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Tilting motion control of narrow tilting vehicles

Chun-Ying Lin[1], C.-P. Chien[2], Jin-Chern Chiou[3], Chih-Liang Chen[1], James H. Wang[2], C. H Li[2]

[1]*PHD student of Department of Electrical and Control Engineering, National Chiao-Tung University of Taiwan*
[2]*MIRL of Industrial Technology Research Institute of Taiwan, ROC*
[3]*Professor of Department of Electrical and Control Engineering, National Chiao-Tung University of Taiwan*

Abstract

In this paper a narrow tilting vehicle (NTV), called (Intelligent Personal Mobility, IPM) was introduced. The IPM body can tilt to prevent from rollover. This paper proposed its tilting control strategy. The tilting motion controller was proposed. The controller is a double-loop PID controller. One loop controls the tilting rate, and the other controls the tilting position and encloses the tilting rate controller. The controller was verified by working with a verified multi-body dynamic model. This model was verified by comparing with the real experimental tests with the IPM concept vehicle. The controller was verified that it can make IPM realize the tilting command well.

Keywords: vehicle anti-roll, double-loop PID, narrow tilting vehicle.

1 Introduction

In recently years, energy-conservation and reducing pollutant emissions have become a major concern of environment and economy. How to manufacture energy-saving vehicles is an important issue in currently car design. Furthermore, growth of traffic congestion is a problem in cities all over the world. Because building new highways to match the growth rate of vehicles is not an easy task, find the way to increase the utility rate of existing highways will play a important role in this problem [1]-[3]. In United States, the average number of occupants per vehicle is 1.58 [4]. It means that vehicles are usually underutilized due to conveying unnecessary weight. In addition, amounts of pollution and fuel are produced and consumed when transport the unnecessary weight.

To solve the problem, the designed configuration of NTV has a seating capacity of 2 passengers. This configuration will decrease the vehicle width, so that the vehicle has great potential to reduce fuel consumption, double road capacity and increase parking capacity (Fig. 1).

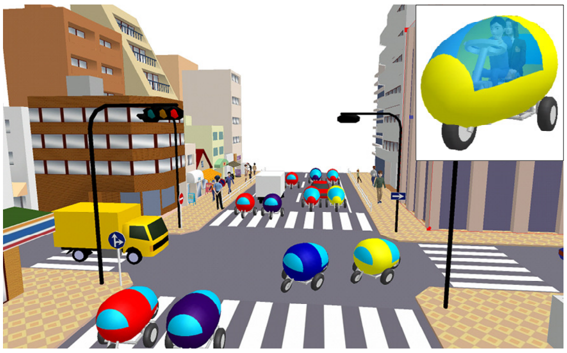

Fig. 1. The NTV concept.

However, NTV must be tall enough to provide good visibility for drivers, but tall narrow vehicle has higher center of gravity and track width ratio so that it includes some problems [5]. If NTVs are handled in curves, they require a tilting function that mimics two-wheeled vehicles. The tilting function should also be designed to protect drivers in accidentally situations, for example, suddenly contacting lateral road slopes or potholes.

Several NTV prototypes have been developed by the automotive industry over the past 50 years. The Gyron, Ford's earliest NTV design, used a 180-pound gyroscope for cornering stabilization and featured retractable wheel pods for parked vehicles [5]; the weight of the gyroscope is now considered excessive. In the 1970s, General Motors developed the three-wheeled Lean Machine, consisting of a non-tilting rear engine pod attached to a rotating body module plus a driver-operated foot pedal that controls a tilt-stabilizing actuator [6]. Also in the 1970s, BSA developed a vehicle based on James Staley and William Hillman's Ariel tricycle, in which driver movement controlled tilt [7]. Yamaha, Kawasaki, and Honda all developed similar prototypes the following decade [8]–[10].

Several NTV concept vehicles are currently under development: The Mercedes-Benz F-300 Life-jet tilt control system makes use of a hydraulic actuator. Carver Europe is working on a Carver One vehicle that also uses a hydraulic actuator. Toyota's state-of-the-art i-Swing has a switching function between two modes: two-wheel mode for low speed and three-wheel mode for high speed. The i-Swing also features artificial intelligence software for learning individual driver habits and a pedal-controlled tilting mechanism that allows operators to turn in the same manner as snowboarders. Other private firms working on prototypes are the Narrow Car Company and COVCO Ltd.. Several academic research centers are making contributions to this subject with the best-known European Compact Low Emission VEhicle for uRban transport (CLEVER).

This decade, in order to control the tilting motion of NTV, A few tilting motion control strategies have developed. University of Minnesota has designed a NTV.[11]-[12] It has two non-driven front wheels, one driven rear wheel, and powered a usual 50c.c. motorcycle engine. The tilting motion was performed by a servomotor.

The design of CLEVER[13] which uses hydraulic tilting actuation has one non-driven front wheel and two driven rear wheel. Its tilting control strategy is using Ackermann theory to calculate an open-loop tilting angle, then use a lateral acceleration signal to complete feedback control. Finally, it uses a yaw rate signal to correct its tilting angle.

The mechanism design and control strategies of Carver One [14] are similar to CLEVER. These developments are all focus on how to increase the cornering stability.

To implement the control strategies, we convert the controller designed in this paper to a double loop PID controller systematically; the stability of the double PID controller was verified in this paper.

2 The Mechanism of NTV

The assembled IPM is shown in Fig. 2. IPM NTV is a major project (Light Electric Vehicle Project) of the Mechanical Industry Research Laboratories of the Industrial Technology Research Institute of Taiwan. The diamond-shaped prototype has one front wheel for steering, two side wheels, and one castor rear wheel—each with suitable shock absorber to increase the stability. The weight is less than 210kg, the length is about 2.3 meter, the width is about 1 meter, and the seat height is about 0.6 meter, as shown in Fig. 3.

Fig. 2. The assemble IPM

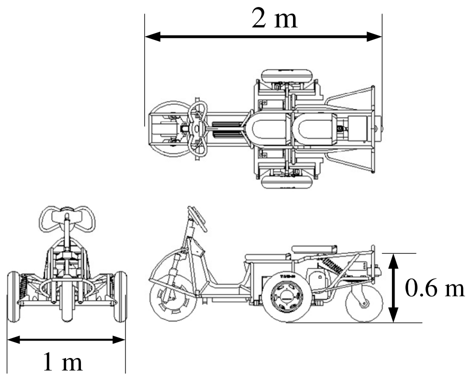

Fig. 3. The measurement of IPM

The entire vehicle is capable of tilting around a roll center. Fig. 4 shows the simplified tilting mechanism (slider-crank six-link system.) of the prototype. To consider driver's safety, tilting limiters have been integrated into the system.

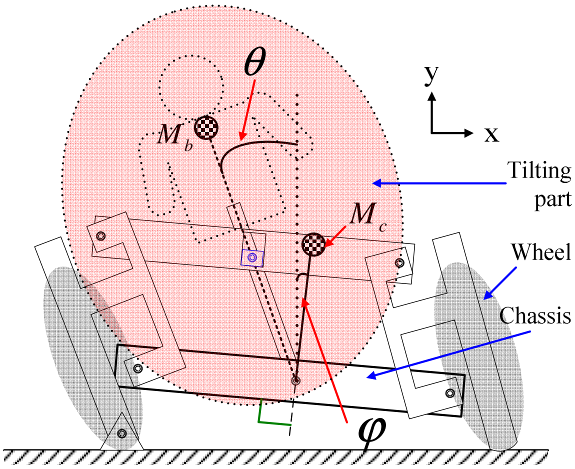

Fig. 4. Simplified tilting mechanism

The situation of vehicle cornering is shown as Fig. 5; IPM uses its tilting mechanism to balance the centrifugal force (rollover torque, yellow dotted line) and the gravity (anti-roll torque, green dotted line). This will increase the cornering stability. The front wheel is powered by a commercially available in-wheel motor from electric scooters. Some parts were designed and made up by our project group, including the steering mechanism mounting frame, rear suspension, and chassis. An original rectangular chassis was used to mount the tilting mechanism, batteries, dampers, side wheels, rear wheel frame, and other vehicle parts. The front fork, shock absorbers, and wheels were taken from commercially available scooters.

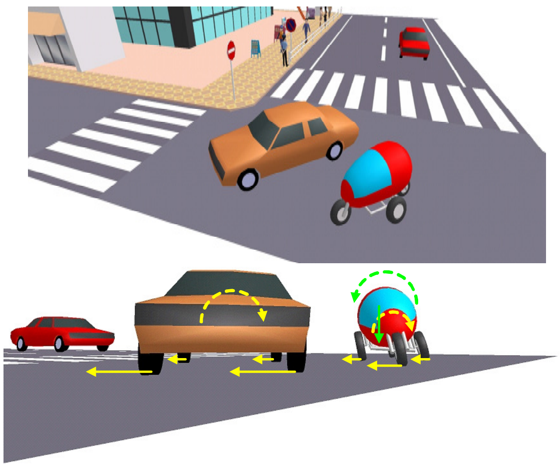

Fig. 5. IPM cornering

To consider convenient for parking and driving on urban streets, the motion of on-spot cornering also be designed, as shown in Fig. 6.

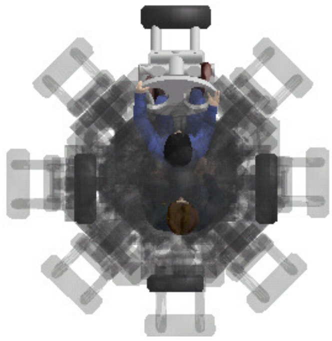

Fig. 6. On-spot cornering

3 IPM Multibody Model

In order to analyze IPM's tilting and rolling dynamics, a planar multibody dynamic system model of IPM were constructed and verified. Essential moving and non-moving parts can be distinguished by observing how they affect system dynamics. The joints are also used for relative motion constraint between vehicle sections. Several data are required in this system: center of mass, moment of inertia, initial position of mass center, principle body axes, joint types, and locations of joint-body connections, then we can construct and solve the differential-algebraic equations (DAEs) easily. This model was shown in Fig. 7. If the external forces are known, we can obtain the dynamics of the IPM. The designed controller would be integrated with the model and verified.

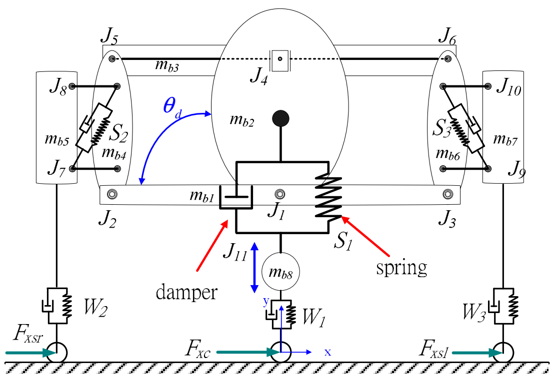

Fig. 7. IPM roll plane multibody model.

4 Verification of the Model

To verify the model, we created the small slalom course illustrated in Fig. 8, *R* and d are denoted the curve radius and width. In our test, R is 25 m and d is 4 m, the driving speeds are 5.5, 6.9 and 8.0 m/sec.

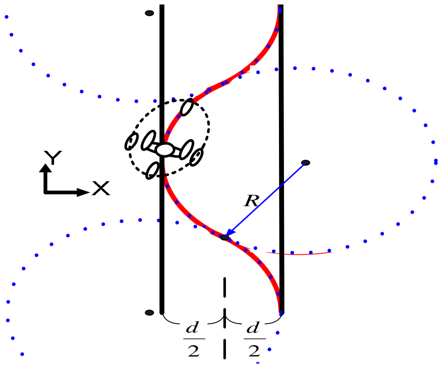

Fig. 8. Designed slalom test

To sense the acceleration of m_{b1} and m_{b2} and tilting angle between them in experiment, two accelerometers and one tilting angle sensor are set up on IPM. Fig. 8 shows IPM in slalom test.

Fig. 8. IPM in slalom test

After obtaining the accelerations and tilting angle, ground force data can be calculated by the proposed method [10], which are necessary to simulations. To compensate for vehicle vibration, acceleration and angle signals were filtered by a 3Hz low pass filter. The data are compared between model and IPM, as shown in follows: m_{b1} roll angles at each speed without tilting motion in Fig. 9, m_{b1} roll angles at each speed with tilting motion in Fig. 10, m_{b2} roll angles at each speed without tilting motion in Fig. 11, and m_{b2} roll angles at each speed with tilting motion in Fig. 12.

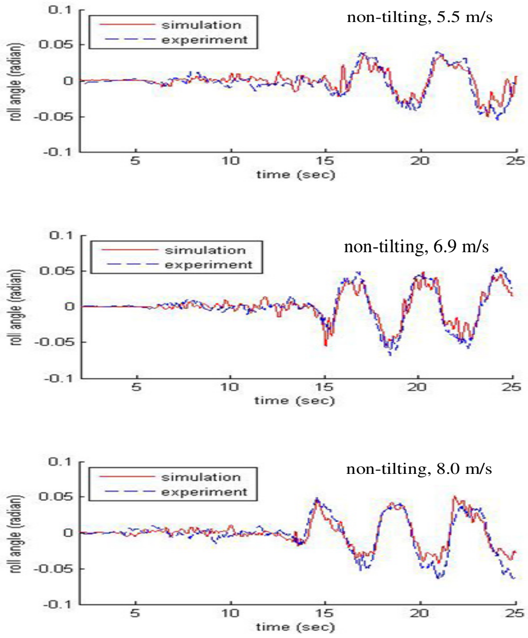

Fig. 9. Roll angle of m_{b1} for model and vehicle without tilting.

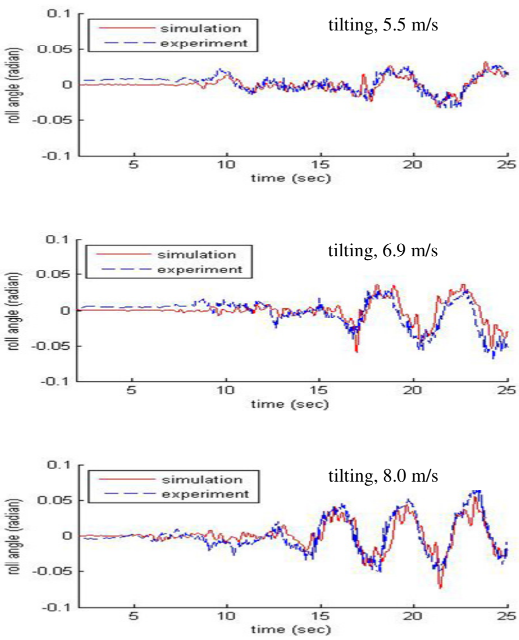

Fig. 10. Roll angle of m_{b1} for model and vehicle with tilting.

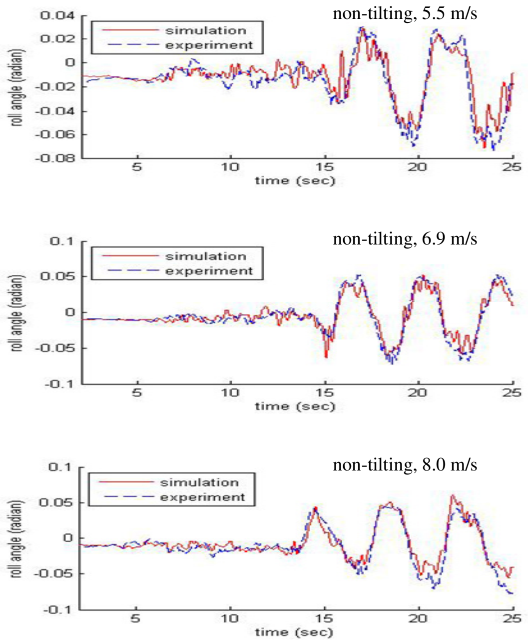

Fig. 11. Roll angle of m_{b2} for model and vehicle without tilting.

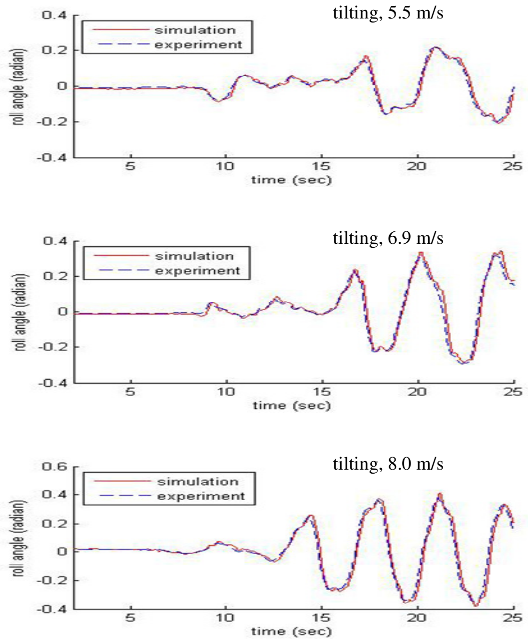

Fig. 12. Roll angle of m_{b2} for model and vehicle with tilting.

As noted in the figures, simulation results were very close to experiment data. Possible reasons for inaccuracy are (a) joint frictions were ignored in the model, (b) small road roughness violated the force input assumptions [2], and (c) sensor signals were inaccurate. However, the model still did accurately approximate the roll plane motion of the vehicle; that proves the model can be used to simulate hazardous driving conditions.

5 Tilting motion controller

5.1 Strategy of Tilting Motion Control

Two control strategies are developed in reference [2] and [7]: Direct Tilting Control, DTC, and Steering Tilt Control, STC. DTC is directly calculating the tilting angle by measured lateral acceleration, and then calculating corresponding torque. STC is using the steer signal convert to approximate cornering track, then calculate the tilting angle and corresponding torque. Advantage of DTC is easy to calculate. However, the lateral acceleration signal is a passive signal after the steering motion, it may produce some problems of time delay. Advantage of STC is faster response, but the approximations of cornering track for different drivers are distinct, some errors will be induced.

In this paper, we integrate strategies of STC and DTC to increase cornering stability of IPM.

5.2 Construction of Double-Loop PID

To realize the tilting motion controller easier, we want to design the tilting motion controller in PID type, because PID controllers have been extensively applied in industry. A general transfer function from PID controller input to output was shown in equation (1). K_P is proportional coefficient. K_I is integration coefficient. K_D is differential coefficient. The controller structure was designed as double-loop PID controller with tilting rate control loop and tilting position control loop as shown in Fig. 13. G_m denotes gain margin and W_g is the corresponding frequency. P_m denotes gain margin and W_p is the corresponding frequency. PID_r denotes the PID controller for tilting rate control. PID_p denotes the PID controller for tilting position control, and it encloses the tilting rate control loop. All the feedback signals are filtered by a 3 Hz low pass filter for filtering out undesired vibrations. This structure can help control tilting motion more precisely.

$$PID(s) = \frac{K_D s^2 + K_P s + K_I}{s} \qquad (1)$$

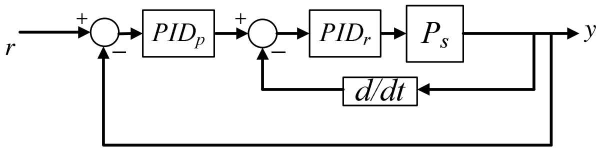

Fig. 13. The double-loop PID controller

6 Road Disturbance Input

Generally, the small road roughnesses are ignored in vehicle dynamic analysis. However, vehicles are always affected by the impact force (red arrow, blue arrow denotes the normal force affected by the impact force) when traveling through a lump, as shown in Fig. 14. To analyze the effect upon the IPM dynamics while it is traveling through a lumpy road, some road disturbances are built. Because we focus on the tilting motion of IPM, we analyzed the vertical road disturbance here (the torque induced by horizontal road disturbances can be treated as a torque from vertical ones). For significant analysis, we simplified the disturbance as sine wave form as shown in Fig. 15. A denotes the amplitude. L denotes the half-wavelength. y and $\dot{y}$ denote height and rising rate of road. According to the relationship between traveling speeds and sine wave, y and $\dot{y}$ can be computed. These road disturbances are imported into tire force model. The inputs and the tire force model can help us to analyze how the disturbances influence IPM dynamics and controller performance.

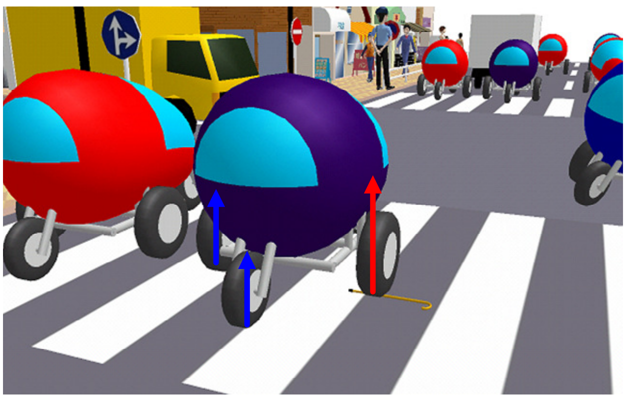

Fig. 14. IPM suffers road disturbance.

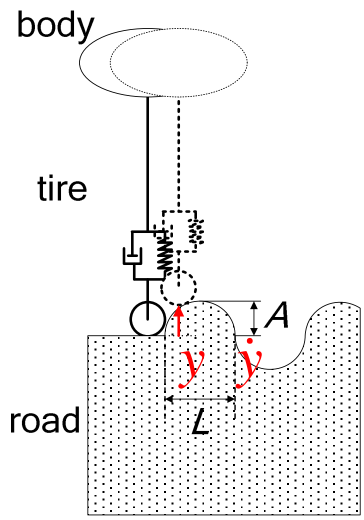

Fig.15. Simplified road disturbances.

7 Verification of the Controller

7.1 Verified double-loop PID controller

The parameters of the double-loop controller are shown in equation (2) and (3). To verify the controller, we executed slalom test which radius is 25m at speed of 8, 10 and 13m/sec. Fig. 16 shows the tilting motion of slalom test at speed 8m/sec, the red line is command from double-loop PID controller and the blue line is actual tilting motion of IPM. Similarly, slalom tests at speed 10 and 13 m/s are shown in Fig. 17 and Fig.18. According to Fig. 14-16, the tilting motion of controlled IPM could follow the tilting command well; this shows the feasibility of the double-PID construction is verified by the experiments.

$$PID_r(s) = \frac{33.7s^2 + 521.9s + 112.2}{s} \tag{2}$$

$$PID_p(s) = \frac{0.3s^2 + 9.3s + 2}{s} \tag{3}$$

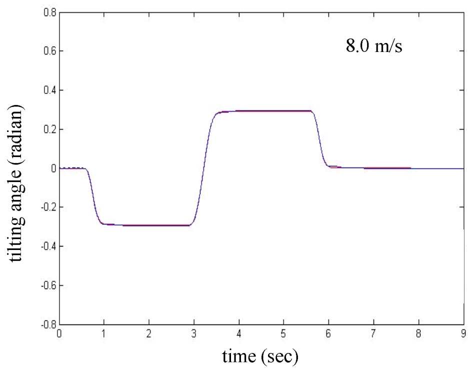

Fig. 16. slalom test at speed of 8 m/sec

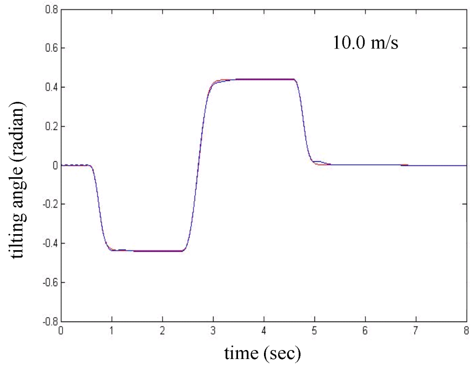

Fig. 17. slalom test at speed of 10 m/sec

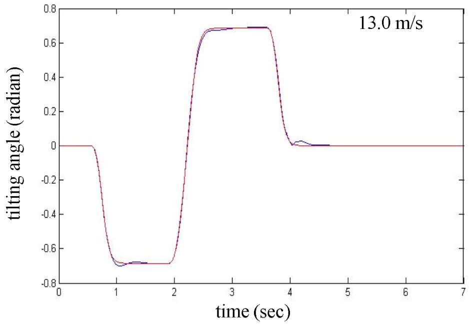

Fig.

Fig. 18. slalom test at speed of 13 m/sec

7.2 Verified the robustness of double-loop PID controller

In order to verify tracking robustness of the double-loop PID controller, it executed the slalom test at speed of 6, 8, 10 and 12 m/s, under tilting command and road disturbances. Fig. 19 shows it executed the slalom test with road disturbances (*A*=0.02m, *L*=0.2m). Fig. 20 shows it executed the slalom test with road disturbances (*A*=0.02m, *L*=0.4m). These figures show the double-loop PID controller can follow the tilting command well under the road disturbances. The tracking errors are smaller than 0.02 radian (1.3 deg). These figures also show the system tracking errors will be larger when tilting angle was close to 0.25 radians (at speed of 8.0 m/s in figures 19 and 20). It means the mode of the system for tilting motions locate in 10~20 Hz at the angle. However, the tilting motion still could be controlled well by the designed controller.

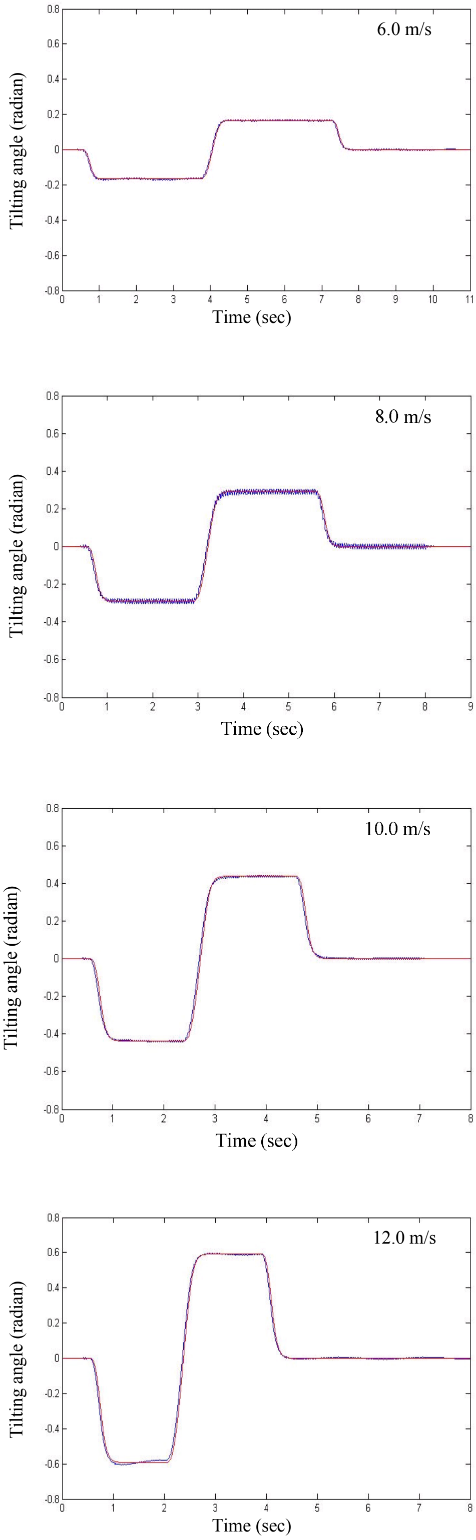

Fig. 19. Tilting motion in the slalom test with road disturbances (A=0.02m, L=0.2m).

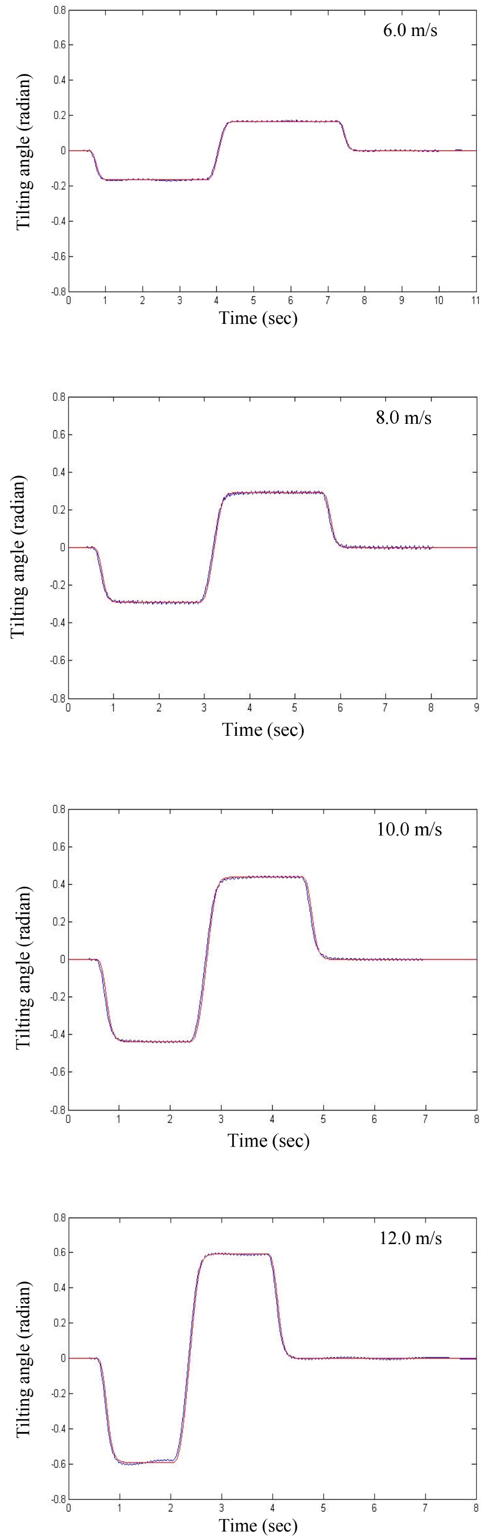

Fig. 20. Tilting motion in the slalom test with road disturbances (A=0.02m, L=0.4m).

7.3 Considering some internal influences

Now we consider some internal influences which may come from transient influences of torques exerting and other immeasurable mechanical interactions. Furthermore, we assume that internal influences induce an internal 2nd order system between the controller and the plant. We assume the settling time is 2.0ms and overshoot is 3%. Then we execute the slalom test at speed of 13m/s, under tilting command and road disturbances. The amplitude and half-wavelength of road disturbances are 0.02 m and 0.2/0.4m. Fig. 21 shows it executed straight traveling with road disturbances (*A*=0.02m, *L*=0.4m). Fig. 22 shows it executed the slalom test without road disturbances. Fig. 23 shows it executed the slalom test with road disturbances (*A*=0.02m, *L*=0.2m). Fig. 24 shows it executed the slalom test with road disturbances (*A*=0.02m, *L*=0.4m). These figures show even if under the assumed internal influences and the above-motioned disturbances, the tracking robustness is still high. The overshoot of tilting motions comes from the transient of the internal 2nd order system. If the settling time of the 2nd order system is shorter, the overshoot will be smaller.

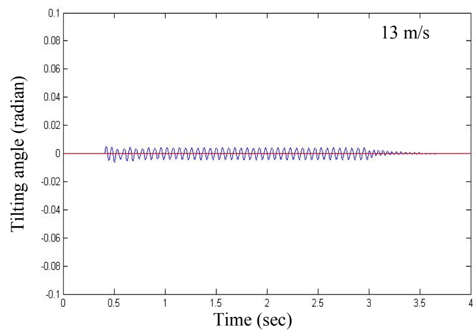

Fig. 21. Tilting motion in straight traveling with road disturbances (*A*=0.02m, *L*=0.4m).

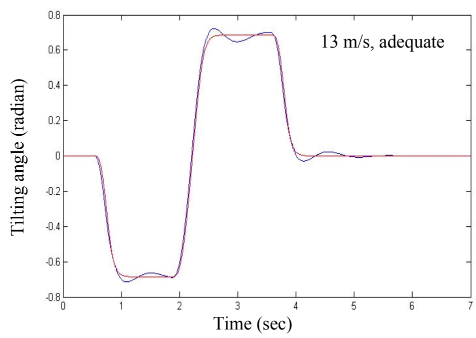

Fig. 22. tilting motion in the slalom test without road disturbances.

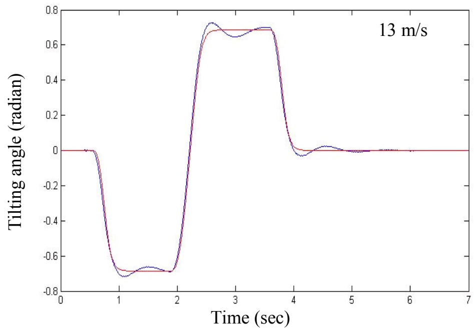

Fig. 23. Tilting motion (consider the internal influences) in the slalom test with road disturbances (A=0.02m, L=0.2m)

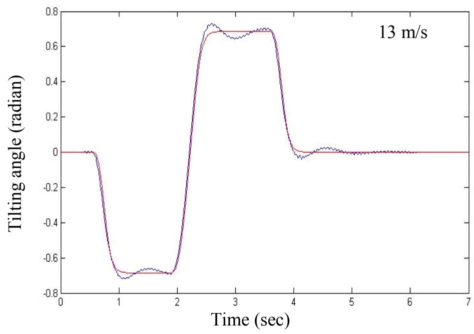

Fig. 24. Tilting motion (consider the internal influences) in the slalom test with road disturbances (A=0.02m, L=0.4m)

7 Conclusion

In this paper, we designed a controller for IPM NTV tilting motion control, for implement purpose ,we translate it into double-loop PID controller by systematic method. The control strategy helps IPM NTV earn more tracking robustness when doing tilting motions. An IPM multibody model and tracking robustness for tilting motions were verified by comparing with real test and executing several tests under road disturbances and some assumed internal influences. The results show the double-loop PID controller has high tracking robustness for tilting motions. With this controller design, we can prove the reliability and safety of IPM NTV when suffering usual road disturbances.

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Authors

Jin-Chern Chiou received the M.S. and Ph.D. degrees in aerospace engineering science from the University of Colorado, Boulder, in 1986 and 1990, respectively. He was a Research Associate at the Center for Space Structure and Control, University of Colorado at Boulder. Since 1992, he has been with the Department of Electrical and Control Engineering, National Chiao Tung University (NCTU), Hsin Chu, Taiwan. His current research interests include micro-electromechanical systems, fuzzy-logic modeling, chemical vapor deposition process control, CD-ROM and DVD servo control, and multibody dynamic system modeling. Dr. Chiou has received awards from the Acer Foundation, NCTU, and the Republic of China National Science Council for his CD-ROM and microelectro-mechanical systems (MEMS) research.

Chun-Ying Lin received the B.S. degree in civil engineering from the National Chiao Tung University, Hsin Chu, Taiwan, in 2004. and the M.S. degree in Department of Electrical Engineering form National Sun Yat-Sen University, Kaohsiung, Taiwan, in 2006. He is currently working toward the Ph.D. degree at the Department of Electrical and Control Engineering, National Chiao Tung University, Hsin Chu, Taiwan. His current research interests include micro-electromchanical systems, vehicle dynamics and circuit design.

C.-P. Chien received the B.S. degree in Energy and Refrigerating Air-Conditioning Engineering from the National Taipei University of Technology, Taipei, Taiwan, in 2001. and 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 with 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.

Chih-Liang Chen received the B.A.Sc. (with honors) degree in power mechanical engineering from the National Tsing Hua University, Hsinchu City, Taiwan, in 2001. He is currently working toward the Ph.D. degree at theDepartment of Electrical and Control Engineering, National Chiao Tung University, Hsin Chu, Taiwan. His current research interests include vehicle dynamics, system modeling, and circuit design.