Estimating Vehicle Kinematics Using Onboard IMU and Wheel Speed Sensors

Investigation of Actuator and Measurement Delay

Ross Alexander
Rushil Goradia
Trey Weber

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Problem Description

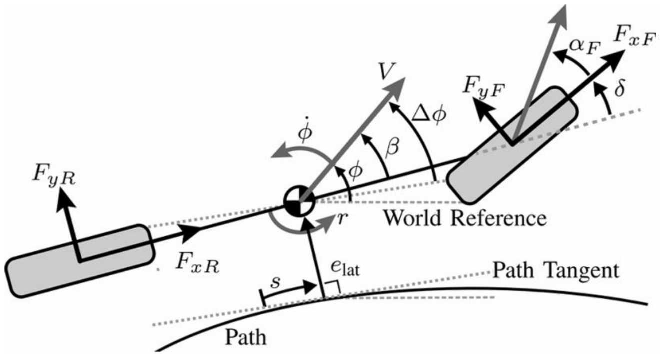
Design an efficient filter architecture for a vehicle that can estimate vehicle states using only an IMU and wheel speed sensors subject to actuator and measurement delays

- Rapid deployment of autonomous vehicles to public roads has made safety essential
- Accurate state estimates are required for safe and effective path-following control
- Market for autonomous vehicles may not support use of expensive, high-precision sensors using GPS, GNSS
- Cheaper sensors like IMUs and wheel speed sensors can be used, but these signals must be filtered effectively in order to construct a suitable state estimate

Dynamics Model

Dynamics model

- Dynamics follow a dynamic bicycle model
- State vector is body-frame longitudinal velocity, lateral velocity, and yaw rate
- Control vector is steering angle and front and rear longitudinal tire forces*



$$\mathbf{x} = [U_x, U_y, r]^\top \qquad \mathbf{u} = [\delta, F_{xf}, F_{xr}]^\top$$

Path tracking

- The dynamic state vector and dynamics model can be augmented with a path state vector and path dynamics for path-tracking

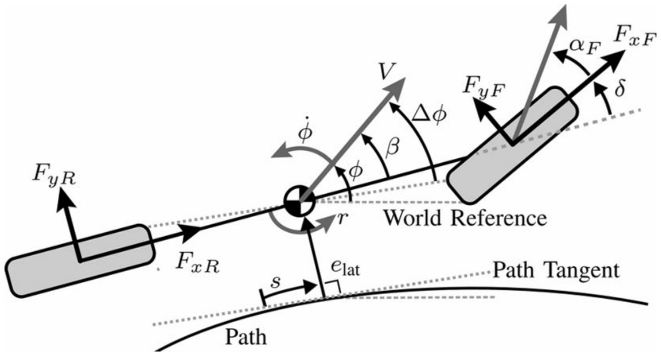
$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u})$$

$$\begin{bmatrix} \dot{U}_x \\ \dot{U}_y \\ \dot{r} \end{bmatrix} = \begin{bmatrix} \frac{1}{m}(F_{xf}\cos\delta - F_{yf}\sin\delta + F_{xr}) + rU_y \\ \frac{1}{m}(F_{xf}\sin\delta + F_{yf}\cos\delta + F_{yr}) - rU_x \\ \frac{1}{I_z}(aF_{xf}\sin\delta + aF_{yf}\cos\delta - bF_{yr}) \end{bmatrix}$$

Measurement Model

Measurement model

- Measurement vector is rear wheel angular velocity and body yaw rate
- Sensors are rear wheel speed sensor and an inertial measurement unit (IMU)
- Assumes that wheel speed is equal to longitudinal velocity*



Path tracking

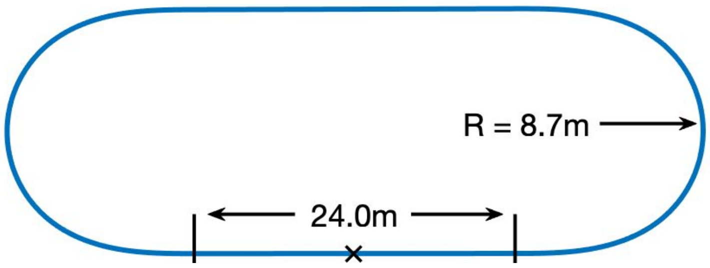
- Path state cannot be directly measured - it must be measured indirectly through dynamic states

$$\mathbf{y} = \begin{bmatrix} \omega_{wheel} \\ \omega_{z,GYRO} \end{bmatrix} = \begin{bmatrix} \frac{1}{r_{wheel}} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} U_x \\ U_y \\ r \end{bmatrix}$$

Experiments

Experiment setup

- Accelerate around an oval-shaped track with specified speed profile using realistic vehicle parameters and noise distributions
- Estimate dynamics state and path state using EKF, iEKF, UKF, and PF with and without actuator and measurement delay



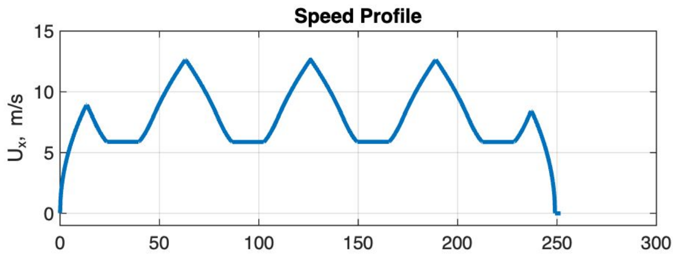
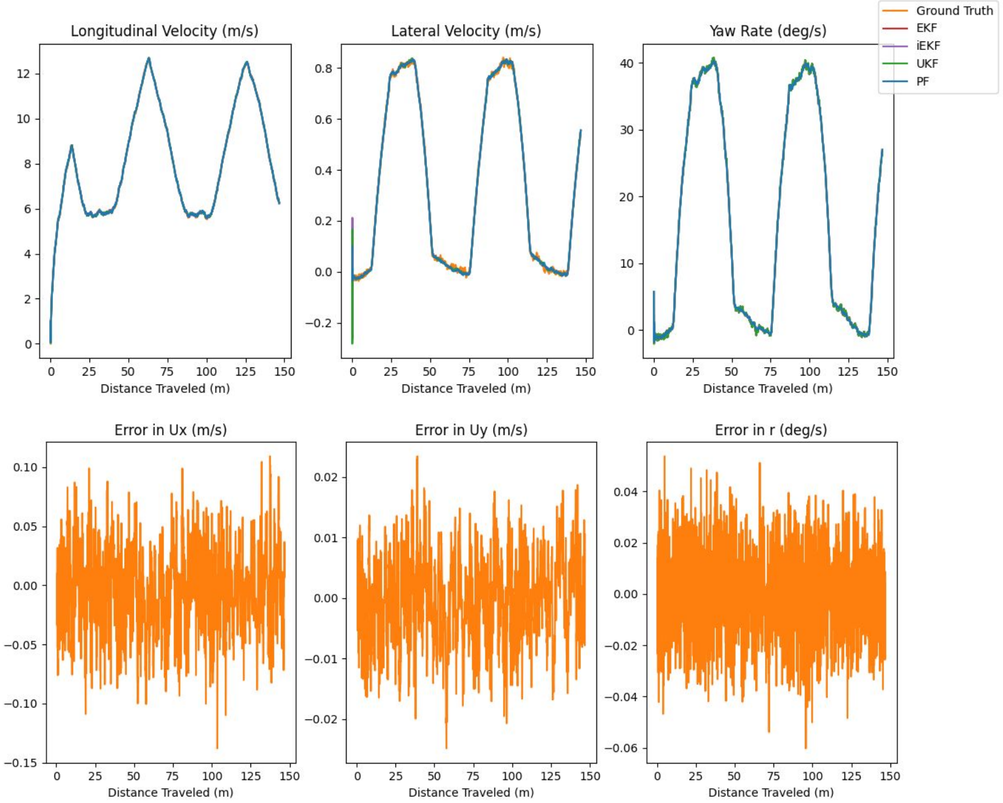


Image credit: ME 227

Results | Simulated Case

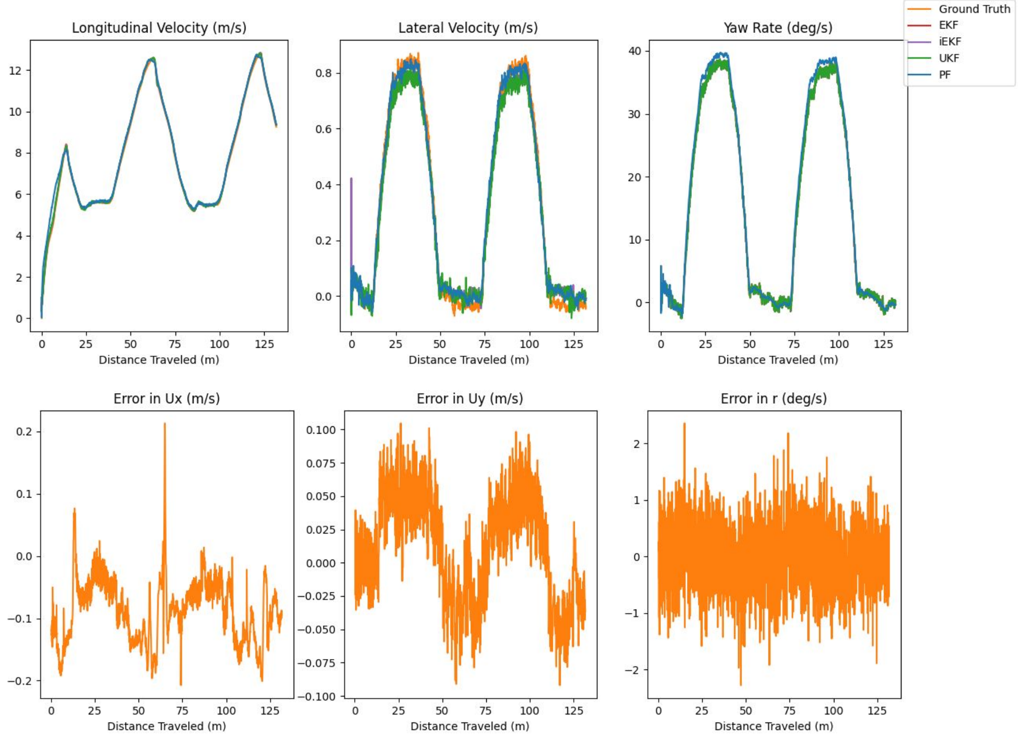
State trajectories are simulated and control inputs are specified through low-level feedforward and feedback controllers for steering angle and throttle/braking

Simulator has dynamic weight transfer, nonlinear tire force model, and actuator delay



Results | Real-World Case

State trajectories are estimated from SOTA navigation box (OxTS-RT3000, used as ground truth) and control inputs are recorded from onboard controller

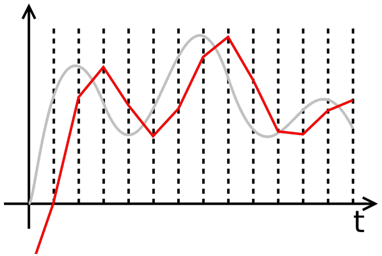


Data credit: ME 227

Future Directions

Model adjustments

- Variable/learned actuator delay
- Incorporation of measurement delay
- Use of measured forces/SWA instead of commanded (IMU)



Code adjustments

- Rewrite in CPP
- Optimize performance (reduce matrix inversions)
- Clean up and make open-source