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Tire Force Estimation for a Passenger Vehicle with the Unscented Kalman Filter

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Abstract

Contribution: The contribution of this paper is a robust method for estimating longitudinal and lateral per-axle tire forces with the Unscented Kalman Filter (UKF) and requires no a-priori knowledge of tire and road properties.
Application: The UKF is used for estimation of vehicle tire forces. A bicycle model with a stochastic tire force model and several sensor signals form appropriate estimator inputs and outputs.
Results: We present estimates for the vehicle longitudinal and lateral per-axle tire forces during a double lane change with braking. The robustness of the proposed UKF estimator is evaluated by introducing disturbances such as sudden changes in tire-road friction.
Discussion: The UKF shows a good accuracy for estimating tire forces during a combined slip maneuver. The estimator is robust against changes in tire-road friction although no tire or road properties are included in the estimator model.

1. Motivation

- Vehicle motion is primarily affected by friction forces transmitted from the road through the tire footprints. Many vehicle control systems (e.g. ABS) rely on the knowledge of tire forces.
- Tire forces depend on several variables such as slip ratios, normal loads and tire-road friction. When using physical or empirical tire force models all of these influences must be known in advance which requires extensive testing and calibrating.
- As a consequence, a practical solution is necessary which does not rely on prior knowledge of road and tire properties and uses cost-effective sensors.

2. Estimation Process Overview

- The inputs to the model are steering wheel angle δ_{sw}, engine torque T_{eng} and braking pressures of the brake cylinders at the front $p_{\text{br,f}}$ and rear $p_{\text{br,r}}$.
- The virtual measurements are longitudinal velocity v_x, longitudinal acceleration a_x, lateral acceleration a_y, yaw rate $\dot{\psi}$ and angular wheel velocities w_f at the front and at the rear w_r.
- A prediction is made based on the dynamic model equations implemented in the filter (bicycle model and random walk tire force model). This prediction is then corrected by the innovation available through the virtual measurements.
- The outputs are state estimates: longitudinal and lateral velocities v_x and v_y, yaw rate $\dot{\psi}$, angular wheel velocities w_f and w_r and longitudinal tire forces at the front and rear axle F_{xf}, F_{xr} and the lateral per-axle forces F_{yf}, F_{yr}.

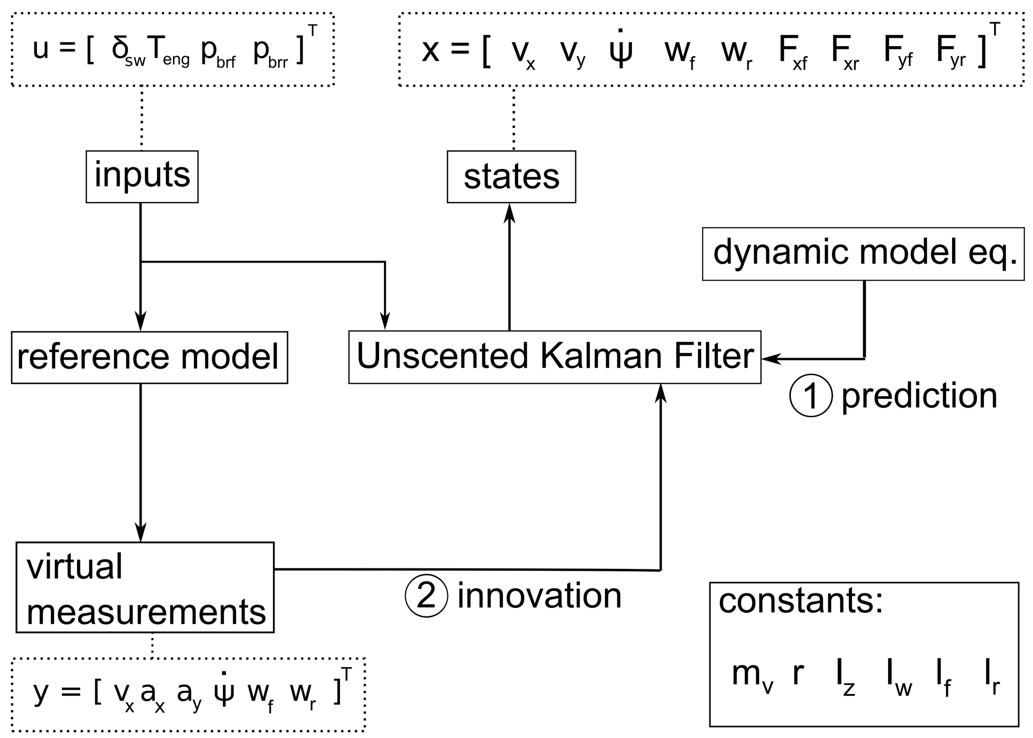

Figure 1: *Estimation process block diagram - Inputs, Virtual Measurements and Outputs*

3. UKF-Estimator Model

- A bicycle model was implemented in the estimator which considers longitudinal (x), lateral (y) and yaw (ψ) motion neglecting roll while traveling on a smooth road. The wheels at the front and rear are lumped together, respectively. Only the front wheel is steerable. Climbing resistance and aerodynamic drag were neglected.

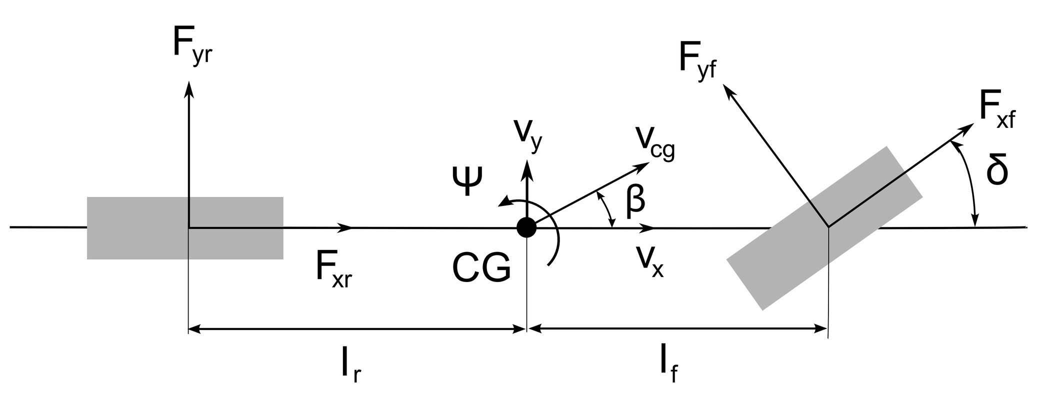

Figure 2: *Bicycle model with parameters and states*

- The dynamic equations are shown in a discrete state-space form:

$$x_{t+1} = x_t + \mathcal{F}(x_t, u_t) \cdot \Delta t + v_t, \qquad y_{t+1} = \mathcal{H}(x_{t+1}) + n_{t+1} \tag{1}$$

where x_{t+1} is the state at time $t+1$, y_{t+1} is the measurement at time $t+1$, u_t is the input at time t, v_t is the process noise with covariance Q and n_{t+1} is the measurement noise with covariance R and Δt is the timestep.

- The state, measurement and input vector are defined as follows:

$$x_t = \begin{bmatrix} v_x & v_y & \dot{\psi} & w_f & w_r & F_{xf} & F_{xr} & F_{yf} & F_{yr} \end{bmatrix}^\top \tag{2}$$

$$y_t = \begin{bmatrix} v_x & a_x & a_y & \dot{\psi} & w_f & w_r \end{bmatrix}^\top, \quad u_t = \begin{bmatrix} \delta_{\text{sw}} & T_{\text{eng}} & p_{\text{br,f}} & p_{\text{br,r}} \end{bmatrix}^\top \tag{3}$$

- The dynamics of the state variables are derived in the following to construct the state-space representation of the process model $\mathcal{F}(x_t, u_t)$:

$$f_{1,t} = \frac{1}{m_v}[F_{xf,t}\cos(\delta_{f,t}) - F_{yf,t}\sin(\delta_{f,t}) + F_{xr,t}] + \dot{\psi}_t v_{y,t} \tag{4a}$$

$$f_{2,t} = \frac{1}{m_v}[F_{yf,t}\cos(\delta_{f,t}) + F_{xf,t}\sin(\delta_{f,t}) + F_{yr,t}] - \dot{\psi}_t v_{x,t} \tag{4b}$$

$$f_{3,t} = \frac{1}{I_z}[l_f(F_{xf,t}\sin(\delta_{f,t}) + F_{yf,t}\cos(\delta_{f,t})) - l_r F_{yr,t}] \tag{4c}$$

$$f_{4,t} = \frac{1}{I_w}[T_{\text{axle,acc,f,t}} - T_{\text{axle,br,f,t}} - rF_{xf,t}], \quad f_{5,t} = \frac{1}{I_w}[T_{\text{axle,acc,r,t}} - T_{\text{axle,br,r,t}} - rF_{xr,t}] \tag{4d}$$

$$f_{6,t} = 0, \quad f_{7,t} = 0, \quad f_{8,t} = 0, \quad f_{9,t} = 0 \tag{4e}$$

where $T_{\text{axle,acc,f,t}}$, $T_{\text{axle,acc,r,t}}$, $T_{\text{axle,br,f,t}}$, $T_{\text{axle,br,r,t}}$ are accelerating and braking torques at the axles. Please note that the random walk model is characterized by Equation 4e.

4. Results

- Figure 3 shows the estimation of tire forces and other states during a double lane change maneuver with strong braking.

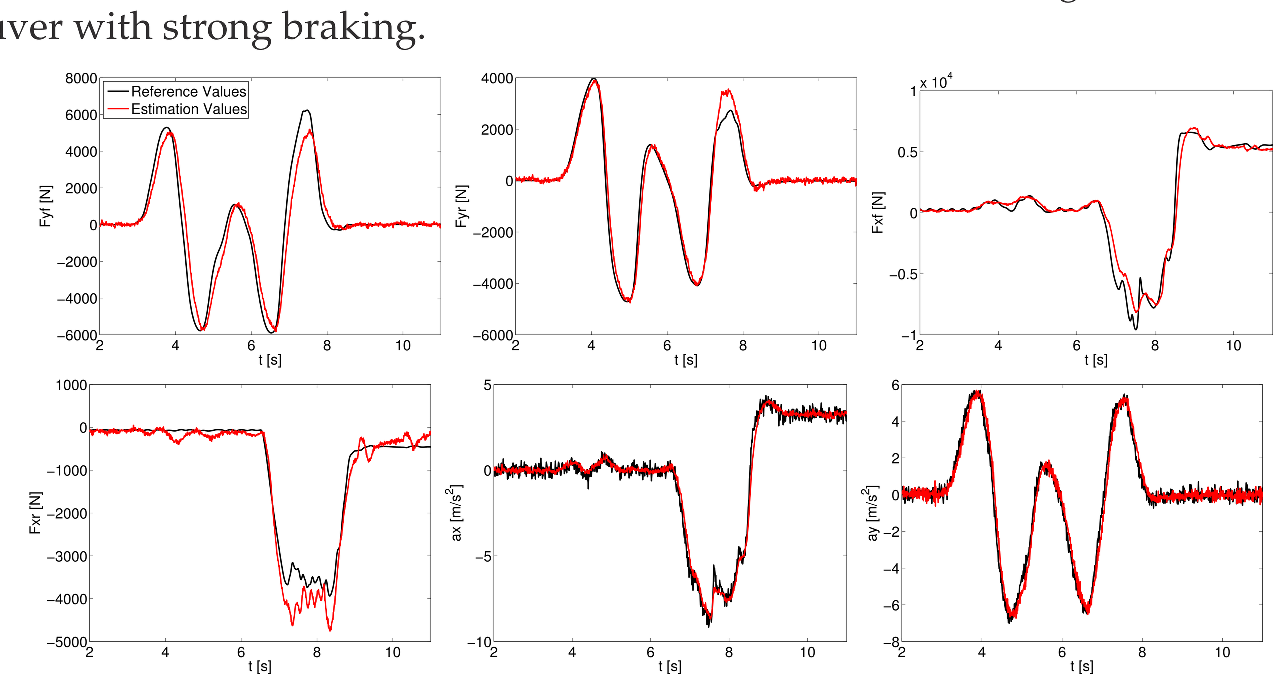

Figure 3: *Lateral tire forces F_{yf}, F_{yr}, longitudinal tire forces F_{xf}, F_{xr} and acceleration signals a_x, a_y over time t*

- Figure 4 shows the estimation of tire forces during the same maneuver but with sudden changes in tire-road friction.

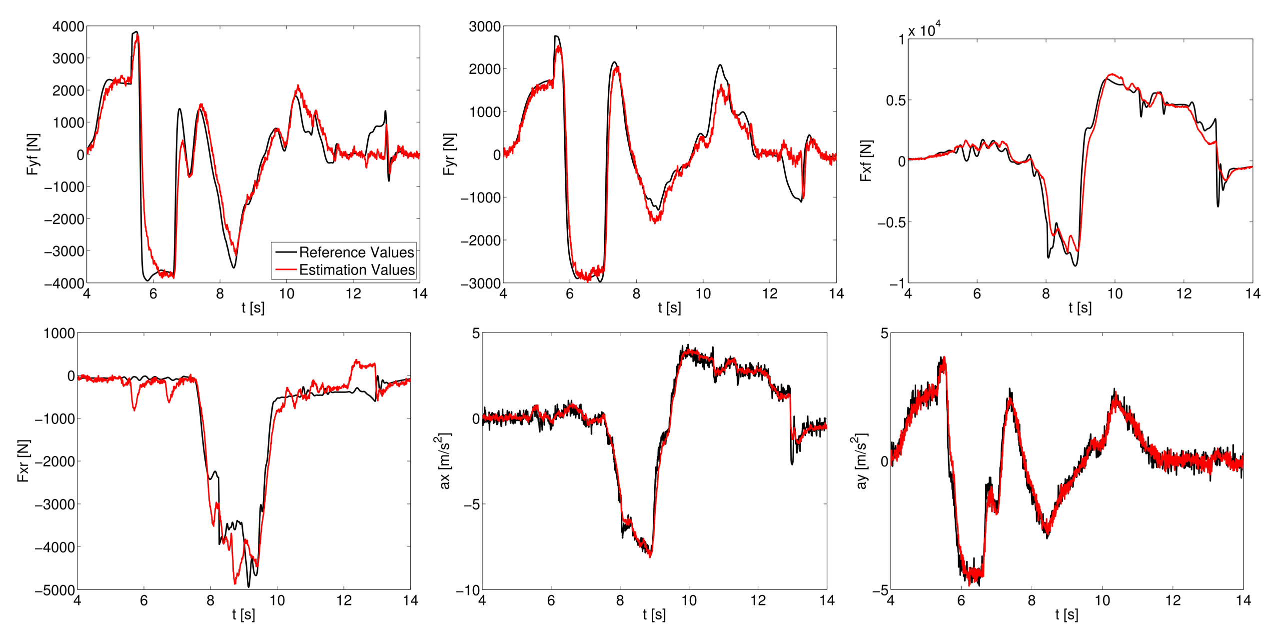

Figure 4: *Lateral tire forces F_{yf}, F_{yr}, longitudinal tire forces F_{xf}, F_{xr} and acceleration signals a_x, a_y over time t for changes in tire-road friction*

5. Conclusions

- The presented UKF estimator tracks tire forces with good accuracy for a combined slip maneuver.
- The estimator is robust against changes in tire-road friction although no tire or road parameters are included in the estimator model.
- Real-time implementation in a test vehicle is necessary in future works to prove the applicability of the UKF.

References

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