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Vehicle Inter-dependent Control Transmission Architectures - VICTA

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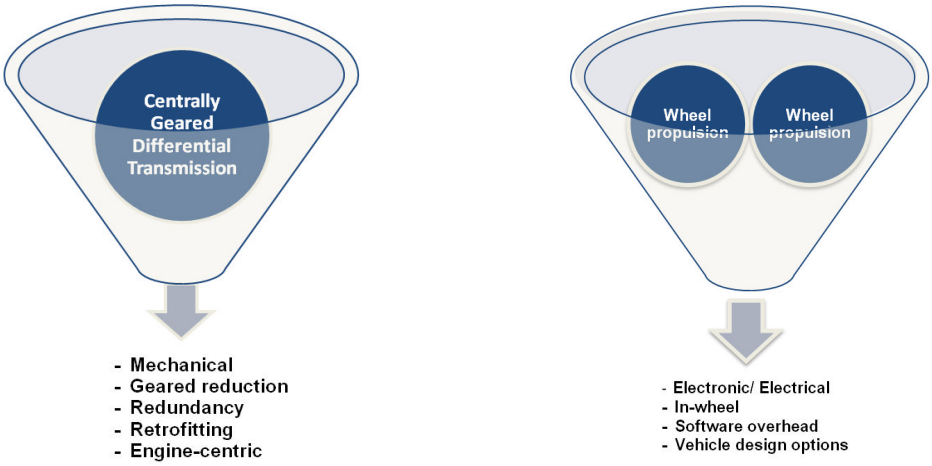
Abstract— This paper proposes a novel hybridized vehicle inter-dependent control transmission architecture (VICTA) that offers key advantages over existing systems. It embodies a compact torque generation system formed by two or more *electric* machines axially linked through a conventional *mechanical* differential gear assembly by means of a simple yet innovative pair of co-axial shafts. The resultant *electric-mechanical* hybridized drivetrain system allows a unique and automatic way of transmitting, differentially and inter-dependently, the electromagnetic torques generated by the motors at either side of differential gear. A realistic virtual prototype of the VICTA based on *MATLAB/Simulink* modules is developed to validate the concept. Comprehensive performance prediction tests, including steering maneuvering and variations of the road surface, are undertaken. Excellent simulation results from the VICTA virtual prototype demonstrate its stability and motility performance. The results also confirm the VICTA concept has key advantages such as reliability, modularity, high efficiency and simplicity, and yet does not inherit the undesirable features of high unsprung mass or complex software control that continue to challenge and even flaw the existing systems.

Keywords—*Electric drivetrain, in-wheel motor, inter-dependent control, differential gears, VICTA.*

1. Overview of Electric Drivetrains

Due to the increasing superiority of modern electric machines over internal combustion engines in terms of dynamic response, torque density, higher efficiency, ability to recuperate energy, low/zero tail-pipe emission, electric drivetrains are becoming popular in the next-generation cars among major automotive manufacturers.

Currently the design mindset for electric drivetrain appears to be deeply influenced by the well-proven centrally driven transmission system, in which an electric motor drives the wheels of the vehicle through a set of reduction and differential gears. Both the efficiency and dynamic response of these systems are generally not high due to the number of gears involved. The assembly is generally complex involving a high number of mechanical components. For low volume production, the overhead cost for assembly and manufacture will be high. Adaptors of this configuration, notably Toyota Prius, tend to use a retrofitting approach to reduce the overhead and minimize risks. Whilst the success of Prius demonstrates the considerable advantage of developing a new technology based on an existing highly successful business model and powerful market position, it may also affects significantly automotive industry's research strategies by undermining lateral thinking. As illustration in



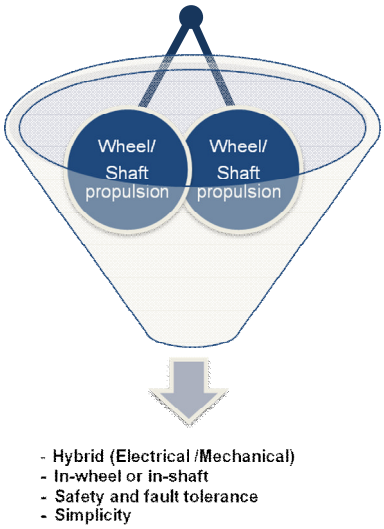
(a) Centralized drive e.g. Prius (b) Independent wheel e.g. MIEV

Fig.1 Design funnels for state of the art electric drivetrain configurations

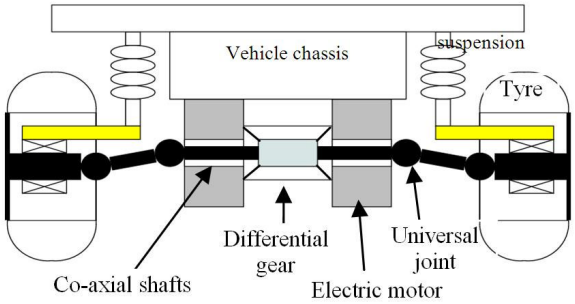
Fig.1(a), the main features filtered out from the 'design funnel' of current mechanical transmission based electric powertrains, such as retrofitting, follow from that of a conventional centrally drivetrain [1]. Nonetheless, Toyota's success appears to have sparked a major paradigm shift for in-wheel propulsion, championed by Mitsubishi's In-wheel motor Electric Vehicle (MIEV) system, which replaces the mechanically-coupled transmissions with independently controlled wheel motors driven by flexible electric wires and sophisticated software. One key feature filtered out by the design funnel, illustrated in Fig.1(b), is compactness of design, more passenger space and new vehicle design option free from the transmission system. Better vehicle handling is possible because of independent wheel control. It should also be noted that the independent in-wheel control drive concept has been previously proposed [2] and rests on the premises that electronic transmission will ultimately replace mechanical transmission, offering superior features in terms of vehicle safety and passenger comfort. However, one of the well-known challenges for in-wheel drives is the increased unsprung mass which could adversely affect stability and handling of the vehicle, and thus could nullify any original advantages of in-wheel drive. Very complex control is required to ensure the motors operate reliably in all conditions. The idea of putting the 'engines' in the wheels also means extra security and costs for the assembly of the wheels. Despite comprehensive research work developed in the 90's [2], the in-wheel independent drive may still be many years away before the technology is viable for the market.

2. Vehicle Inter-dependent Control Transmission Architecture

This paper introduces a novel system called Vehicle Inter-dependent Control Transmission Architecture (VICTA), as illustrated in Fig.2. The design concept of VICTA is a radical departure from the existing systems. As shown in Fig.2(a), it is a hybridized concept that inherits many advantages of the in-wheel drive system while maintaining the robustness and reliability of the differential gear used in the centralized drive [3]. Fig.2(b) shows the VICTA system as a hybridized *electric-mechanical* system involving two motors mechanically linked through a differential gear by means of two coaxial shafts. The torque from each motor is coupled together through the differential housing. The small bevel gears, driven by the housing, will be responsible for transmitting and distributing the torques to the wheels on each side through the large bevel gears that connect with their respective semi-axles. The system thus allows a unique way of transmitting, differentially and inter-dependently, the electromagnetic torques generated by the motors at either side of differential gear**.** It will become evident that the VICTA results in higher redundancy, modularity and simplicity due to this unique hybridized configuration. Besides, it does not suffer from high unsprung weight currently associated with in-wheel electric drives.



(a) Design Funnel



(b) Schematic

Fig.2 Proposed VICTA system

3. Virtual Model of VICTA

The MATLAB/Simulink based virtual prototype consists of two main modules, one for the vehicle and the other for VICTA. The vehicle module consists of the modules of the vehicle body, the suspension and steering systems, the tyres and the motors. It has a total of 18 degrees of freedom, including a vehicle body with six degrees of freedom, and four identical wheels with a total of 12 degrees of freedom [4]. The VICTA module is essentially based on a set of dynamic and kinetic equations guided by the mechanics of the differential gear, and is linked with the vehicle module in dynamic simulation mode. The virtual prototype is developed using typical data of a passenger car. The data for the mass and moment of inertia of the vehicle parts used in the models are shown in Table 1, whereas the key vehicle dimensions, the stiffness and damping coefficients of the suspension system, and the elastic constant of the tyres, are shown in Table 2.

Table 1: Mass and moment of inertia

Mass	kg	Moment of Inertia	kg.m^2
Per Wheel	38	X-axle	347
Front Unsprung Mass	95	Y-axle	1,676
Rear Unsprung Mass	108	Z-axle	1,809
Vehicle total	1,483	Wheel	5.11

Table 2: Dimensions and the specifications of suspension and tyres

Vehicle Dimensions	m	Coefficients for Suspension and Tyres	Nm^{-1}
Wheelbase	2.662	Stiffness of Front Suspension	15,400
Tread	1.44	Stiffness of Rear Suspension	19,000
GC to Front Axle	1.225	Damping of Front Suspension	1,150
GC to Rear Axle	1.437	Damping of Rear Suspension	6,000
Height of GC	0.525	Elastic Constant of Tyre	175,000
Radius of Wheel	0.285	Damping Constant of Tyre	50

4. Performance Predictions

To test the performance of the VICTA system, steering maneuvering, variation of road surface and torque input tests are carried out on the virtual prototype to predict the stability and handling abilities of the vehicle. In particular, the slipping action, an important indicator of the differential function of the VICTA system, will be under scrutiny in the tests.

4.1 Steering Maneuver

Steering maneuver offers ideal testing conditions for the differential unit. During steering, each of the four wheels follows a different track, which will necessitate the differential gear to ensure all the tyres rotate without slip.

In this test, the vehicle starts from rest and the target speed is set to 80km/h. At the 10th second, a 15 degree step input is applied to the steering wheel to turn the vehicle to the left. Fig.3 shows the profile of the vehicle speed accelerating from rest to its target speed, reaching top speed at around t=5s.. At the 10th second, the road resistance becomes larger due to change of vehicle direction under steering, resulting in a small drop of speed afterward.

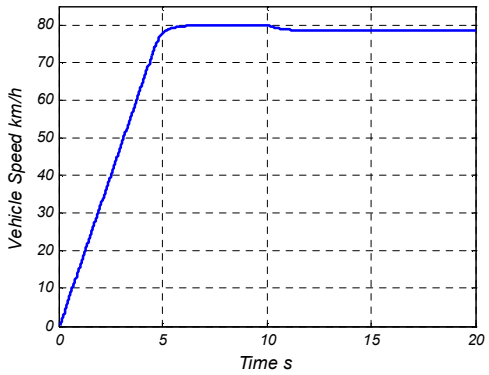


Fig.3 Vehicle speed profile with step steering at t=10s.

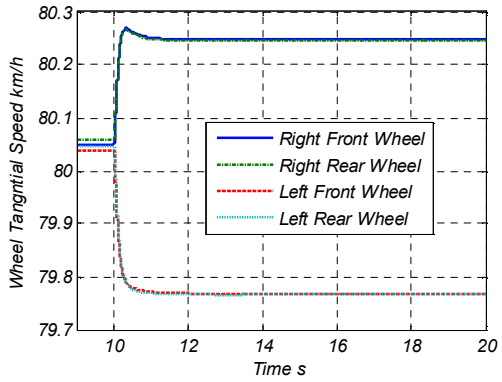


Fig.4 Wheel tangential speeds with step steering at t=10s

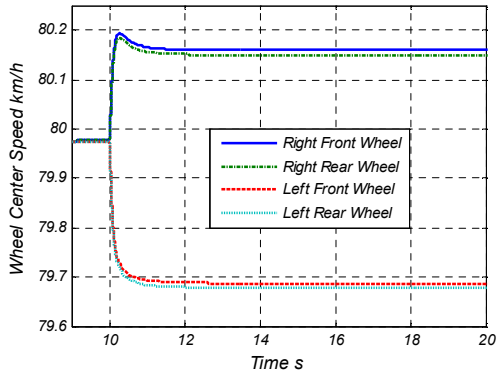


Fig.5 Wheel center speeds with step steering at t=10s

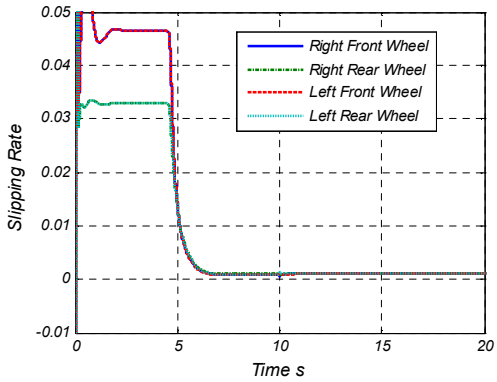


Fig.6 Slipping rates of wheels from start with step steering at t=10s.

For conventional vehicles, the wheel center speed should be almost equal to the wheel tangential speed due to the action of the differential gear. With VICTA system, the tangential and wheel speeds of the vehicle wheels are shown in Fig. 5 and Fig.6 respectively. It is evident that the tangential speed of the four wheels is essentially the same as the wheel center speed, with the outer front and rear wheels rotating faster and thus a higher velocity (80.25km/h) than that of the inner wheels (79.87km/h). Fig.7 shows the change of slipping rates of the four wheels during the step steering. It can be seen that, at the beginning of the accelerating, the slipping rate is very high but only for a very short time. It is reduced to less than 5% in less than 2 seconds. Importantly for the VICTA system, with the step steering input at the 10th second, the slipping rate is kept nearly to zero, which indicates that the differential function of VICTA works as expected.

4.2 Variation of Road Roughness

Apart from steering maneuvers, the performance on uneven road surfaces is another important criterion for the evaluation of the differential. Besides, it has great impacts on the control of vehicle vibration due to road roughness and road irregularities, and hence the quality and comfort of the drive.

In this simulation test, the prototype vehicle first accelerates to 50 km/h. At the 9.5th second, the vehicle's right front wheel enters a different terrain with a sinusoidal variation of its surface, as shown in Fig.8. The resultant slipping rates for each of the four wheels are shown in Fig.9, which shows the slipping rates of the wheels are small and at the 9.5th second, they start to follow a

sinusoidal variation as a result of the sinusoidal variation of the surface experienced by the right front wheel. Fig.10 and Fig.11 shows respectively the corresponding tangential and centre speeds of the four wheels are essentially the same, confirming the excellent performance of the differential of the VICTA system under the test condition.

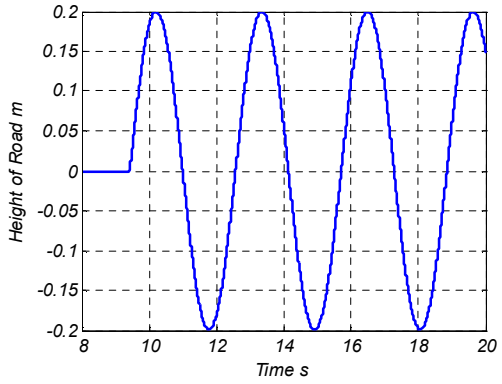


Fig.8 Variation of road surface on front right wheel

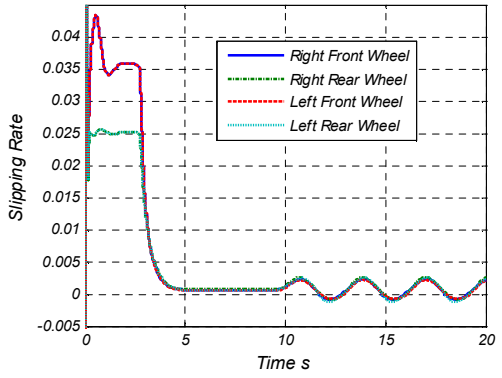


Fig.9 Slipping rates of the wheels corresponding to conditions of Fig.8

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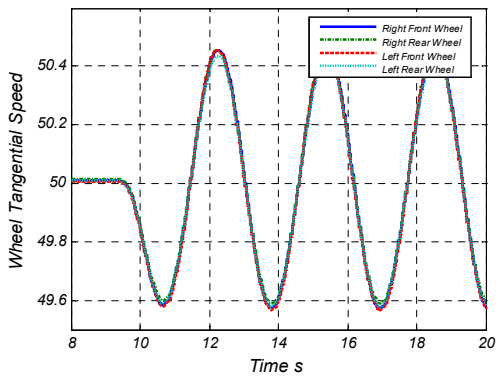


Fig.10 Wheel tangential speeds corresponding to conditions of Fig.8

Fig.12 and Fig.13 further show two more insightful dynamic responses of the four wheels under the same test condition. In Fig.12, when the front right wheel first makes contacts with the uneven road at a speed of 50kw/h, there is a sudden jump of vertical movement of the wheels, and the reaction of the suspension rapidly dampening down the vehicle vibration. Within less than one second of the first contact of the road surface change (after time=10s), the vertical velocity of the front right wheel follows a sinusoidal variation (with a 90 degrees shift as expected) due to the variation of the road surface, and very small variations in the other wheels. Fig.13 shows the corresponding center position of each of four wheels, which have a radius of 0.285m.

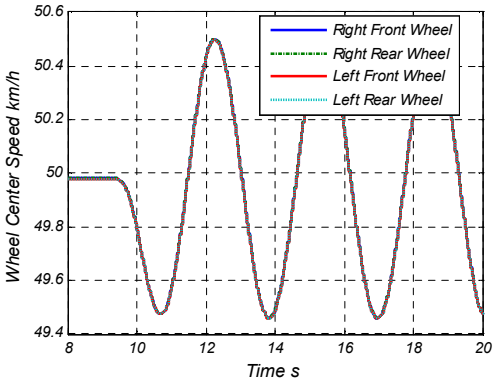


Fig.11 Wheel center speeds corresponding to conditions of Fig.8

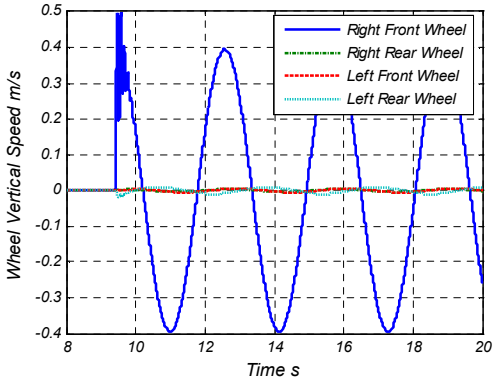


Fig.12 Wheel vertical speeds corresponding to conditions of Fig.8

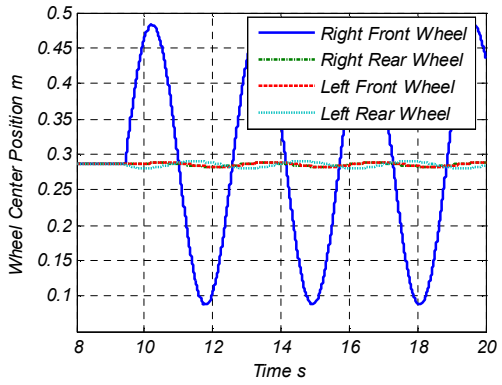


Fig.13 Wheel center positions corresponding to conditions of Fig.8

To further evaluate the performance of the VICTA system under more demanding (albeit fictitious in nature) conditions, all the four wheels of vehicle are now subject to different sinusoidal variations of road surfaces as shown in Fig. 14, with the right front wheel experiencing a larger magnitude of variation than the other three wheels, which are all subject to a smaller sinusoidal variation with the same magnitude. As before, the vehicle first accelerates to the speed of 50km/h and then enters the new terrains at t=9.5s.

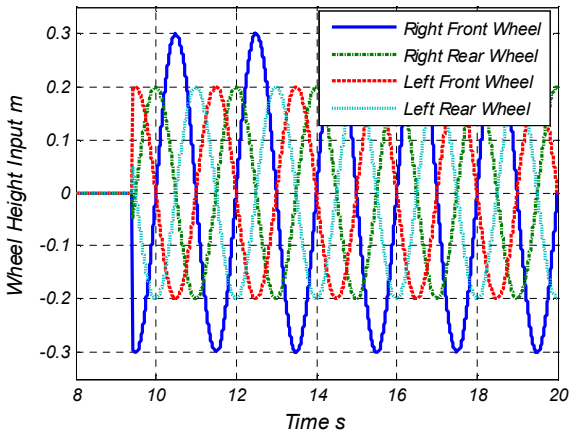


Fig.14 Variations of road surfaces on the vehicle's wheels

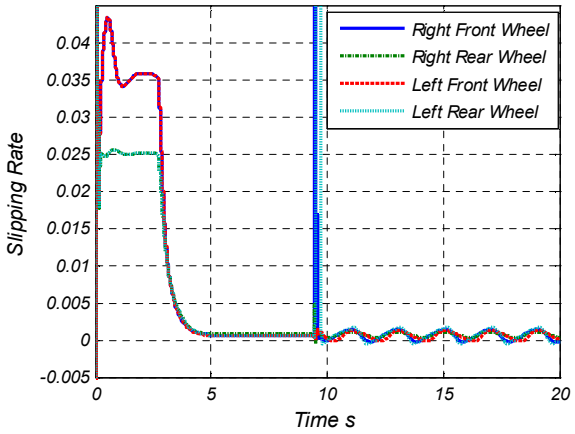


Fig.15 Slipping rates of the wheels corresponding to conditions of Fig.14

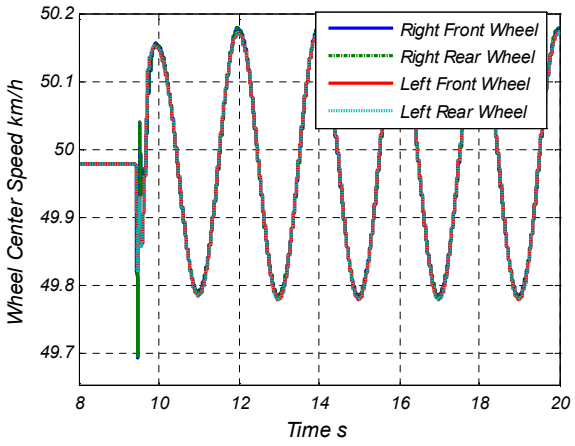


Fig.16 Wheel center Speeds corresponding to conditions of Fig.14

Fig.15 shows the respective changes of the slipping rates for each of the wheels. At t=9.5s, when each of the wheels hits the new terrain with their respective uneven surfaces, the slipping rates all jump up rapidly for a very short time, but then are quickly dampened and controlled to virtually zero by the suspension system and the excellent operations of the VICTA system. It is also shown that that the slipping rate for the front right is practically not affected by the higher magnitude of the unevenness it experiences.

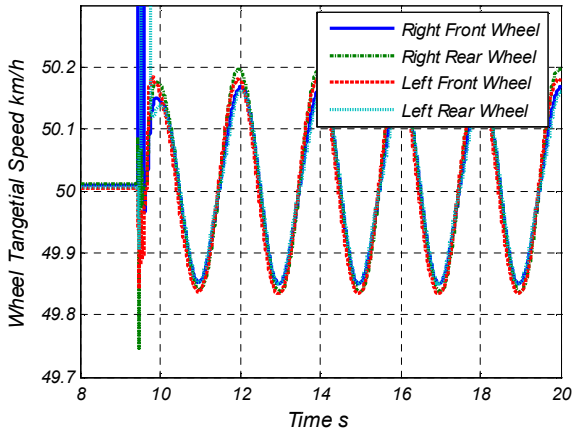


Fig.17 Wheel tangential speeds corresponding to conditions of Fig.14

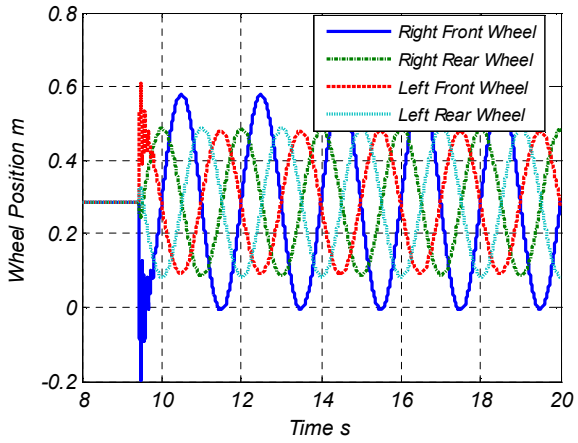


Fig.18 Wheel center positions corresponding to conditions of Fig.14

Fig. 16 and Fig.17 show the center speeds and tangential speeds of each of the wheels respectively. Similar to the effects on the slipping rates, the first wheel contacts on the uneven roads generate large overshoots on the wheel center and tangential speeds, but quickly dampened and controlled back to the normal values. After that the four wheels are synchronously running on their respectively different road surfaces. Fig.18 shows the positions of the wheels, confirming that each wheel is rotating on its own surface without slipping. These results reflect that the differential function of the VICTA system works well under demanding conditions.

4.3 Different Driving Torque Maneuver

A key feature of the VICTA system is its ability to allow the torque generated by each motor to be readily transmitted, differentially and automatically, when the wheels are subject to different loading conditions. This is a key difference from the in-wheel drive which requires complex control on each wheel.

In this test, each of the wheels is driven by its respective motor at four different torque levels - 600Nm, 480Nm, 360Nm and 240Nm respectively during acceleration as shown in Fig.19. This condition of having 4 motors of different torque outputs can be seen as an unusual condition in practice as normally the motors should be of equal rating. However, it does show that the key function of VICTA. The slipping rate is highest for the wheel driven by the highest torque, and so on, during the acceleration period until t=5s, when top speed is reached. Then, the corresponding slipping rate for each of the wheels is kept at less than 3% during this period, as can be seen in Fig.20 in conjunction with Fig.19.

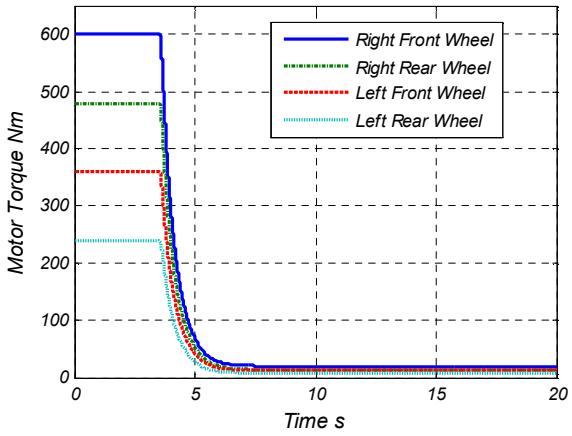


Fig.19 Different motor torque inputs to respective wheels

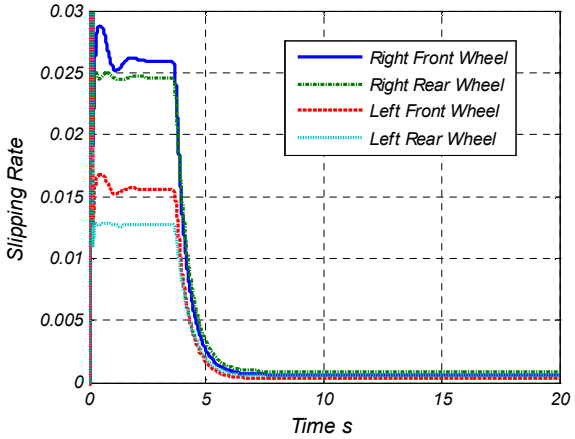


Fig.20 Wheel slipping rates corresponding the conditions of Fig.19

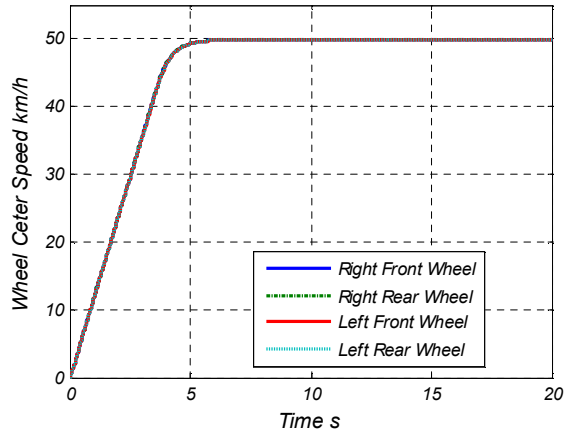


Fig. 21 Wheel center speeds corresponding the conditions of Fig.19

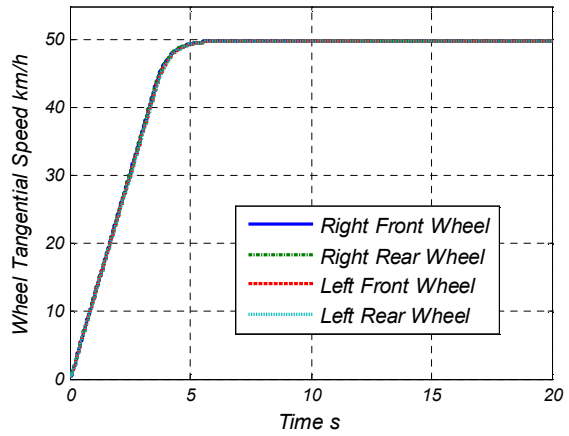


Fig.22 Wheel tangential speeds corresponding the conditions of Fig.19

When the target speed is reached at around t=5s, the slipping rates are reduced to nearly zero. The results thus show that the VICTA system manages to transmit the different torques from the motors very effectively to the wheels such that there is minimum slipping occurring even during acceleration. At steady state, there is no slipping on any wheels, even the motors are exerting different torques on each of the wheels. The speed curves in Figs.20-22 further confirm there is no slipping. The results show that the VICTA system allows motors of different output

ratings (hence different physical sizes) and/or running at different capacities to work cooperatively and automatically. This shows the key advantages of scale-ability and modularity of the VICTA system over its counterparts.

5. Conclusion

A novel electric drivetrain system called VICTA is first proposed in this paper. It is based on an innovative hybridized *electric-mechanical* concept that is radically different from the existing centralized and wheel driven systems. This is remarkably achieved by means of utilizing the well-known and well-proven operations of the differential gear. The validity of the proposed system is demonstrated by the development of a realistic virtual prototype based on Matlab/Simulink modules. The comprehensive test results, involving steering, variations of road surfaces and motor output torques, on the virtual prototype demonstrate the many advantages of the proposed VICTA system over the existing systems, which are illustrated in the comparison matrix in the Table 3.

Table 3: Comparisons Matrix for VICTA and existing systems

	Centralized drive	VICTA	In-wheel drive
Unit Cost	***	*****	*
Reliability	****	*****	**
Fault-Tolerance	**	*****	*
Efficiency	***	****	*****
Torque density	***	*****	****
Unsprung weight	*****	*****	*
No. of inverters	*****	*****	*
Clearance	***	***	*****
Maneuverability	***	***	*****
Safety	*****	*****	***
Retrofitability	*****	*****	***
Scaleability	****	*****	***

Key: ***** *excellent* * *poor*

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Dr Liqiang Jin is associate professor at the State Key Laboratory of Automotive Dynamic Simulation, Automotive College of Jilin University, China. He is a leading academic in the research of in-wheel electric driving systems in China. He holds several Chinese patents in electric drive trains. He has been the recipient of several key state funded research programmes in-wheel electric driving systems.



Changjian Hu was a 4-month internship student at Cranfield University, UK in 2010. He was instrumental in assisting the early stage developments of the VICTA model during his internship. He finished his BSc and masters from Jilin University, and he is currently enrolled for a PhD programme at Texas A&M University, US. His main research interests are in electric vehicles, including plug-ins.



Dr Ken Jinupun is currently a research fellow in the Weapon and Vehicle Group, in the Department of Engineering and Applied Science, Cranfield Defence and Security, Cranfield University, U.K. His main research interests are in electrical machines, electric vehicles, and their applications in the defence sectors.