EVS24
Stavanger, Norway, May 13-16, 2009

Stability Control of Light Electric Vehicle with Active-tilting and Anti-skid Systems

Li C-H, Chien C-P, Peng Y-Y, James, H. Wang, Gau T-H, Chang C-C

Industrial Technology Research Institute, Hsinchu, Taiwan, ChengHoLee@itri.org.tw

Abstract

A novel rhombus-shaped light electric vehicle (LEV) has been researched for last few years by ITRI. In this work, two main systems for the stability control of the LEV are presented; the active-tilting control system and the anti-skid control system. As for the active-tilting system, the adequate tilting angle is precisely controlled based on the driver's steer intention, vehicle speed and lateral acceleration. The active-tilting system is capable of actuating a 180-kg body, providing the tilting response of 1.1 rad/s. When the active-tilting system is enabled, the vehicle's anti-rollover capability achieves 0.4G, 30% improvement equivalently. As for the anti-skid system, the LEV is driven by two digital-controlled independently powered-wheels. The differential relation is first guaranteed, and then the skid prevention is done by observing and controlling the slip ratio of each driving wheel. Based on the experimental results, the under steer gradient increases while the anti-skid system is enabled, say, in a 20-m constant radius turn test, the maximal vehicle speed can be increased to 12% without skidding. In summary, the integrated system of active-tilting and anti-skid controllers could facilitate drivers manoeuvring the LEV, meanwhile, the stability of the vehicle dynamics is easily taken control.

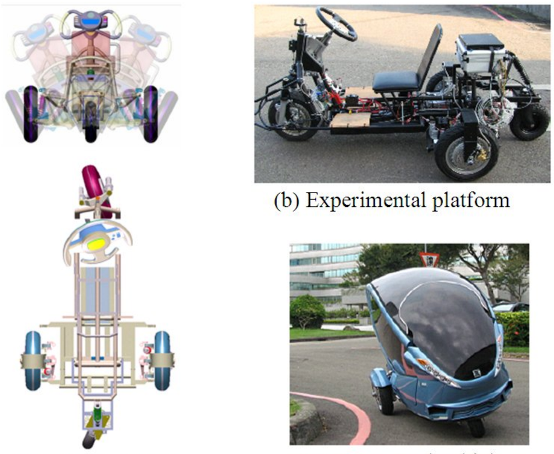
Keywords: control system, electric drive, mobility, traction control

1 Introduction

A novel rhombus-shaped light electric vehicle (LEV) has been researched for last few years by ITRI. The primary purpose of the development was to solve the major urban cities problems, such as traffic congestion, parking. Accordingly, the LEV provides a great maneuverability; it can perform zero-radius turning, actively tilt the body when cornering, therefore the dynamic stability is excellent in spite of the light and narrow style. In this work, two main systems for the stability control of the LEV are presented; the active-tilting control system and the anti-skid control system. As for the active-tilting system, the LEV could tilt or lean the body and all wheels simultaneously through a sophisticated mechanism, achieving the maximal effective tilting angle of 32°. The adequate tilting angle is precisely controlled based on the driver's steer intention, vehicle speed and lateral acceleration. The active-tilting system is capable of actuating 180-kg body, providing the tilting response of 1.1 rad/s. Preliminary test results indicate that when the active-tilting system is enabled, the vehicle's anti-rollover capability achieves 0.4G, 30% improvement equivalently. As for the anti-skid system, the LEV is driven by two digital-controlled independently wheels. The differential relation is first guaranteed, and then the skid prevention is done by observing and controlling the slip ratio of each driving wheel. Based on the experimental results, the steer characteristic can be easily modified by tuning the gain parameters in the controller. The under steer gradient increases while the anti-skid system is enabled, say, in a 20-m constant radius turn test, the maximal vehicle speed can be increased to 45 kph from 37 kph without skidding. In summary, the integrated system of active-tilting and anti-skid controllers facilitates drivers manoeuvring the LEV, meanwhile, the stability of the vehicle dynamics is easily taken control.

2 ITRI LEV

In order to solve the traffic congestion and reduce exhaust emission for personal mobility in urban city, a few micro vehicles were created in the world. A narrow LEV with diamond-shape chassis was developed in past few year by ITRI. The brief specification of ITRI LEV is list in Table 1.



(a) Virtual design (b) Experimental platform (c) Conceptual vehicle

Figure1: ITRI LEV

Table1: Dimensions & specification of ITRI LEV

Front wheel base (mm)	1250
Full wheel base (mm)	1900
Tread (mm)	990
weight (kg)	300
front wheels	120/70-12”
side wheels w/ hub motor	130/60-13”
Top speed(kph)	50
Gradient ability	20kph@12deg

ITRI LEV has a "four-wheeled" layout, including one steering wheel in front, two middle-side wheels and one full-free-rotation rear wheel. It can make manoeuvrable in tight spaces easier without involving complex chassis and mechanism design. The amazing circumrotating radius is just 1.3 m, almost close to front wheel base, under turn-on-spot operation.

A tilting mechanism-Stephenson six-bar linkage is introduced in this vehicle auto-tilting system, whereby it enables all-wheel tilting to shift the center-of-gravity around corners to achieve excellent anti-rollover capability, especially relevant with narrow track design. Also, the auto-stand-lock control technology is implemented for low-speed driving or stand stop.

The electric power system for the ITRI LEV includes two high-efficiency hub motors in both side wheel and one set of modularised Li-ion battery pack, hence achieve compact design, zero-emissions, and energy-efficiency.

3 Stability control of LEV

To assure the driving stability of the ITRI LEV, two systems are – the active tilting system and the anti-skid system. The active tilting system is for enhance the anti-rollover capability of the LEV which is relatively narrower than conventional cars. The anti-skid system is for avoiding over-slip of the independently-powered driving wheels.

3.1 Active tilting system

The active tilting system is a novel technology for narrow vehicles that makes the all wheels and body tilting during cornering, according to the driver’s intention. The stability and anti-rollover capability can be effectively improved in spite of the small, narrow style of vehicles.

3.1.1 Tilting mechanism []

In the active tilting system, a Stephenson III Six-bar linkage is utilized to generate the tilting motion. The vehicle body and both side wheels could tilting or leaning at the same time. As shown in Fig. 1, the tilting mechanism consists of a ternary link ABC, links CD, DF, AF, BE and a slider connected to the joint E. Joints A, B, C, D, and F are all revolute joints. The link BE should be rigidly conjunct to the vehicle body (or the cabin), and links AF and CD are connected to the left wheel and the right wheels respectively.

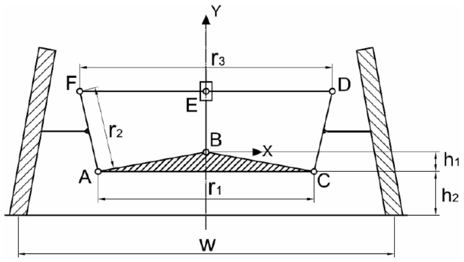


Figure2: Tilting mechanism of six-bar linkage

Two side wheels would also tilt while the vehicle body is tilting. Since identical performance is expected in both left and right tilting, the mechanism dimensions are arranged symmetrically with regard to the vertical axis Y, i.e., the link lengths of AF and CD are equal; E is at the mid point of the link FD, and B is lying on the perpendicular bisector of the segment AC.

3.1.2 Active tilting control

To implement the tilting control strategies and integrate the system, the rapid development system – MicroAutoBox is used to carry out the active tilting control strategies. The active tilting control scheme is as shown in Fig. 3.

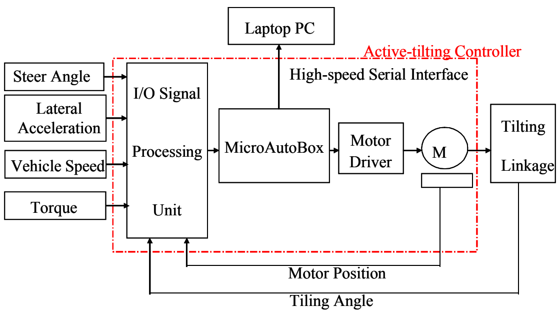


Figure3: Active tilting control scheme

In Fig. 3, motor is the supplementary power to assist in tilting motion; the driver's intention can be detected by torque sensor, then the motor supply the tilting torque when driver's intention and turning state are matched. This approach below to passive control and accessory control system, the body of vehicle will not tilt if driver have not tilting intention. In fact, let driver to decide tilting state is the concept of this control strategy and the tilting angle is calculated according to the Eq. (1), the roll angle is φ, the system parameter is D and Z, the system just help driver to finish tilting motion and avoid dangerous situations. Advantages of this strategy are summarized below: 1. Simple actuating system. 2. More comfortable. 3. Less error motions.

$$\phi = \sin^{-1}[\frac{t\sin\varphi}{Z} + \frac{a\cos(\varphi-\gamma_1)-T}{Z} + \frac{gRt}{v^2 Z}(2\beta\cos\gamma_1 - \cos\varphi)] + D - \varphi \qquad (1)$$

3.2 Anti-skid System

3.2.1 Electric differential control

As shown in Fig. 1, the ITRI LEV is a rhombus-shape vehicle. The geometry is illustrated in Fig. 4. The front wheel is for steering purpose, without power. The side wheels in the middle of the vehicle are independently driven by hub motors. The rear wheel is able to both rotate and roll freely.

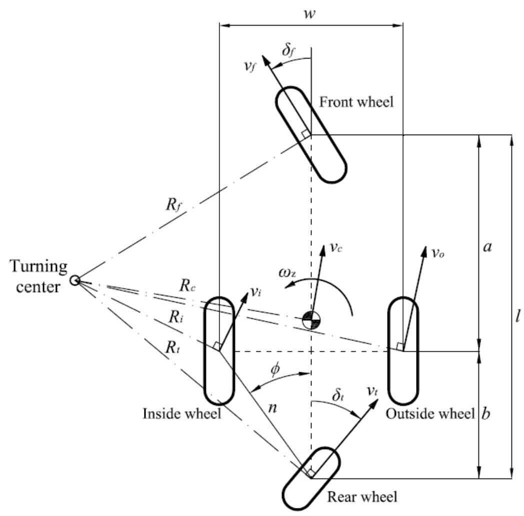


Figure4: Geometry of rhombus-shape LEV

Referring to Fig. 4, the wheelbase is l, and the distance from the turning center to the front wheel and the rear wheel are R_f and R_t. Because the steering angle, δ_f, and rear wheel angle, δ_t , could be easily measured by using angle sensors, the corresponding radii of the front and the rear wheels can be expressed in terms of δ_f and δ_t straightforwardly by applying sine rule.

To calculate the reasonable speeds of side wheels, the turning radii of side wheels are required. The radius of inner wheel is designated by R_i, and the radius of the outer wheel is designated by R_o. As to R_o, the triangle formed by R_o, R_r and n is considered. By using the cosine rule, the radius of outer wheel, R_o, could be yield, as expressed by Eq. (2).

$$R_o = \sqrt{R_t^2 + n^2 - 2R_t \cdot n \cdot \cos\left(\frac{\pi}{2} - \delta_t + \phi\right)} \quad (2)$$

Similarly, the radius of inner wheel, R_i, could be yield as shown by Eq. (3).

$$R_i = \sqrt{R_t^2 + n^2 - 2R_t \cdot n \cdot \cos\left(\frac{\pi}{2} - \delta_t - \phi\right)} \quad (3)$$

According to the kinematics of the rigid-body motion, the vehicle body shall have a unique angular motion, and its angular velocity can be expressed as follows. Although there is only one body angular velocity, the v_r, v_i, and v_o are different linear velocities since they are at different positions.

$$\omega_z = \frac{v_t}{R_t} = \frac{v_i}{R_i} = \frac{v_o}{R_o} \quad (4)$$

The v_t can be obtained by measuring the angular velocity of the rear wheel. Therefore, the adequate linear speeds of inner and outer wheels could be calculated. Thus the desired speeds of the inside and outside wheels (referring to Fig. 5), v_{xi}, and v_{xo}, could be yield straightforwardly by taking the vector component of v_i, and v_o in longitudinal direction.

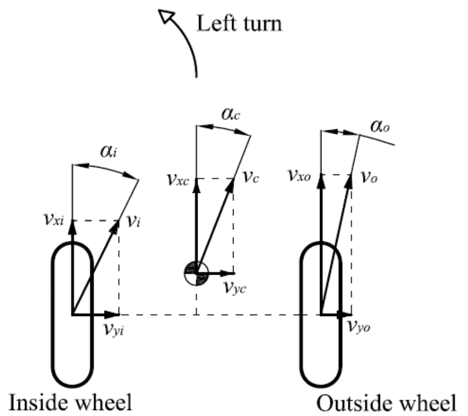


Figure5: Velocity vector components of driving wheels (top view)

3.2.2 Slip ratio control

When the vehicle is turning left as shown in Fig. 5, the speeds of driving wheels should be controlled at the desired speeds of v_{xi}, and v_{xo} to satisfy differential relation. In order to avoid skidding, the slip ratio needs to be monitored and controlled.

The slip ratio can be calculated by using Eqs. (5) and (6)

$$\lambda_i = \frac{r_i\,\omega_i - v_t \dfrac{R_i}{R_t}\cos\alpha_i}{r_i\,\omega_i} \quad (5)$$

$$\lambda_o = \frac{r_o\,\omega_o - v_t \dfrac{R_o}{R_t}\cos\alpha_o}{r_o\,\omega_o} \quad (6)$$

The symbols r_i and r_o represent the inside and the outside wheels' radii, respectively. The symbols ω_i and ω_o represent the inside and the outside wheels' angular velocities, respectively. The vehicle speed is estimated by using the speed v_t of the rear wheel, which can freely roll and rotate.
The slip ratios of driving wheels are controlled not exceeding 0.2, to keep the traction force in the stable zone and not drop abruptly.

4 Experimental study

4.1 Experimental platform

The experimental platform is as shown in Fig. 6. Two independent powered-wheels are equipped, which are driven by a 3-kW hub motor, respectively.

Figure6: Experimental platform of ITRI LEV

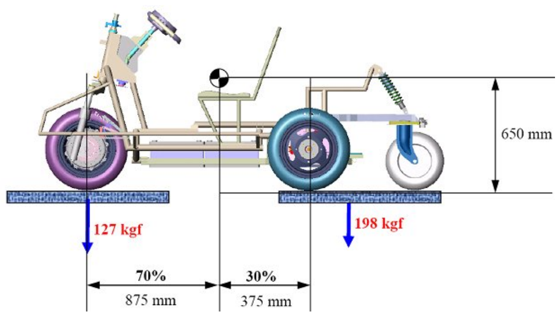


Figure7: Weight distribution of experimental platform

The experimental platform is weighted 250 kg, and the test driver is 75 kg. The total weight is 325 kg, and its weight distribution is arranged as Fig. 7.

4.2 Driving tests

The experimental platform was driven to trace a 20-m radius circle. For safety purpose, the maximal speed was limited to 32 kph which generated 0.4G lateral acceleration. The speeds of front wheel and independent powered-wheels were measured, and the steer angle was also recorded. Some results are discussed in the following sub-section. When the experimental platform was tracing the 20-m radius circle, the vehicle could tilt as shown in Fig. 8.

Figure8: Tilting motion of experimental platform

4.3 Results and discussions

According to the experimental results, the proposed stability control system could effectively alter the over-slip of the driving wheels.

The normalized speed difference is defined as the following equation:

$$\Delta v_n = \frac{\Delta v}{\bar{v}} \tag{7}$$

where Δv is the speed difference (experimental data) of driving wheels, and $\bar{v}$ is the approximate vehicle speed based on the front wheel speed. Ideally, the Δv_n should be a constant that implies the driving wheels' speeds' are kept in a perfect differential relation, in spite of different vehicle speeds.

Referring to Fig. 9, the normalized speed differentiation is plotted. When the vehicle was under control, the normalized speed difference was maintained 0.12 averagely. However, if the stability controller was disabled, the normalized speed difference fluctuated ranged within 0-0.6 that represented improper speed difference occurred due to over-slip of the driving wheels. The proposed control system could alleviate the over-slip and reduce the risk of unfavorable skid.

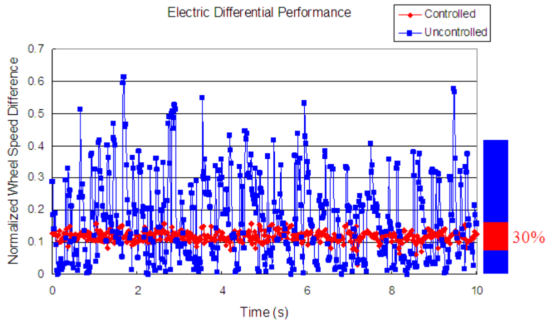


Figure9: Anti-skid performance

Figure 10 shows the steer characteristic of the LEV. In general, the steer characteristic was oversteering since the steer angle decreased along with the increasing cornering speed (increasing lateral acceleration). However, if the stability controller was disabled, the driver had to fix the steer angle hardly to keep the vehicle on track. On contrast, if the stability controller was enabled, the driver was relatively easier to maneuver the vehicle on track without fixing the steering angle all the time. The steer angle variation became severe when lateral acceleration is larger than 0.3G without control, but the steer angle decreased relatively smoothly although the lateral acceleration reached 0.4G with control. That is 25% improvement in lateral acceleration, equivalently 12% improvement in cornering speed.

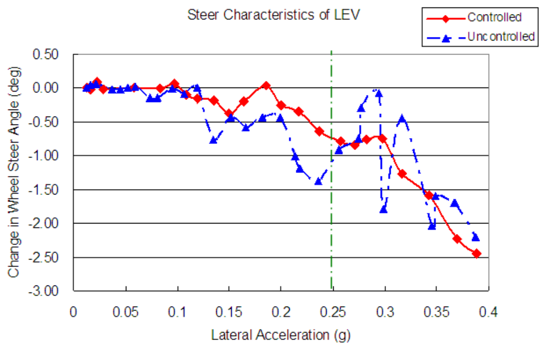


Figure10: Experimental platform of ITRI LEV

5 Conclusions

This paper introduces the stability control system of ITRI LEV in overall. The purpose, control scheme and experimental validations are presented. According to experimental results, when the active-tilting system is enabled, the vehicle's anti-rollover capability achieves 0.4G, 30% improvement equivalently. As for the anti-skid system, the maximal vehicle speed can be increased to 12% without skidding. In summary, the integrated system of active-tilting and anti-skid controllers could facilitate drivers manoeuvring the LEV, meanwhile, the stability of the vehicle dynamics is easily taken control.

References

[1] Y. Y. Peng, C. H. Li, J. H. Wang, and T. H. Gau, *Highly Maneuverable Mobility Platform for Personal Vehicle*, SAE International Proceedings, Transaction of Vehicle Dynamics and Simulation, SP-2138(2007), 311-318

[2] C. H. Li, Y. Y. Peng, T. H. Gau, J. H. Wang, and C. P. Chien, *Differential Control System for Rhombus-chassis Electric Vehicles with Independent-powered Wheels*, Proceedings of International Mechanical Engineering Congress and Exposition – ASME, Paper No. IMECE2008-66211(2008), Boston, USA

[3] Y. Hori, *Future Vehicle Driven by Electricity and Control—Research on Four-Wheel-Motored "UOT Electric March II"*, IEEE Transactions on Industrial Electronics, 51(2004), No. 5, 954-962

[4] B. C. Cheng, C. C. Yu, W. S. Lee, and W. F. Hsu, *Design of an Electric Differential System for Three-wheeled Electric Welfare Vehicles with Driver-in-the-Loop Verification*, IEEE Transactions on Vehicular Technology, 56(2007), No. 4, 1498-1505

[5] M. Shino and M. Nagai, *Independent Wheel Torque Control of Small-scale Electric Vehicle for Handling and Stability Improvemen*t, JSAE Review, 24(2003), 449-456

Authors

Li Cheng-Ho received the Ph.D. degree in power mechanical engineering from the National Tsing-Hua University, Hsinchu, Taiwan, R.O.C., in 2008. He is a researcher in the division of intelligent mobility technology at the Industrial Technology Research Institute.
His research interests include vehicle dynamics control, and vehicle mechanism design, analysis.

Chien Ching-Ping received the M.S. degree in Department of Energy and Refrigerating Air-Conditioning Engineering form National Taipei University of Technology, Taipei, Taiwan, in 2003. He has been working at the Department of Green Vehicle System Technology ,Industrial Technology Research Institute (ITRI), Hsin Chu, Taiwan. His current research interests include micro-electromchanical systems, vehicle dynamics and circuit design.