Institution: University of Surrey		
Unit of Assessment: 12 Engineering		
Title of case study: Developing advanced controllers for electrified vehicles		
Period when the underpinning research was undertaken: 2010 - 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Aldo Sorniotti Patrick Gruber Davide Tavernini	Professor Professor Lecturer	March 2007 – present July 2009 – present January 2016 – present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

The next generation of electric vehicles require superior control systems to ensure that comfort and performance requirements are met. Car manufacturers are rapidly scaling up electrification activities. Thus, they are looking to identify control system tools and designs that will enable them to shorten development time and, ultimately, produce better products.

Control design methodologies and advanced controllers, for electric and hybrid electric vehicles with multiple motors or multiple chassis actuators, developed within the University of Surrey's Centre for Automotive Engineering have been adopted by car manufacturers, applying this insight to next- generation vehicles. As a direct result, McLaren, Elaphe, Tenneco and others have achieved efficiencies and cost savings in design development and improved performance of vehicles already in production.

2. Underpinning research (indicative maximum 500 words)

Research into controllers for electric vehicles has been conducted through a series of projects from 2010 to 2020, largely in the Centre for Automotive Engineering at the University of Surrey. The Centre itself was established in 2013 by Professor Sorniotti and now has 8 academic and >25 research staff.

The research concerns controllers for vehicles with electrified powertrains. This is a timely topic, as 80% of innovations in modern cars come from computer systems (M. Broy *et al.*, "Engineering Automotive Software," *Proceedings of the IEEE*, 2007), and information and communications technologies contribute 30% to 40% of the total value of a car (C. Buckl *et al.*, "The Software Car: Building ICT Architectures for Future Electric Vehicles," *IEEE International Electric Vehicle Conference*, 2021).

Accelerated control development techniques for vehicles with multiple chassis actuators

A first-of-its-kind methodology for the off-line design of nonlinear feedforward contributions of yaw moment **[R1]** and active suspension **[R2]** controllers was conceived, based on a quasi-static vehicle model and an optimisation routine. The method allows the computation of the control action required to achieve a reference cornering response and includes consideration of secondary criteria and relevant constraints.

The methods described above **[R1, R2]** were applied to generate feedforward vehicle dynamics control contributions **[R2, R3, R4]**, effective also in the nonlinear region of the vehicle cornering response, as confirmed by the implementations by the industrial beneficiaries **[R2, R4, R5, R6]**. This was not possible with the pre-existing control design methods and permits the 'de-tuning' of the feedback contributions, limiting the effect of sensor noise, which previously compromised the smoothness of continuously active feedback controllers.

Developing novel controllers

The Centre extended research on accelerated control development techniques and developed novel controllers for electric vehicles with multiple motors. These novel controllers:

i) enhance active safety by increasing the achievable steady-state lateral acceleration as well as yaw and sideslip damping during transients. This includes a reference yaw rate formulation that constrains sideslip angle (patent application WO 2018/178652 A1, authored by Sorniotti, Gruber, submitted by Roborace/Arrival) and tyre force-vectoring (**[R2]** and patent application WO 2020/040930 A1 authored by Sorniotti, Tavernini, submitted by Tenneco) and detailing algorithms for the variable vertical tyre load distribution through controllable suspension actuators, to track a reference yaw rate

ii) reduce energy consumption and tyre workload through optimal torque distribution (**[R4]** and patent application EP3621843 A1 authored by Sorniotti, Gruber, submitted by Roborace/Arrival) and reference understeer characteristics

iii) improve vehicle comfort, through anti-jerk control using wheel speed in addition to motor speed **[R5]**.

The anti-jerk and tyre force-vectoring can be applied also to internal combustion engine driven vehicles.

The novel controllers have been experimentally tested in collaboration with industrial partners on multiple vehicles, see Figures 1-3 **[R2, R5, R6]**.

Figure 1 – Obstacle avoidance test performed with the Elaphe's BMW X6 prototype with in-wheel powertrains, without (left) and with (right) the torque-vectoring controller developed by the Centre for Automotive Engineering, from the same initial speed.

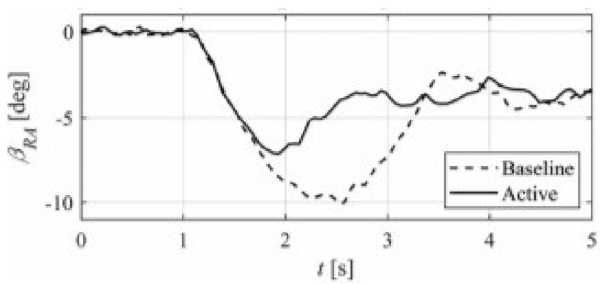

Figure 2 – Demonstrator vehicle by Tenneco with tyre force-vectoring control (left) and example (right) of the enhanced sideslip angle (β_{RA}) damping performance of the controlled (Active) vehicle with respect to the passive (Baseline) vehicle **[R2]**.

Driving cycle	Energy consumptions (kWh)			CA improvements (%) with respect to	
	Single-axle	Even distribution	With CA	Single-axle	Even distribution
NEDC	2.921	3.059	2.918	0.1	4.6
Artemis-road	4.487	4.634	4.442	1.0	4.1
EUDC 8% slope	5.793	5.740	5.709	1.5	0.5

Figure 3 – Demonstrator vehicle of the E-VECTOORC and iCOMPOSE projects with the wheel torque distribution controller developed by Surrey tested on a rolling road (left), and example (right) of the obtained energy consumption results along driving cycles (the control allocation algorithm developed by Surrey is abbreviated as CA) **[R6]**

3. References to the research (indicative maximum of six references)

[R1] L. De Novellis, **A. Sorniotti, P. Gruber**, "Wheel torque distribution criteria for electric vehicles with torque-vectoring differentials," (2014) *IEEE Transactions on Vehicular Technology*, vol. 63, no. 4, pp. 1593-1602. DOI: 10.1109/TVT.2013.2289371

[R2] M. Ricco, M. Zanchetta, G. Cardolini Rizzo**, D. Tavernini, A. Sorniotti**, C. Chatzikomis, M. Velardocchia, M. Geraerts, M. Dhaens, (2019) "On the design of yaw rate control via variable front-to-total anti-roll moment distribution," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 1388-1403. DOI: 10.1109/TVT.2019.2955902

[R3] C. Chatzikomis, M. Zanchetta, **P. Gruber, A. Sorniotti**, B. Modic, T. Motaln, L. Blagotinsek, G. Gotovac, (2019) "An energy-efficient torque-vectoring algorithm for electric vehicles with multiple motors," *Mechanical Systems and Signal Processing*, vol. 128, pp. 655-673. DOI: 10.1016/j.ymssp.2019.03.012

[R4] C. Chatzikomis, **A. Sorniotti, P. Gruber**, M. Bastin, R.M. Shah, Y. Orlov, (2017) "Torque-vectoring control for an autonomous and driverless electric racing vehicle with multiple motors," *SAE International Journal of Vehicle Dynamics, Stability, and NVH*, vol. 1, 2017-01-1597, pp. 338-351. DOI: 10.4271/2017-01-1597

[R5] L. De Novellis, **A. Sorniotti, P. Gruber**, J. Orus, J.M. Rodriguez Fortun, J. Theunissen, J. De Smet, (2015) "Direct yaw moment control actuated through electric drivetrains and friction brakes: theoretical design and experimental assessment," *Mechatronics*, vol. 26, pp. 1-15. DOI: 10.1016/j.mechatronics.2014.12.003

[R6] A.M. Dizqah, B. Lenzo, **A. Sorniotti, P. Gruber**, S. Fallah, J. De Smet, (2016) "A Fast and Parametric Torque Distribution Strategy for Four-Wheel-Drive Energy-Efficient Electric Vehicles," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 7, pp. 4367–4376. DOI: 10.1109/TIE.2016.2540584

Funding:

- European Union FP7, 284708 E-VECTOORC, €591,372 (Sept 2011 - Aug 2014) University of Surrey;
- European Union FP7, 608897 iCOMPOSE, €511,964 (Oct 2013 – Sept 2016) University of Surrey.

4. Details of the impact (indicative maximum 750 words)

Despite the negative impact of the Covid-19 pandemic, in 2020 the global yearly sales of new fully electric and plug-in hybrid electric cars reached 3.24 million, which is a 43% increase over 2019 (https://www.ev-volumes.com/). The drivability and performance of these vehicles is dependent on a new generation of dedicated controllers.

Commercial adoption of technology – McLaren

McLaren Automotive have adopted the optimisation-based routine **[R1, R4]** in the toolchain for the accelerated design of wheel torque distribution controllers. McLaren states: "*The benefit is a major reduction of the vehicle testing time and associated cost as the initial control tunings now already appropriately consider the nonlinear operating region of the vehicle*" **[S1]**.

The optimisation-based routine significantly reduces the vehicle control development. Major impact has been generated in the vehicle dynamics team of McLaren, as the tool allows: i) the *a priori* identification of the limits of the vehicle cornering response, which permits the precise specification of the target cornering characteristics and levels of chassis control actuation in the very early design stages, which was not possible with the software tools previously used by McLaren; and ii) the design and attainment of a feasible reference set of understeer characteristics, without the conventional design iterations that were the previous practice of the Company. This includes definition of the slope of the linear region, the shape of the transition to the nonlinear region, and the maximum lateral acceleration.

McLaren Automotive are also using control structures prioritising nonlinear feedforward contributions based on Surrey's research **[R1]**. Precise feedforward contributions, which were unachievable with the previous software tools, reduce the significance of the feedback contribution that could result in comfort issues. "*This aspect will facilitate the development of continuously active chassis control systems to be implemented on the next generation passenger vehicles*" **[S1]**.

The first-of-its-kind anti-jerk control concept using wheel speed input in addition to motor speed, developed at the Centre **[R5]**, is now deployed on all production McLaren passenger cars **[S1]**. The controller was enhanced in collaboration with McLaren, making it also applicable to internal combustion engine driven vehicles. The requirement was to achieve an anti-jerk functionality capable of damping drivetrain oscillations similar to that achieved with conventional controllers, but with reduced – by >30% – wheel torque delays, to maintain the sportiness expected from McLaren vehicles.

"*The controller represents a paradigm shift in the industrial practice of anti-jerk control, as it uses the wheel speed information, normally available in passenger cars but not used for anti-jerk control so far, to estimate and reduce the drivetrain torsion rate <…> an internal comparison with existing solutions demonstrated the benefits of the controller. As a result, the controller was implemented on our production vehicles*" **[S1]**.

Commercial adoption of technology – Elaphe Propulsion Technologies

Elaphe Propulsion Technologies have applied the Centre's research **[R3]** and collaboratively developed a torque-vectoring controller used in Elaphe's powertrain control units (PCU) **[S2, S3]**.

On average, the controller increases the maximum lateral acceleration by >5% and the entry speed in obstacle avoidance tests by >7%, while reducing energy consumption by >3%, with respect to the same vehicle with even wheel torque distribution **[R3, R4, R6]**.

Elaphe have also embedded the modelling and simulation-based methodologies developed by the Centre **[R1-R6]** confirming "*they help us to quickly develop prototype vehicles using our in-wheel powertrain setup that can be showcased to our international partners and customers*."

The series production of the Elaphe's PCU is starting in the USA in 2021 with the Lordstown pick-up trucks **[S4, S5]**. The Company is further developing and implementing the controller on multiple vehicle demonstrators, in collaboration with global car makers, such as Audi **[S2]**.

Commercial adoption of technology – Roborace

Roborace is a UK company developing electric and autonomous race vehicles with multiple motors, with the aim of initiating a new race series for driverless vehicles. Roborace have adopted the feedforward torque-vectoring controller, underpinned by research from the Centre for Automotive Engineering **[R1, R4]**. In collaboration with Roborace the controller has been implemented on the DevBot automated race car "*Prof Sorniotti's team designed and implemented a torque-vectoring controller for our prototype vehicles called DevBot*" **[S6]**.

Commercial adoption of technology – Tenneco Automotive

Tenneco Automotive, world leading supplier of automotive suspension components, embed the Centre's research **[R2]** in tyre force-vectoring controllers in their controllable suspension system portfolio. Furthermore, they utilise the suspension control design methodologies developed by the University of Surrey, which they state "*have had an impact on our internal practices*" **[S7]**. The tyre force-vectoring controllers have been progressively refined in the ongoing collaboration with Tenneco Automotive, with the plan of incorporating these into all future suspension systems. Tenneco states the collaboration has "*direct impact on our products launched in 2022 and beyond*" **[S7]**.

Contribution to vehicle electrification road maps

Finally, the Centre's research was fundamental to the E-VECTOORC and iCOMPOSE projects, which contributed to the powertrain and control architecture roadmaps of Jaguar Land Rover and Skoda Auto. The first release of the torque-vectoring controllers by Surrey **[R5]** was developed in collaboration with Jaguar Land Rover and was experimentally tested on a Range Rover Evoque with four on-board electric powertrains **[S8]**. The results informed their internal electrification and control development roadmaps.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] Testimonial from McLaren Automotive Limited (PDF)

[S2] Testimonial from Elaphe Propulsion Technologies (PDF)

[S3] https://www.youtube.com/watch?v=v02rHE0wuaM, video discussing the performance of the BMW X6 electric vehicle with in-wheel powertrains by Elaphe Propulsion Technologies, including the torque-vectoring controller developed by Surrey.

[S4] https://www.sec.gov/Archives/edgar/data/1759546/000110465920119279/tm2034197d1_ex10-15.html, the text of the facilities and support agreement between Lordstown and Elaphe Propulsion Technologies, stating that the electric axle by Elaphe, including the powertrain control unit (PCU), is going to production on the Lordstown pick-up trucks in 2021

[S5] https://insideevs.com/news/422884/lordstown-teams-inwheel-motor-elaphe/, which discusses the exclusive licensing agreement of Lordstown with Elaphe Propulsion Technologies for in-wheel axles

[S6] Testimonial from Roborace (PDF)

[S7] Testimonial from Tenneco Automotive (PDF)

[S8] https://www.youtube.com/watch?v=nlektAaD5gI, video describing the research of the E-VECTOORC project using the Range Rover Evoque.