Advanced Stability Control of Electric Vehicle with In-wheel Motor and Active Steering System

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The University of Tokyo

The Fujimoto Research Laboratory in Japan is studying motion algorithms for electric vehicles.

E-motion

http://hflab.k.u-tokyo.ac.jp/
Hori/Fujimoto Lab.

Research Field: Control Engineering, Motion Control, Electric Vehicle, Wireless Power Transfer, Nano-scale Servo, Power Electronics, Robotics,

Lab Members: 8 staffs (P, AP, Assistant P, 2 PDs, Engineer, 2 secretaries)
33 students (9 Ph.D, 19 M.S., 4 B.S., 1 R.S., including 13 international students)

EV Garage (250㎡)

EV test field (2600㎡)

Kashiwa New Campus
(40 min from center of Tokyo)
Motion Control of EVs over ICVs

Advantages of motors → High Control Perf.

- Quick torque response
  Torque of Motors (1ms)
  >> Torque of Engines (500ms)
  → Anti-slip Control

- Measurable torque
  → Estimate of Road Cond.

- Individual wheel control by IWMs
  → Vehicle Stability Control in 2D
1. Introduction
2. Development and Control of Original EV FPEV2-Kanon
3. Vehicle Stability Control with Wheel Side Force Sensor
4. Range Extension Control System
5. Conclusion
In-wheel motors

- **Outer rotor type**
  - Big torque generation

- **Direct drive system**
  - No Transmission Loss of Gear
  - High Efficiency and Small Noise
  - Quick response
  - Estimation by reaction force

<table>
<thead>
<tr>
<th></th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maker</strong></td>
<td>Toyo Denki Seizo K.K., Ltd</td>
<td></td>
</tr>
<tr>
<td><strong>Motor type</strong></td>
<td>Outer rotor type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Direct drive system</td>
<td></td>
</tr>
<tr>
<td><strong>Rated torque</strong></td>
<td>110 [Nm]</td>
<td>137 [Nm]</td>
</tr>
<tr>
<td><strong>Max torque</strong></td>
<td>500 [Nm]</td>
<td>340 [Nm]</td>
</tr>
<tr>
<td><strong>Rated power</strong></td>
<td>6.0 [kW]</td>
<td>4.3 [kW]</td>
</tr>
<tr>
<td><strong>Max power</strong></td>
<td>20.0 [kW]</td>
<td>10.7 [kW]</td>
</tr>
<tr>
<td><strong>Max speed</strong></td>
<td>1113 [rpm]</td>
<td>1500 [rpm]</td>
</tr>
<tr>
<td><strong>Motor mass</strong></td>
<td>32 [kg]</td>
<td>26 [kg]</td>
</tr>
<tr>
<td><strong>Cooling</strong></td>
<td>Natural air cooling</td>
<td></td>
</tr>
</tbody>
</table>
FPEV-2 (Kanon)
Future Personal Electric Vehicle

- Inverter and Chopper
- Li-ion Battery
- Steer-by-wire and 4WS (Front and Rear Steering Control by Motors)
- DD in-wheel motors
- Side force sensors

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Active Front/Rear Steering System

- 2 DC Motors (Maxon 250W) for Steering
- Front steering shaft is removable.
  → Steer-by-wire

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Development of Original EV

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Principle of Driving Force Estimation

Motion Equation of Wheel

\[ J_\omega \frac{d\omega}{dt} = T - rF_d \]

- **Inertia of wheel**: Constant
- **Angular Accel.**: Measured by Current
- **Motor torque**: Measured by Sensors
- **Radius of wheel**: 

Driving Force \( F_d \) can be estimated by this equation. In our system, it is calculated realtime with 0.1ms sampling.
Anti-slip Control

Dynamics of EV

Inverse Dynamics on Grip

Toque on adhesion w.r.t wheel speed

Controller

Wheel Speed

Wheel Speed

Dynamics of EV

Inverse Dynamics on Grip

Toque on adhesion w.r.t wheel speed

Controller

Wheel Speed

Dynamics of EV

Inverse Dynamics on Grip

Toque on adhesion w.r.t wheel speed

Controller

Wheel Speed

Dynamics of EV

Inverse Dynamics on Grip

Toque on adhesion w.r.t wheel speed

Controller

Without control

Without control

With control

With control
Direct Yaw Control (DYC)

Motor for SBW

steering angle sensor

δ*

acceleration and yaw-rate sensor

ax, ay, γ

Controller (AURIC DS1103)

Li-ion Battery 150V

Chopper 300V

L inverter

R inverter

L motor

R motor

Motor for SBW

Yaw rate γ

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DYC results

Without control

With control

Counter steering

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Slip-ratio Control with Regenerative Braking

Mechanical Braking Only

Electric and Mechanical Braking
Collaboration with Mitsubishi Motors

<table>
<thead>
<tr>
<th>Motor (Outer rotor)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>PMSM</td>
</tr>
<tr>
<td>Max power</td>
<td>50[kW] × 4</td>
</tr>
<tr>
<td>Max torque</td>
<td>518[Nm] × 4</td>
</tr>
<tr>
<td>Max speed</td>
<td>1500[rpm]</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Battery</th>
<th>-</th>
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</thead>
<tbody>
<tr>
<td>Type</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>Capacity</td>
<td>95 [Ah]</td>
</tr>
<tr>
<td>Volt/module</td>
<td>14.8V × 24 modules</td>
</tr>
<tr>
<td>Dimensions(L×W×H)</td>
<td>4490×1770×1450[mm]</td>
</tr>
<tr>
<td>Weight</td>
<td>1816.5[kg](with two persons)</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>0.35[m]</td>
</tr>
<tr>
<td>Wheel Inertia</td>
<td>2.55[Nms²]</td>
</tr>
<tr>
<td>Vehicle Controller</td>
<td>Micro Auto Box</td>
</tr>
</tbody>
</table>

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   i. Lateral Force Sensor
   ii. Yaw-rate Control by IWMs and Active Front/Rear Steering
4. Range Extension Control System
5. Conclusion
ESC: Electronic Stability Control

System to stabilize the vehicle motion by controlling yaw-rate by 4 wheel brake independently. One of the active safety technologies. ESCs have already been implemented in many commercialize cars.

- A study of dynamics performance improvement by rear right and left independent drive system [Sugano (Mazda)]
- Friction circle estimation and integrated control of 4 wheels independent dive and 4WS [Ono (Toyota CRL)]
- Electric Control Torque Split 4WD [Nissan]
- Development of 4 wheel driving force control system [Mori (Honda)]
- Integrated Vehicle Motion Control System “S-AWC” [Miura (Mitsubishi Motors)]
- Motion Control of Electric Vehicle with Tire Workload [Iwano (Bridgestone)]
- Effects of Model Response on Model Following Type of Combined Lateral Force and Yaw Moment Control Performance for Active Vehicle Handling Safety [O. Mokhiamar (Kanagawa U)]
- Mini-max Optimal Distribution of Lateral and Driving/Braking Forces [Nishihara (Kyoto Univ)]
Lateral force detection by sensors in Hub-unit
Possible to measure lateral force under suspension

- Expected Big Contribution to Active Safety
- Intelligent wheels by these sensors and in-wheel motors (and steer-by-wire)

Recent development in Japan
- NSK: Sensing by wheel speed sensor and encoders
- NTN: Sensing by strain gauge
- J-Tekt

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Equation of Motion for 4 wheels independent drive/steering

- **Longitudinal Motion**
  \[ F_{xf_l} + F_{xf_r} + F_{xrl} + F_{xrr} = F_{x0} \]

- **Lateral Motion**
  \[ F_{yf_l} + F_{yf_r} + F_{yrl} + F_{yrr} = F_{y0} \]

- **Yawing Motion** \((\delta_f, \delta_r << 1)\)
  \[-\frac{d_f}{2} F_{xf_l} + \frac{d_f}{2} F_{xf_r} - \frac{d_r}{2} F_{xrl} + \frac{d_r}{2} F_{xrr} = N_z \]  
  \[ l_f (F_{yf_l} + F_{yf_r}) - l_r (F_{yrl} + F_{yrr}) = N_t \]
  \[ N_z + N_t = M_z \]

Active steering or 4 wheel independent vehicles have redundancy in control input.

- Sum of squares workload minimization (Abe03)
- Minimax (Nishihara06)
- Workload equalization (Ono07)
Load change in decelerating turning

Force saturation on rear left

Decrease of yaw-moment caused by saturation destabilizes vehicle motion.
Yaw-control of front/rear independent steering and rear IWMs

\[
\begin{bmatrix}
0 & 0 & 1 & 1 \\
2 & 2 & 0 & 0 \\
2l_f & -2l_r & -\frac{d_r}{2} & \frac{d_r}{2}
\end{bmatrix}
\begin{bmatrix}
Y_f \\
Y_r \\
F_{xrl} \\
F_{xrr}
\end{bmatrix}
= 
\begin{bmatrix}
F_{x0} \\
F_{y0} \\
M_z
\end{bmatrix}
\]

Workload \( \eta \equiv \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \)

Objective function: sum of squares of workload

\[
J = \sum_{i=f,r,j=l,r} \frac{F_{xij}^2 + F_{yij}^2}{F_{zij}^2} = x^T W x
\]

Optimal distribution

\[
\begin{bmatrix}
Y_f \\
Y_r \\
F_{xrl} \\
F_{xrr}
\end{bmatrix}
= W^{-1} A^T (A W^{-1} A^T)^{-1}
\begin{bmatrix}
F_{x0} \\
F_{y0} \\
M_z
\end{bmatrix}
\]
Conventional (YMO): torque diff. only

Test by decelerating turning

- Accelerates to 30km/h → step-type steering (\( \delta_f = 0.06 \text{rad} \))
- Decelerating turning with braking force -800N
- Command signals: constant turning radius

\[ \gamma^* = \frac{V}{l} \delta_f, \quad a_y^* = \frac{V^2}{l} \delta_f \]
Movie of Experiments

Torque difference only

Torque diff and active F/R steer

Red: Force Vector Locus, Blue: wheel load, Blue dashed: Amplitude of force
Control input in experiments

Torque difference only

Torque diff and active F/R steer

Steering

Torque Command

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Experimental results (yaw-rate, workload)

- Torque difference only
- Torque diff and active F/R steer

- Yaw rate
- Workload

Equalization of each wheel workload

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Critical Problem of EVs

Critical issues for EVs

Mileage per charge

Comparison of ICV and electric vehicle

<table>
<thead>
<tr>
<th></th>
<th>Mileage</th>
<th>Capacity</th>
<th>Cruising range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline vehicle (i)</td>
<td>21 km/L</td>
<td>gasoline 35L</td>
<td>735km</td>
</tr>
<tr>
<td>Electric vehicle (i-MiEV)</td>
<td>8 km/kWh (battery capacity 16 kWh)</td>
<td>130km</td>
<td></td>
</tr>
</tbody>
</table>

[M. Kamachi, AVEC08]

EV's cruising range is shorter than ICV's range.

In order to solve this problem:

- High efficiency motor [K. Sakai, JIASC09]
- Novel driving method by two reduction gear [A. Sorniotti, AVEC10]
Range Extension Control System: RECS

Try to enhance the cruising range of EV’s by control technologies
(Assumption: EV has multiple motors)

3 types of RECS developed

• RECS I: Optimal torque distribution [Fujimoto, Sumiya IECON2011]
• RECS II: Minimization the cornering resistance
• RECS III: Minimization motor output [Egami, Fujimoto, IECON2011]
• Total optimization (RECS I + III) [Fujimoto, Egami, IECON2012]
RECS I: Optimal torque distribution

Assumption: Front and rear independent motors. Straight road

The sum of the torque only needs to satisfy the driver demands.

Torque distribution

Efficiency map of motor + inverter

Optimize overall efficiency by distribution
Experiment of RECS I

**Experimental conditions**
- Speed command: 30 km/h
- Total torque command: 180 Nm
- Evaluation on the chassis dynamometer

**Extended mileage**
- 1 kWh: 500 m
- 16 kWh: 8 km

<table>
<thead>
<tr>
<th>ν</th>
<th>0</th>
<th>0.5</th>
<th>0.88</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>km/kWh</td>
<td>3.2</td>
<td>3.6</td>
<td>4.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Collaboration with Mitsubishi Motors

Prototype PHEV with 2 on-board motors
- 2 motors has different efficiency map.
- 2 differential gears for F/R wheels
- Engine is stopped. Evaluate as Battery EV

EV cruising range extension

Cruising distance [km/kWh] (at 50km/h constant speed)

<table>
<thead>
<tr>
<th>Battery Capacity</th>
<th>Without RECS</th>
<th>With RECS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1kWh</td>
<td>8.27 km</td>
<td>9.79 km</td>
</tr>
<tr>
<td>16kWh</td>
<td>132.38 km</td>
<td>156.61 km</td>
</tr>
</tbody>
</table>

1.52km extend per 1kWh
24.2km extend per 16kWh
**RECSII: Cornering resistance minimization**

RECS on curving road by left and right independent motors

- Minimize front steering angle by $N_z$
- Cornering resistance is reduced
- Mileage per charge is extended!

$\delta_c > \delta_p$

$N_z$: yaw-moment generated by driving force
difference between left and right motors
\[ \text{Cruse distance (km/kWh)} \]

<table>
<thead>
<tr>
<th>Motor output</th>
<th>Without RECS</th>
<th>With RECS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 [kWh]</td>
<td>11.3 [km]</td>
<td>11.9 [km]</td>
</tr>
<tr>
<td>5 [kWh]</td>
<td>56.5 [km]</td>
<td>59.6 [km]</td>
</tr>
<tr>
<td>16 [kWh]</td>
<td>180.8 [km]</td>
<td>190.4 [km]</td>
</tr>
</tbody>
</table>

Input power of inverter

- \( V = 15 \text{ [km/h]} \), \( R = 8 \text{ [m]} \)

Front Steering Angle

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Control Technologies of EV Developed in Hori/Fujimoto Lab.

Advanced Safety
- Slip-ratio control
- Yaw-rate control
- Slip-angle control
- ....

Driving Comfort
- Pitching control
- Roll control

Range Extension Control System
- Optimal Distribution
- Minimize Resistance
Conclusion

1. Small-scale EV “FPEV2-Kanon” are designed and developed with active front/rear steering and direct drive in-wheel motors.

2. Control theories developed with FPEV2-Kanon was applied to the prototype EVs of industries.

3. Developed technologies are available not only Battery EVs but also (Plug-in) hybrid vehicles and FCEVs.
New Developing EV (FPEV4 Sawyer)

- Main Unit
  - Li-ion Battery
- L/R Individual On-board Motor (N of Turns: 42T/21T)
- In-wheel Motor (N of Turns: 12T/8T)
- Non-driven Unit
- On-board motor / Differential Gear
- Left/Right Individual On-board Motor
- In-wheel motors

- Drive Unit in Sub-unit which is installed both rear and front
  => Many configurations are examined with fair comparison
- Provide common test platform (e.g. On-board motor + Drive shaft vibration suppression control = IWM?)
- Active Front and Rear Steering, Steer by wire
- Suspension geometry is tunable
- Lateral force sensors

Test drive @ EV test field in Kashiwa