Estimation of Tire-Ground Interaction Forces in a 4-Wheel Vehicle under All-terrain Conditions

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Summary

Summary

Introduction

Intelligent Vehicles

- Two typical researches:
  1. Advanced Driver Assistance Systems (ADAS)
     - Indirect: Pedestrian Warnings
     - Direct: Anti-lock Breaking System (ABS)
  2. Autonomous Vehicles (AVs)
     - No human-driver direct actions
- Sensors are a main key!
  - Precision
  - Price

Heudiasyc Internship – BEPE

Objective

Estimate tire-ground interaction forces in all directions at off road conditions

- Main goals
  - Estimate vertical, lateral and longitudinal tire forces
  - Estimate tire forces under irregular ground profiles
- Previous Heudiasyc estimator
  - Estimator presented in [Jiang *et al.*, 2014]
  - Vertical and lateral tire forces estimators
  - Planar grounds with slopes
  - Random walk models

VERO vs DYNA

VERO – CTI

- Autonomous platform
- Electrical propulsion
- Full-sensored (GPS, IMU, lasers)
- Objective: off-road autonomous vehicle

DYNA – Heudiasyc

- Ordinary passengers car
- Combustion propulsion
- Usually vehicle's sensors + suspension displacement
- Tire-ground forces transducers (validation)
- Objective: ADAS development

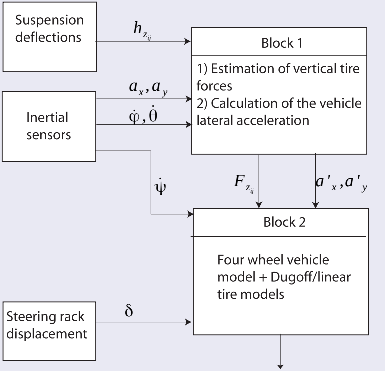
Inputs/Sensors

- 3-Axis accelerations/Integrated IMU
- 3-Axis angular speed/Integrated IMU
- Extremities vertical displacement/Lasers
- Longitudinal speed/Vehicle's odometry
- Wheel spin speed/Encoder

Summary

Heudiasyc Estimator

Characteristics



- Vertical and lateral force estimators
- Cascade-observers structure
- Based on 2D models
- Equivalent torsional suspensions
- Random-walk models

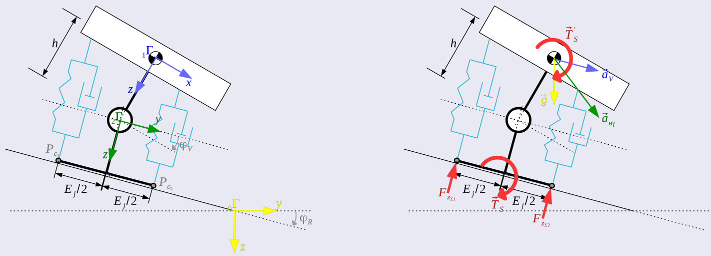
Heudiasyc Estimator

Vertical Model

- Based on two 2D models
  - 2D roll dynamic model
  - 2D pitch dynamic model

Heudiasyc Estimator

Vertical Model → Roll dynamics

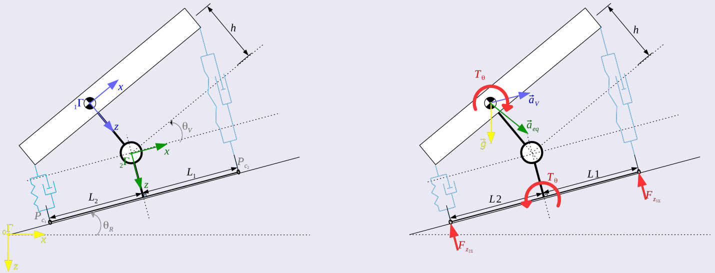


Dynamics Equations

- $J_{xx}\ddot{\phi}_v = -K_r\phi_v - C_r\dot{\phi}_v + mha_{v_y}$
- $E_1/2(F_{z_{12}} - F_{z_{11}}) = \left(-K_r\phi_v - C_r\dot{\phi}_v\right)\dfrac{F_{z_{11}} + F_{z_{12}}}{\sum F_z}$
- $ma_{z_{eq}} = (F_{z_{11}} + F_{z_{21}}) + (F_{z_{12}} + F_{z_{22}})$
- $E_2/2(F_{z_{22}} - F_{z_{21}}) = \left(-K_r\phi_v - C_r\dot{\phi}_v\right)\dfrac{F_{z_{21}} + F_{z_{22}}}{\sum F_z}$

Heudiasyc Estimator

Vertical Model → Pitch dynamics



Dynamics Equations

- $J_{yy}\ddot{\theta}_v = -K_p\theta_v - C_p\dot{\theta}_v + mha_{v_x}$
- $ma_{z_{eq}} = (F_{z_{11}} + F_{z_{21}}) + (F_{z_{12}} + F_{z_{22}})$
- $-L_1(F_{z_{11}} + F_{z_{12}}) + L_2(F_{z_{21}} + F_{z_{22}}) = -K_p\theta_v - C_p\dot{\theta}_v$

Heudiasyc Estimator

Vertical Model → Vertical Forces

- Solving the system for vertical forces
  - $F_{z_{ij}} = -\frac{m(L-L_i)}{2L}a_{z_{eq}} + (-1)^j\frac{(L-L_i)}{E_iL}T_r - (-1)^i\frac{1}{2L}T_p + (-1)^{(i+j)}\frac{T_rT_p}{ma_zE_iL}$

    where $T_r = -K_r\phi - C_r\dot{\phi}$ e $T_p = -K_p\theta - C_p\dot{\theta}$.
- Time derivative (neglecting the coupling term)
  - $\dot{F}_{z_{ij}} = -\frac{m(L-L_i)}{2L}\dot{a}_{z_{eq}} + (-1)^j\frac{(L-L_i)}{E_iL}\dot{T}_r - (-1)^i\frac{1}{2L}\dot{T}_p$

    where $\dot{T}_r = -K_r\dot{\phi} - C_r/J_{xx}(T_r + mha_{v_y})$ e $\dot{T}_p = -K_p\dot{\theta} - C_p/J_{yy}(T_p + mha_{v_x})$.

Heudiasyc Estimator

Vertical Model → State-Space Linear model

$$
\dot{X} = \begin{cases}
\dot{x}_1 = \dot{\phi} \\
\dot{x}_2 = \ddot{\phi} = -\frac{K_r}{I_{xx}}\phi - \frac{C_r}{I_{xx}}\dot{\phi} - \frac{mh}{I_{xx}}a_y \\
\dot{x}_3 = \dot{\theta} \\
\dot{x}_4 = \ddot{\theta} = -\frac{K_p}{I_{yy}}\theta - \frac{C_p}{I_{yy}}\dot{\theta} - \frac{mh}{I_{yy}}a_x \\
\dot{x}_5 = \dot{F}_{z_{11}} = +\frac{L_2K_r}{LE_1}\dot{\phi} + \frac{L_2C_r}{LE_1}\ddot{\phi} - \frac{K_p}{2L}\dot{\theta} - \frac{C_p}{2L}\ddot{\theta} - \frac{L_2m}{2L}\dot{a}_z \\
\dot{x}_6 = \dot{F}_{z_{12}} = -\frac{L_2K_r}{LE_1}\dot{\phi} - \frac{L_2C_r}{LE_1}\ddot{\phi} - \frac{K_p}{2L}\dot{\theta} - \frac{C_p}{2L}\ddot{\theta} - \frac{L_2m}{2L}\dot{a}_z \\
\dot{x}_7 = \dot{F}_{z_{21}} = +\frac{L_1K_r}{LE_2}\dot{\phi} + \frac{L_1C_r}{LE_2}\ddot{\phi} + \frac{K_p}{2L}\dot{\theta} + \frac{C_p}{2L}\ddot{\theta} - \frac{L_1m}{2L}\dot{a}_z \\
\dot{x}_8 = \dot{F}_{z_{22}} = -\frac{L_1K_r}{LE_2}\dot{\phi} - \frac{L_1C_r}{LE_2}\ddot{\phi} + \frac{K_p}{2L}\dot{\theta} + \frac{C_p}{2L}\ddot{\theta} - \frac{L_1m}{2L}\dot{a}_z \\
\dot{x}_9 = \dot{a}_x \\
\dot{x}_{10} = \ddot{a}_x = 0 \\
\dot{x}_{11} = \dot{a}_y \\
\dot{x}_{12} = \ddot{a}_y = 0 \\
\dot{x}_{13} = \dot{a}_z \\
\dot{x}_{14} = \ddot{a}_z = 0
\end{cases}
$$

Heudiasyc Estimator

Vertical Model $\rightarrow$ Inputs/Outputs

- Inputs
  - None
- Outputs/Measures
  - Direct measured outputs: $a_{v_x}, a_{v_y}, a_{v_z}, \dot{\phi}, \dot{\theta}$
  - Pseudo-measured outputs: $\phi_v(h_{z_{ij}}), \theta_v(h_{z_{ij}}), a_{eq}(a_v, \phi_v, \theta_v)$, $F_{z_{ij}}\left(a_{eq_z}, \phi(h_{z_{ij}}), \dot{\phi}, \theta_v(h_{z_{ij}}), \dot{\theta}\right)$
    - $hz_{ij} \rightarrow$ Extremities vertical distance to ground
    - $\phi_v \approx \dfrac{h_{z_{11}} - h_{z_{12}} + h_{z_{21}} - h_{z_{22}}}{E_1 + E_2}$
    - $\theta_v \approx \dfrac{h_{z_{11}} - h_{z_{21}} + h_{z_{12}} - h_{z_{22}}}{2L}$
    - $a_{eq} = R_{\theta_v} R_{\phi_v} a_v$
      where R is a Rotation Matrix ($R^T = R^{-1}$)
    - $F_{z_{ij}} \approx -\dfrac{m(L - L_i)}{2L} a_z + (-1)^j \dfrac{(L - L_i)}{E_i L} T_r - (-1)^i \dfrac{1}{2L} T_p + (-1)^{(i+j)} \dfrac{T_r T_p}{m a_z E_i L}$

Heudiasyc Estimator

Lateral Model

- 2D yaw dynamic model
- Dugoff tire model
- First order dynamic model $\rightarrow$ Relaxation lengths
- Longitudinal forces dynamics are neglected
  - Motorized (front) wheels $\Rightarrow$ random walk model
  - Non-motorized (rear) wheels $\Rightarrow F_x = 0$
- Vertical forces as inputs (cascade observer)

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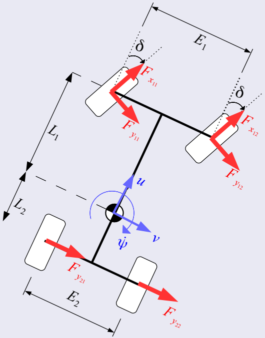
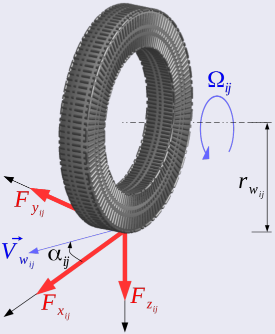
Lateral Model → Yaw Dynamics



- $m(a_x - v\dot{\psi}) =$
  $F_{x_{11}} \cos\delta - F_{y_{11}} \sin\delta + F_{x_{12}} \cos\delta - F_{y_{12}} \sin\delta$
- $m(a_y + u\dot{\psi}) =$
  $F_{y_{11}} \cos\delta + F_{x_{11}} \sin\delta + F_{y_{12}} \cos\delta + F_{x_{12}} \sin\delta + F_{y_{21}} + F_{y_{22}}$
- $J_{zz}\ddot{\psi} =$
  $L_1 \left(F_{y_{21}} \cos\delta + F_{x_{11}} \sin\delta + F_{y_{12}} \cos\delta + F_{x_{12}} \sin\delta\right) -$
  $L_2 \left(F_{y_{21}} + F_{y_{22}}\right) +$
  $\frac{E_1}{2} \left[\left(F_{x_{11}+F_{x_{12}}}\right) \cos\delta + \left(-F_{y_{11}} + F_{y_{12}}\right) \sin\delta\right]$

Heudiasyc Estimator

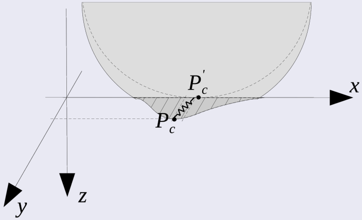
Lateral Model → Dugoff tire model



- $\alpha_{11} = \tan^{-1}\left(\dfrac{v + \dot{\psi}L_1}{u + \dot{\psi}E_1/2}\right) - \delta$
- $\alpha_{12} = \tan^{-1}\left(\dfrac{v + \dot{\psi}L_1}{u - \dot{\psi}E_1/2}\right) - \delta$
- $\alpha_{21} = \tan^{-1}\left(\dfrac{v - \dot{\psi}L_2}{u + \dot{\psi}E_2/2}\right)$
- $\alpha_{22} = \tan^{-1}\left(\dfrac{v - \dot{\psi}L_2}{u - \dot{\psi}E_2/2}\right)$
- $\chi_{ij} = \min\left\{1, \dfrac{\mu F_{z_{ij}}}{2C_{\alpha_{ij}}|\tan\alpha_{ij}|}\right\}$
- $\overline{F_{y_{ij}}} = -C_{\alpha_{ij}}\tan\alpha_{ij}\,(2 - \chi_{ij})\,\chi_{ij}$

Heudiasyc Estimator

Lateral Model $\rightarrow$ Lateral Force Dynamic



- Single-Contact-Point Transient Model [Pacejka, 2002]
- Constant lateral relaxation length: $\rho_{y_{ij}} = \dfrac{C_{\alpha_{ij}}}{C_{t_y}}$
- $\dot{F}_{y_{ij}} = \dfrac{u - (-1)^j \dot{\psi} E_i/2}{\rho_{y_{ij}}} \left(\overline{F_{y_{ij}}} - F_{y_{ij}}\right)$

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Lateral Model $\rightarrow$ Longitudinal Force approximation

- Considering front-wheel propulsion (Dyna):
  - $F_{x_{11}} = \frac{F_{z_{11}}}{F_{z_{11}} + F_{z_{12}}}(F_{x_{11}} + F_{x_{12}})$
  - $F_{x_{12}} = \frac{F_{z_{12}}}{F_{z_{11}} + F_{z_{12}}}(F_{x_{11}} + F_{x_{12}})$
  - $F_{x_{21}} = F_{x_{22}} = 0$
- Random walk model
  - $(F_{x_{11}} \dot{+} F_{x_{12}}) = w_F$ where w_F is a white noise.

Heudiasyc Estimator

Lateral Model → State-Space model

$$
\dot{X} = \begin{cases}
\dot{x}_1 &= \dot{u} = +v\dot{\psi} + \frac{1}{m}\Big((F_{x_{11}} + F_{x_{12}}) \cos\delta - F_{y_{11}} \sin\delta - F_{y_{12}} \sin\delta \Big) \\
\dot{x}_2 &= \dot{v} = -u\dot{\psi} + \frac{1}{m}\Big(F_{y_{11}} \cos\delta + F_{y_{12}} \cos\delta + (F_{x_{11}} + F_{x_{12}}) \sin\delta + F_{y_{21}} + F_{y_{22}} \Big) \\
\dot{x}_3 &= \dot{\phi} = \frac{1}{J_{zz}} \Bigg[L_1 \Big(F_{y_{11}} \cos\delta + F_{y_{12}} \cos\delta + (F_{x_{11}} + F_{x_{12}}) \sin\delta \Big) - L_2 \Big(F_{y_{21}} + F_{y_{22}} \Big) + \\
& \quad + \frac{E_1}{2} \Bigg(\frac{F_{z_{11}} - F_{z_{12}}}{F_{z_{11}} + F_{z_{12}}} (F_{x_{11}} + F_{x_{12}}) \cos\delta + (-F_{y_{11}} + F_{y_{12}}) \sin\delta \Bigg) \Bigg] \\
\dot{x}_4 &= \dot{F}_{y_{11}} = \frac{u + \dot{\psi} E_1/2}{\rho_{y_{11}}} \Big(\overline{F_{y_{11}}} - F_{y_{11}} \Big) \\
\dot{x}_5 &= \dot{F}_{y_{12}} = \frac{u - \dot{\psi} E_1/2}{\rho_{y_{12}}} \Big(\overline{F_{y_{12}}} - F_{y_{12}} \Big) \\
\dot{x}_6 &= \dot{F}_{y_{21}} = \frac{u + \dot{\psi} E_2/2}{\rho_{y_{21}}} \Big(\overline{F_{y_{21}}} - F_{y_{21}} \Big) \\
\dot{x}_7 &= \dot{F}_{y_{22}} = \frac{u - \dot{\psi} E_2/2}{\rho_{y_{22}}} \Big(\overline{F_{y_{22}}} - F_{y_{22}} \Big) \\
\dot{x}_8 &= (F_{x_{11}} \dot{+} F_{x_{12}}) = 0
\end{cases}
$$

Heudiasyc Estimator

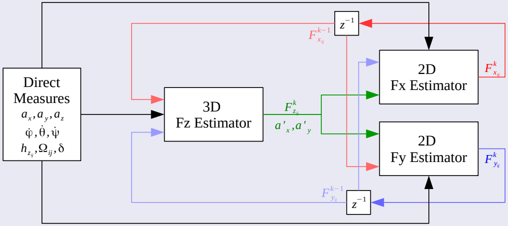
Lateral Model $\rightarrow$ Inputs/Outputs

- Inputs
  - Measured commands: δ
  - Cascade-observer inputs: $F_{z_{ij}}$
- Outputs
  - Direct measured measures: $\dot{\psi}$, u
  - Cascade-observer measures: a'_x,a'_y
    - Accelerations without gravitational components

Proposed New Estimator

Characteristics

- All-forces estimation
- 3D-based model for vertical forces
- No "random-walk" model
- Linear suspension model
- Unsprung mass neglected
- Delayed interconnected cascade-observer structure



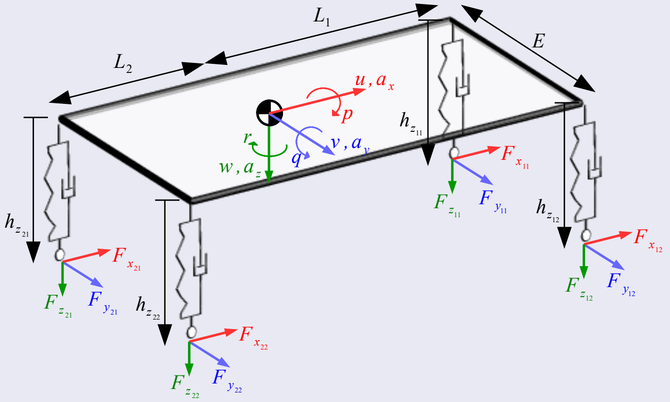
Proposed New Estimator

Vertical model

- 3D vehicle model
- Linear suspension model
- Horizontal ground assumption
- Ground is locally planar in each wheel
- Unsprung mass neglected

Proposed New Estimator

Vertical model → 3D dynamics



Proposed New Estimator

Vertical model → 3D dynamics → Linear

- $m\dot{u} = m(vr - wq - g\sin\theta) + F_{x_{11}}\cos\delta_{11} - F_{y_{11}}\sin\delta_{11} + F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12} + F_{x_{21}} + F_{x_{22}}$
- $m\dot{v} = m(wp - ur + g\sin\phi\cos\theta) + F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11} + F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12} + F_{y_{21}} + F_{y_{22}}$
- $m\dot{w} = m(uq - vp + g\cos\phi\cos\theta) + F_{z_{11}} + F_{z_{12}} + F_{z_{21}} + F_{z_{22}}$

Vertical model → 3D dynamics → Angular

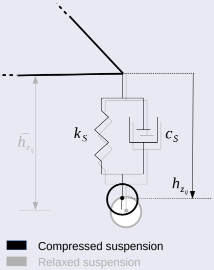
- $J_{xx}\dot{p} = (J_{yy} - J_{zz})\,qr - E/2(F_{z_{11}} + F_{z_{21}}) + E/2(F_{z_{12}} + F_{z_{22}}) - h_{z_{11}}(F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11}) - h_{z_{12}}(F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12}) - h_{z_{21}}F_{y_{21}} - h_{z_{22}}F_{y_{22}}$
- $J_{yy}\dot{q} = (J_{zz} - J_{xx})\,pr - L_1(F_{z_{11}} + F_{z_{12}}) + L_2(F_{z_{21}} + F_{z_{22}}) + h_{z_{11}}(F_{x_{11}}\cos\delta_{11} - F_{y_{11}}\sin\delta_{11}) + h_{z_{12}}(F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12}) + h_{z_{21}}F_{x_{21}} + h_{z_{22}}F_{x_{22}}$
- $J_{zz}\dot{r} = (J_{xx} - J_{yy})\,pq + L_1(F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11} + F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12}) - L_2(F_{y_{21}} + F_{y_{22}}) - E/2(F_{x_{11}}\cos\delta_{11} - F_{y_{11}}\sin\delta_{11} + F_{x_{21}}) + E/2(F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12} + F_{x_{22}})$

Proposed New Estimator

Vertical model → 3D kinematics → Angular

- $\dot{\phi} = p + (q \sin\phi + r \cos \cos\phi) \tan\theta$
- $\dot{\theta} = q \cos\phi - r \sin\phi$

Vertical model → Suspension



- $F_{z_{ij}} = -k_s \left(\bar{h}_{z_{ij}} - h_{z_{ij}}\right) - c_s \frac{d}{dt}\left(\bar{h}_{z_{ij}} - h_{z_{ij}}\right)$
- Planar ground:
  $\frac{d}{dt}\left(\bar{h}_{z_{ij}} - h_{z_{ij}}\right) \approx w + (-1)^i q L_i + (-1)^j p E/2$

Proposed New Estimator

Vertical Model → State-Space model

$$\dot{X} = \begin{cases} \dot{x}_1 = \dot{u} = vr - wq - g\sin\theta + \frac{1}{m}\left(F_{x_{11}}\cos\delta_{11} - F_{y_{11}}\sin\delta_{11} + F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12} + F_{x_{21}} + F_{x_{22}}\right) \\ \dot{x}_2 = \dot{v} = wp - ur + g\sin\phi\cos\theta + \frac{1}{m}\left(F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11} + F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12} + F_{y_{21}} + F_{y_{22}}\right) \\ \dot{x}_3 = \dot{w} = uq - vp + g\cos\phi\cos\theta + \frac{1}{m}\left(F_{z_{11}} + F_{z_{12}} + F_{z_{21}} + F_{z_{22}}\right) \\ \dot{x}_4 = \dot{p} = \frac{J_{yy} - J_{zz}}{J_{xx}}qr + \frac{E}{2J_{xx}}\left(-F_{z_{11}} - F_{z_{21}} + F_{z_{12}} + F_{z_{22}}\right) - \frac{h_{z_{11}}}{J_{xx}}\left(F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11}\right) - \\ \qquad - \frac{h_{z_{12}}}{J_{xx}}\left(F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12}\right) - \frac{h_{z_{21}}}{J_{xx}}F_{y_{21}} - \frac{h_{z_{22}}}{J_{xx}}F_{y_{22}} \\ \dot{x}_5 = \dot{q} = \frac{J_{zz} - J_{xx}}{J_{yy}}pr - \frac{L_1}{J_{yy}}\left(F_{z_{11}} + F_{z_{12}}\right) + \frac{L_2}{J_{yy}}\left(F_{z_{21}} + F_{z_{22}}\right) + \frac{h_{z_{11}}}{J_{yy}}\left(F_{x_{11}}\cos\delta_{11} - F_{y_{11}}\sin\delta_{11}\right) + \\ \qquad + \frac{h_{z_{12}}}{J_{yy}}\left(F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12}\right) + \frac{h_{z_{21}}}{J_{yy}}F_{x_{21}} + \frac{h_{z_{22}}}{J_{yy}}F_{x_{22}} \\ \dot{x}_6 = \dot{r} = \frac{J_{xx} - J_{yy}}{J_{zz}}pq + \frac{L_1}{J_{zz}}\left(F_{y_{11}}\cos\delta_{11} + F_{x_{11}}\sin\delta_{11} + F_{y_{12}}\cos\delta_{12} + F_{x_{12}}\sin\delta_{12}\right) - \frac{L_2}{J_{zz}}\left(F_{y_{21}} + F_{y_{22}}\right) + \\ \qquad \frac{E}{2J_{zz}}\left(-F_{x_{11}}\cos\delta_{11} + F_{y_{11}}\sin\delta_{11} - F_{x_{21}} + F_{x_{12}}\cos\delta_{12} - F_{y_{12}}\sin\delta_{12} + F_{x_{22}}\right) \\ \qquad \vdots \end{cases}$$

Proposed New Estimator

Vertical Model → State-Space model

$$\dot{X} = \begin{cases} \vdots \\ \dot{x}_7 = \dot{\phi} = p + (q \sin\phi + r \cos\cos\phi)\tan\theta \\ \dot{x}_8 = \dot{\theta} = q\cos\phi - r\sin\phi \\ \dot{x}_9 = \dot{h}_{z_{11}} = -w + qL_1 + p\frac{E}{2} \\ \dot{x}_{10} = \dot{h}_{z_{12}} = -w + qL_1 - p\frac{E}{2} \\ \dot{x}_{11} = \dot{h}_{z_{21}} = -w - qL_2 + p\frac{E}{2} \\ \dot{x}_{12} = \dot{h}_{z_{22}} = -w - qL_2 - p\frac{E}{2} \end{cases}$$

- Where:

- $F_{z_{11}} = -k_s\left(\bar{h}_{z_{11}} - h_{z_{11}}\right) - c_s\left(w - qL_1 - p\frac{E}{2}\right)$
- $F_{z_{12}} = -k_s\left(\bar{h}_{z_{12}} - h_{z_{12}}\right) - c_s\left(w - qL_1 + p\frac{E}{2}\right)$
- $F_{z_{21}} = -k_s\left(\bar{h}_{z_{21}} - h_{z_{21}}\right) - c_s\left(w + qL_2 - p\frac{E}{2}\right)$
- $F_{z_{22}} = -k_s\left(\bar{h}_{z_{22}} - h_{z_{22}}\right) - c_s\left(w + qL_2 + p\frac{E}{2}\right)$

Proposed New Estimator

Vertical Model $\rightarrow$ Inputs/Outputs

- Inputs
  - Measured commands: δ
  - Cascade-observer delayed feedback: $F_{x_{ij}}$ e $F_{y_{ij}}$
    - Initial conditions is zero
- Outputs
  - Direct-measured measures: a_x, a_y, a_z, p, q, r, $h_{z_{ij}}$
  - Pseudo-measured outputs: $\phi(h_{z_{ij}})$ e $\theta(h_{z_{ij}})$
    - $\phi \approx \dfrac{h_{z_{11}} - h_{z_{12}} + h_{z_{21}} - h_{z_{22}}}{2E}$
    - $\theta \approx \dfrac{h_{z_{11}} - h_{z_{21}} + h_{z_{12}} - h_{z_{22}}}{2L}$
  - Calculated vertical forces: $F_{z_{ij}}$

Proposed New Estimator

Lateral model

- Heudiasyc lateral dynamic model
  - Without random walk approximation
  - $F_{x_{ij}}$ as input instead of state
  - Hypothesis: $F_{x_{ij}}^{k} \approx F_{x_{ij}}^{k-1}$

Proposed New Estimator

Lateral Model $\rightarrow$ State-Space model

$$
\dot{X} = \begin{cases}
\dot{x}_1 = \dot{u} = +v\dot{\psi} + \frac{1}{m}\left(F_{x_{11}} \cos\delta_{11} - F_{y_{11}} \sin\delta_{11} + F_{x_{12}} \cos\delta_{12} - F_{y_{12}} \sin\delta_{12} + F_{x_{21}} + F_{x_{22}}\right) \\
\dot{x}_2 = \dot{v} = -u\dot{\psi} + \frac{1}{m}\left(F_{y_{11}} \cos\delta_{11} + F_{x_{12}} \sin\delta_{11} + F_{y_{12}} \cos\delta_{12} + F_{x_{12}} \sin\delta + F_{y_{21}} + F_{y_{22}}\right) \\
\dot{x}_3 = \dot{\phi} = \frac{L_1}{J_{zz}}\left(F_{y_{11}} \cos\delta_{11} + F_{x_{11}} \sin\delta_{11} + F_{y_{12}} \cos\delta_{12} + F_{x_{12}} \sin\delta_{12}\right) - \frac{L_2}{J_{zz}}\left(F_{y_{21}} + F_{y_{22}}\right) + \\
\qquad + \frac{E}{2J_{zz}}\left(-F_{x_{11}} \cos\delta_{11} + F_{y_{11}} \sin\delta_{11} - F_{x_{21}} + F_{x_{12}} \cos\delta_{12} - F_{y_{12}} \sin\delta_{12} + F_{x_{22}}\right) \\
\dot{x}_4 = \dot{F}_{y_{11}} = \frac{u + \dot{\psi}E/2}{\rho_{y_{11}}}\left(\overline{F_{y_{11}}} - F_{y_{11}}\right) \\
\dot{x}_5 = \dot{F}_{y_{12}} = \frac{u - \dot{\psi}E/2}{\rho_{y_{12}}}\left(\overline{F_{y_{12}}} - F_{y_{12}}\right) \\
\dot{x}_6 = \dot{F}_{y_{21}} = \frac{u + \dot{\psi}E/2}{\rho_{y_{21}}}\left(\overline{F_{y_{21}}} - F_{y_{21}}\right) \\
\dot{x}_7 = \dot{F}_{y_{22}} = \frac{u - \dot{\psi}E/2}{\rho_{y_{22}}}\left(\overline{F_{y_{22}}} - F_{y_{22}}\right)
\end{cases}
$$

Proposed New Estimator

Lateral Model → Inputs/Outputs

- Inputs
  - Measured Commands: δ
    - Ackerman Geometry correction: $\delta_{1j} = \tan^{-1}\left(\frac{L\tan\delta}{L-(-1)^j\frac{E}{2}\tan\delta}\right)$
  - Cascade-observer inputs: $F_{z_{ij}}$
  - Cascade-observer delayed feedback: $F_{x_{ij}}$
- Outputs
  - Direct measured measures: $\dot{\psi}$, u
  - Cascade-observer measures: a'_x,a'_y
    - Accelerations without gravitational components

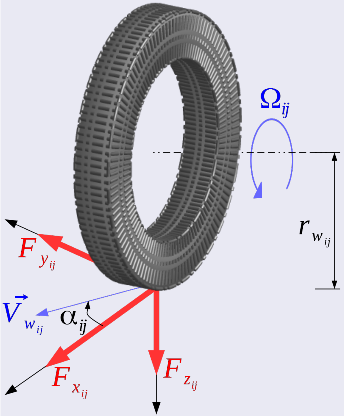
Proposed New Estimator

Longitudinal model

- Same 2D yaw dynamic as the lateral model
- Also uses Dugoff tire model
  - Long./Lat. force coupling neglected
- No propulsion model
  - Propulsion model $\leftarrow$ Propulsion torque measure
    - Dyna does not provide this measure (just VERO provides)
    - This model should increase estimator's results
    - Instead, it uses measured wheel speed as input

Proposed New Estimator

Longitudinal Model → Duggof tire model



- $\sigma_{11} = \dfrac{-(u + \dot{\psi}E/2) + \Omega_{11} r_{w_{11}}}{\max\left(u + \dot{\psi}E/2, \Omega_{11} r_{w_{11}}\right)}$
- $\sigma_{12} = \dfrac{-(u - \dot{\psi}E/2) + \Omega_{12} r_{w_{12}}}{\max\left(u - \dot{\psi}E/2, \Omega_{12} r_{w_{12}}\right)}$
- $\sigma_{21} = \dfrac{-(u + \dot{\psi}E/2) + \Omega_{21} r_{w_{21}}}{\max\left(u + \dot{\psi}E/2, \Omega_{21} r_{w_{21}}\right)}$
- $\sigma_{22} = \dfrac{-(u - \dot{\psi}E/2) + \Omega_{22} r_{w_{22}}}{\max\left(u - \dot{\psi}E/2, \Omega_{22} r_{w_{22}}\right)}$
- $\chi_{ij} = \min\left\{1, \dfrac{\mu F_{z_{ij}}}{2 C_{\sigma_{ij}} |\sigma_{ij}|}\right\}$
- $\overline{F_{x_{ij}}} = C_{\sigma_{ij}} \sigma_{ij} \left(2 - \chi_{ij}\right) \chi_{ij}$

Proposed New Estimator

Longitudinal Model → State-Space model

$$\dot{X} = \begin{cases} \dot{x}_1 = \dot{u} & = +v\dot{\psi} + \frac{1}{m}\left(F_{x_{11}} \cos\delta_{11} - F_{y_{11}} \sin\delta_{11} + F_{x_{12}} \cos\delta_{12} - F_{y_{12}} \sin\delta_{12} + F_{x_{21}} + F_{x_{22}}\right) \\ \dot{x}_2 = \dot{v} & = -u\dot{\psi} + \frac{1}{m}\left(F_{y_{11}} \cos\delta_{11} + F_{x_{12}} \sin\delta_{11} + F_{y_{12}} \cos\delta_{12} + F_{x_{12}} \sin\delta + F_{y_{21}} + F_{y_{22}}\right) \\ \dot{x}_3 = \dot{\phi} & = \frac{L_1}{J_{zz}}\left(F_{y_{11}} \cos\delta_{11} + F_{x_{11}} \sin\delta_{11} + F_{y_{12}} \cos\delta_{12} + F_{x_{12}} \sin\delta_{12}\right) - \frac{L_2}{J_{zz}}\left(F_{y_{21}} + F_{y_{22}}\right) + \\ & \quad + \frac{E}{2J_{zz}}\left(-F_{x_{11}} \cos\delta_{11} + F_{y_{11}} \sin\delta_{11} - F_{x_{21}} + F_{x_{12}} \cos\delta_{12} - F_{y_{12}} \sin\delta_{12} + F_{x_{22}}\right) \\ \dot{x}_4 = \dot{F}_{x_{11}} & = \frac{u + \dot{\psi}E/2}{\rho_{x_{11}}}\left(\overline{F_{x_{11}}} - F_{x_{11}}\right) \\ \dot{x}_5 = \dot{F}_{x_{12}} & = \frac{u - \dot{\psi}E/2}{\rho_{x_{12}}}\left(\overline{F_{x_{12}}} - F_{x_{12}}\right) \\ \dot{x}_6 = \dot{F}_{x_{21}} & = \frac{u + \dot{\psi}E/2}{\rho_{x_{21}}}\left(\overline{F_{x_{21}}} - F_{x_{21}}\right) \\ \dot{x}_7 = \dot{F}_{x_{22}} & = \frac{u - \dot{\psi}E/2}{\rho_{x_{22}}}\left(\overline{F_{x_{22}}} - F_{x_{22}}\right) \end{cases}$$

Proposed New Estimator

Longitudinal Model → Inputs/Outputs

- Inputs
  - Measured Commands: δ e Ω_{ij}
    - Ackerman Geometry correction: $\delta_{1j} = \tan^{-1}\left(\dfrac{L\tan\delta}{L-(-1)^j\frac{E}{2}\tan\delta}\right)$
  - Cascade-observer inputs: $F_{z_{ij}}$
  - Cascade-observer delayed feedback: $F_{y_{ij}}$
- Outputs
  - Direct measured measures: $\dot{\psi}$, u
  - Cascade-observer measures: a'_x,a'_y
    - Accelerations without gravitational components

Summary

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Extended Kalman Filter

System assumption

$$\dot{X} = f(X, U) + W$$
$$Y = h(X, U) + V$$

where W and V are uncorrelated white noises

- Same goal of Kalman Filter
  - $\min E\left\{(X - \hat{X})^T (X - \hat{X})\right\}$
- Difference: Locally linearized systems

$$A_{k-1} = I + T_S \nabla_x f(X, U) \Big|_{X=X_{k-1},\, U=U_k}$$
$$C_k = \nabla_x h(X, U) \Big|_{X=X_k,\, U=U_k}$$

- Discrete system: Direct Euler Discretization

$$X_{k+1} = X_k + T_S f(X_k, U_k)$$

Extended Kalman Filter

Algorithm

1. Initialization: time $k = 0$; $\hat{X}_0 = X_0$; $\hat{P}_0 = P_0$;
2. Time update: $k = k + 1$;
3. State prediction: $\overline{X}_k = \hat{X}_{k-1} + T_S f(\hat{X}_{k-1}, U_k)$;
4. Output prediction: $\overline{Y}_k = h(\overline{X}_k, U_k)$;
5. State linearization: $A_{k-1} = I + T_S \nabla_X f(X, U)\Big|_{X=\hat{X}_{k-1},\, U=U_k}$;
6. Output prediction linearization: $\overline{C}_k = \nabla_X h(X, U)\Big|_{X=\overline{X}_k,\, U=U_k}$;
7. State covariance prediction: $\overline{P}_k = A_{k-1}\hat{P}_{k-1}A_{k-1}^T + Q$;
8. Output covariance prediction: $\overline{S}_k = \overline{C}_k\overline{P}_k\overline{C}_k^T + R$;
9. Kalman Filter gain: $K_k = \overline{P}_k\overline{C}_k^T\overline{S}_k^{-1}$;
10. Innovation: $\eta_k = Y_k - \overline{Y}_k$;
11. State estimation: $\hat{X}_k = \overline{X}_k + K_k\eta_k$;
12. State covariance estimation: $\hat{P}_k = \left(I - K_k\overline{C}_k\right)\overline{P}_k$;
13. Back to step 2;

Summary

Results

Observers Comparison

- Data obtained with DYNA mission
- Mission was at Compiegne's town center
  - No map description because DYNA does not have GPS data
- Data obtained from:
  - Tire forces and moments transducers (one for each wheel)
  - IMU system
  - Vehicle's CAN data
  - Simple laser ground distance (one for each extremity)
- Mechanical specifications available

Results

Observers Comparison → Resume

Characteristics	Heudiasyc	New
Vert. dynamics	"Random-walk" model	Force model
Lat. dynamics	Force model	Force model
Suspension	2 Torsional	4 Linear
Tire model	Dugoff	Dugoff
Steering	Simple ($\delta_{11} = \delta_{12}$)	Ackerman ($\delta_{11} \neq \delta_{12}$)
Estimator type	EKF	EKF
Structure	Direct cascade	Interconnected cascade
Vert. model	16 states	12 states
Lat. model	8 states	7 states
Long. model	none	7 states
Ground type	Planar/Slopes	Irregular/Horizontal

Results

BEPE HEUDIASYC

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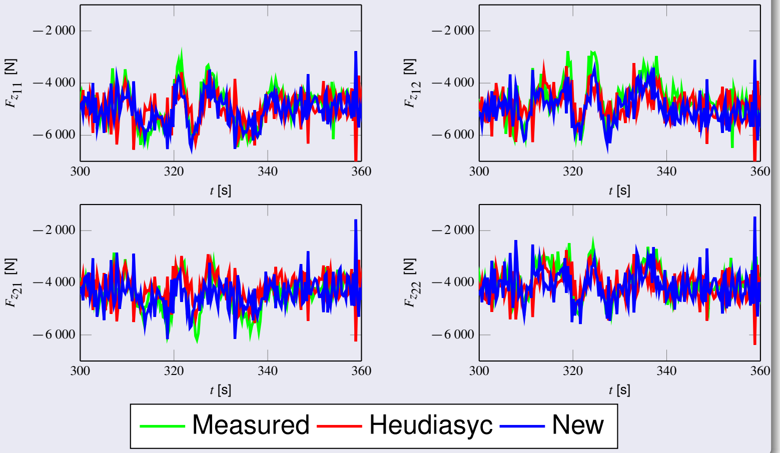
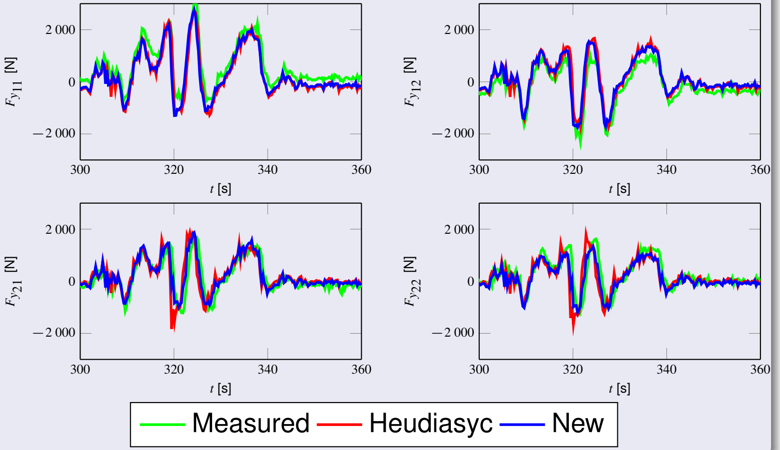
F_z comparison



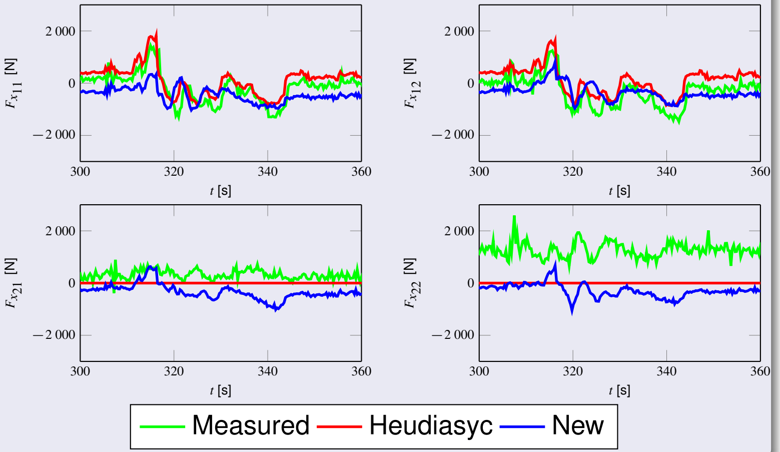
Results

F_y comparison



Results

F_x comparison



Results

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Metrics comparison

- Mean-square error
  - ➥ $\text{mse} = \sqrt{\frac{1}{N}\sum_{k}\left(\hat{F}_k - F_k\right)^2}$
- Maximun absolute error
  - ➥ $\text{mae} = \max_{k}\left|\hat{F}_k - F_k\right|$

Results

Metrics comparison

		Mean-square error (N)			
		F_{11}	F_{12}	F_{21}	F_{22}
F_z	Heud.	627.6	660.0	658.4	578.2
	New	557.2	634.2	636.7	612.6
F_y	Heud.	381.7	355.1	516.2	491.4
	New	403.0	368.8	328.4	316.6
F_x	Heud.	377.0	481.5	373.1	1286.1*
	New	555.9	434.9	723.9	1590.1*

		Maximum Absolute error (N)			
		F_{11}	F_{12}	F_{21}	F_{22}
F_z	Heud.	3670.2	3143.0	3541.4	2843.4
	New	4574.0	3652.7	3316.0	3663.0
F_y	Heud.	1815.3	1724.1	3165.6	2819.7
	New	1841.3	1487.7	1626.7	1660.0
F_x	Heud.	1234.2	1495.9	2094.6	2957.7*
	New	1873.9	1329.3	2501.2	3073.9*

Summary

Conclusions

Estimators

- Both has good results
- New proposal has better response on rear wheels
- Longitudinal estimator is not accurate as expected
  - Need propulsion model
  - Longitudinal speed sensor

Future Works

- Use forces in path tracking control
- Development of delayed interconnected cascade-observer

Final

Thank you for your attention!

Questions?

Summary

References I

Bouton, N., Lenain, R., Thuilot, B., & Martinet, P. 2008 (Sept).
A rollover indicator based on a tire stiffness backstepping observer: Application to an All-Terrain Vehicle.
Pages 2726–2731 of: Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on.

Cordeiro, R. A. 2013.
Modelagem e Controle de Trajetória de um Veículo Robótico Terrestre de Exterior.
M.Phil. thesis, Faculdade de Engenharia Mecânica, UNICAMP, Campinas, Brasil.

Cordeiro, R.A., Azinheira, J.R., de Paiva, E.C., & Bueno, S.S. 2012 (Set).
Efeitos da Dinâmica Tridimensional no Controle de Trajetória de um Veículo Robótico Terrestre de Quatro Rodas.
In: XIX Congresso Brasileiro de Automática (CBA 2012).

Cordeiro, R.A., Azinheira, J.R., de Paiva, E.C., & Bueno, S.S. 2013a (Out).
Controle de Trajetória de um Veículo Robótico de Exterior em Terrenos Complexos, via Abordagem LQR Bioinspirada.
In: XI Simpósio Brasileiro de Automação Inteligente (SBAI 2013).

Cordeiro, R.A., Azinheira, J.R., de Paiva, E.C., & Bueno, S.S. 2013b (Nov).
Dynamic Modeling and Bio-Inspired LQR Approach for Off-Road Robotic Vehicle Path Tracking.
In: 16th IEEE International Conference on Advanced Robotics (ICAR 2013).

References II

Doumiati, M. 2009.
Embedded estimation of vehicle's vertical and lateral tire forces for behavior diagnoses on the road.
Ph.D. thesis, Université de Technologie de Compiègne, France.

Doumiati, M., Victorino, A.C., Charara, A., & Lechner, D. 2011.
Onboard Real-Time Estimation of Vehicle Lateral Tire-Road Forces and Sideslip Angle.
Mechatronics, IEEE/ASME Transactions on, **16**(4), 601–614.

Dugoff, H., Fancher, P. S., & Segal, L. 1969 (August).
Tire Performance Characteristics Affecting Vehicle Response To Steering And Braking Control Inputs.
Tech. rept. Contract CST-460 (Final). Office of Vehicle Systems Research, US National Bureau of Standards, Washington, DC.

Hirschberg, W., Rill, G., & Weinfurter, H. 2007.
Tire model TMeasy.
Vehicle System Dynamics, **45**(sup1), 101–119.

Jiang, K., Pavelescu, A., Victorino, A., & Charara, A. 2014 (out).
Estimation of vehicle's vertical and lateral tire forces considering road angle and road irregularity.
In: Intelligent Transportation System, 2014. ITSC '14., IEEE Conference on.

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References III

M'sirdi, N. K., Rabhi, A., Zbiri, N., & Delanne, Y. 2005.
Vehicle-road interaction modelling for estimation of contact forces.
Vehicle System Dynamics, **43**(sup1), 403–411.

Pacejka, H. B. 2002.
Tire and Vehicle Dynamics.
Oxford: Butterworth-Heinemann.
697p.

Ray, Laura R. 1997.
Nonlinear Tire Force Estimation and Road Friction Identification: Simulation and Experiments.
Automatica, **33**(10), 1819 – 1833.

Wang, B. 2013.
State observer for diagnosis of dynamic behavior of vehicle in its environment.
Ph.D. thesis, Université de Technologie de Compiègne, France.