IBEO ALASCA XT laser scanner
- Both sensors have a update rate of 10Hz
Lidar Lane Detection

- Bound Scan Data
- Find minimum RMS error
- Check for false positive
- Filter data and weighted averaging
- Final Position

<table>
<thead>
<tr>
<th></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>
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<tr>
<td>Grass Bordering</td>
<td>0.169</td>
<td>0.329</td>
<td>76.86</td>
</tr>
</tbody>
</table>

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Vision / INS

- Commercial lane departure warning systems use camera vision to detect lane markings
- Various problems can hinder lane detection
  - Environment (lighting conditions, weather, population density)
  - Eroded lane marking lines or objects on the road
- Integration of other sensors can provide lateral distance in the road when camera vision fails
Lane Detection with Camera

- Thresholding / Edge Detection
- Hough Transform
- Least Squares Interpolation
  - Interpolate 2\textsuperscript{nd} order polynomial as model for lane
- Kalman filter
  - Estimate polynomial coefficients
- Polynomial Bounds
  - Lines for subsequent frames lie within polynomial boundary curves

<10 cm accuracy on straight roads
GPS / Camera / LiDAR / INS

Plot of NCAT Test Track in North-East Frame of Reference

- middle lane markings
- lane
- outside lane markings
- RTK corrected GPS solution
- stand-alone GPS measurement
- GPS, LiDAR, and IMU solution
Positioning w/ Limited GPS Satellites

Urban Environment where only a few GPS Satellites may be available

Validated at Auburn’s NCAT Test Track using:
• Lateral Constraint
• Vertical Constraint
• 2 GPS Satellites
Positioning Results

Plot of NCAT Test Track in North, East Frame of Reference

- middle lane markings
- lane
- outside lane markings
- 2 Observations
- Full Constellation
Estimated Lateral Error with Limited GPS Observations

- Plots show Estimated Lane Position without vision (left) and with vision (right) for several different satellite failure cases
- All Satellites except ones listed in legend are turned off 30 seconds into the run and turned back on after 1 min
- Without vision, the lane position estimate is not only biased but also drifts when less than 4 GPS observations are available
- With vision, the lane position estimate is unaffected by the number of GPS observations available
Estimated Longitudinal Error with Limited GPS Observations

- Plots show estimated longitudinal lane error without vision (left) and with vision (right) for several different satellite failure cases
  - Longitudinal lane error is error in the axis parallel with the direction of travel (perpendicular to the lane position axis)
  - Error is based on RTK GPS Solution
- All Satellites excepts ones listed in legend are turned off 30 seconds into the run and turned back on after 1 min
- Without vision, the longitudinal lane error continuously grows when less than 4 GPS observation are available
- With vision, the longitudinal lane error growth is contained as long as 2 GPS observations are available
- Also with vision, there is no noticeable improvement using 1 GPS observation over having no GPS
Lane Positioning Results - Full System

Estimated Lane Position

- Truth (RTK GPS)
- Full System
- Lidar Measurement
- Camera Measurement

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