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From Electrification on Component-Level to Software-Defined Vehicles: The Role of Modular Smart Corner Systems in Next-Generation Electric Vehicle Architecture

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Abstract. The transition to software-defined vehicles (SDVs) necessitates a paradigm shift in both control strategies and vehicle architecture. The EU-funded *SmartCorners* project addresses this challenge by developing integrated smart corner systems (SCS), which combine in-wheel motor (IWM) propulsion, brake-by-wire, active suspension actuator, and steer-by-wire functionality in a single module. These SCS are embedded within a highly adaptable skateboard chassis architecture, enabling scalable deployment across diverse vehicle platforms. The *SmartCorners* project targets to demonstrate significant advancements, including improvement in real-world driving range, reduction of component and system costs, an increasement in interior volume, and a development time drop of the EV systems enabled by digital-twin-based design methodologies. Beyond these performance gains, *SmartCorners* establishes the foundational principles of modularity, adaptability, and software integration that underpin the evolution toward SDVs. These achievements highlight a critical bridge between electrified component innovation and the holistic software-defined mobility systems of the future.

Keywords: Electric Mobility · SDVs · Smart Corner Systems · Control Strategies · Vehicle Architecture

1 Introduction

The arising era of SDVs is revolving around the mechatronics design on vehicle-level, requiring seamless integration of purely mechanical systems, embedded electronics, and information processing to launch increasingly complex systems, while achieving safety, performance, and cost targets [1, 2]. This transition toward SDV architectures is leading to increased autonomy, connectivity, safety and security functionalities, novel driving

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experiences, and new business models for original equipment manufacturers (OEMs) [3]. As SDVs need well-aligned software and electronics it is essential to address the topics of reliability, cybersecurity, interoperability, and standardisation together with its backbone, the information and communication technology (ICT) [4]. Besides technological in-vehicle advancements the entire mobility ecosystem will be transformed by the ongoing digitalisation and the trend toward connected, cooperative and automated mobility (CCAM).

In the EU-funded SmartCorners project—focusing on user-centred optimal design of EV with smart e-corners—artificial intelligence (AI)-based approaches and machine learning (ML) methods provide a great contribution to the four ambitious project objectives, including: (a) accelerated design and testing methodologies of adaptable, efficient, right-sized, flexible and user-centric SCS based on in-wheel powertrains, (b) new series of scalable and flexible SCS for next-generation EVs, (c) predictive, user-centric, AI - and model-based control solutions for SCS equipped EVs, and (d) holistic thermal and passenger comfort management. In SmartCorners AI and/or ML are utilized for structural health monitoring and force estimation, proactive vehicle motion control, control of the thermal management, control strategies of operating conditions, identification of trends and patterns like of usage, user behaviours, routes, weather conditions, fault mitigation, and the model predictive control framework, among others.

This paper provides a technological deep dive dedicated to the SCS investigated in SmartCorners. Finally, in the conclusion section, the SCS' benefits, business opportunities, and market impact are addressed.

2 Methodology/Results

EVs offer different possibilities and configurations, mainly dependent on the location of the electric traction motor. Within the SmartCorners project, a new modular SCS is proposed, merging traction, braking, suspension, and steering. In detail, the IWM can both drive and brake the vehicle, while active suspension and steering actuators focus on handling and comfort performance. In particular, the suspension actuator plays a key role to counteract the negative impact of adding the IWM mass to the unsprung mass both in terms of vibrations transmissibility and road holding. Additionally, the brake-by-wire covers the braking functionalities in all the scenarios where the regenerative braking is not anymore sufficient for the safe stop of the vehicle. All those systems are arranged as compact, preassembled unit called SCS that can be mounted directly onto the vehicle frame. In the end, a concept of a modular four-wheel drive (4WD) battery electric vehicle (BEV) is proposed by equipping a skateboard-like flat vehicle chassis, so-called "skateboard platform", with four SCS at its corners. The integration of the SCS on the skateboard platform reduces assembly/disassembly time and frees up space. In fact, due to this compact and modular design, less components and complex assembly/disassembly operations are needed, hence the interior space for passengers and luggage is expected to increase by 15% and 20%, respectively.

Figure 1 showcases the proposed SCS; it takes advantage of the suspension subframe of the reference demo-vehicle and then it fits to its body-in-white (BIW). Indeed, the project firstly targets the retrofit integration of the SCS into a demo-vehicle, i.e., an

Alfa Romeo Stelvio, to demonstrate its potentiality as an add-on feature for vehicles already on the market. Then, the concept is optimally deployed on a custom-designed skateboard platform. However, a limited number of changes to the vehicle's BIW are required, thus the skateboard platform of battery electric vehicles (BEVs) is intended to propose an optimal solution. The proposed suspension architecture is a low-type double wishbone with virtual steering axis. Together with the removal of the usual linear damper and coil spring, this configuration allows to get rid of any stiff structural component at higher points of the vehicle body, which are critical for pedestrian impact scenarios. The knuckle is an aluminium component custom designed to fix the suspension arms, wheel hub, steering link, and IWM. The upper control arm (blue arm in Fig. 1) of the suspension is manufactured through a Sheet Moulding Compression (SMC) process, as it is made of a composite material based on vinyl-ester resin filled with 50% chopped carbon fibres. The piezoresistive properties of this composite material allow the integration of conductive electrodes for real-time stress-state monitoring. The latter is not only fundamental for passengers' safety but also enables predictive maintenance strategies by warning the vehicle owner before any significant damage occurs. Reduction of the vehicle downtimes is particularly important for commercial vehicles since companies can schedule the use and repair of their fleet to avoid any service interruption. The two lower arms are aluminium components, and the rear arm (yellow arm) integrates flanges to allow the connection of the push/pull-rod of the active suspension actuator (ASA) and for a torsional spring, replacing the usual coil spring as illustrated in Fig. 2. To completely avoid clash possibilities during suspension travel and steering, the ASA is located inward with respect to the main rail of the skateboard platform, as the internal combustion engine removal frees up space in the original engine compartment. The ASA is flanged to the main rail, and a bell-crank element transmits the motion of the rear lower control arm to the ASA shaft. The ASA is a custom-designed rotary actuator made up of a planetary speed and a rotary brushless three-phase electric machine [5]. The torque-control of the electric machine permits the force-control of the suspension. A primary push/pull-rod connects the suspension arm to the bell-crank component and a secondary rod the bell-crank to the ASA crank lever. The latter rod is also produced in composite material as its piezoresistive properties allows force sensing, hence force-feedback for control purposes. In the end, a by-wire actuator controls both steering and toe angle as it acts directly on the single corner module. It integrates three critical components: a linear actuator, i.e., a rack-pinion mechanism, to control the steering link, two redundant power-sourced rotary devices to drive the system with self-sensing capabilities, and a control unit. The rotary device deploys a motor and a geartrain to reach the targeted forces. The intelligent corner design allows for independent control of torque, camber angle, and toe angle for each corner, resulting in an over-actuated EV.

With respect to conventional powertrain systems, the IWMs used in SCS demonstrate a superior torque response rate, which is attributed to the following two reasons. Firstly, the rotational inertia (which quantifies the object's rotational resistance) between rotor and tire is reduced thanks to the omission of both shaft and gearbox from the system. This direct linkage between motor and tyre facilitates more rapid torque regulation, increasing vehicle responsiveness, which is an advantage from the vehicle dynamics point of view. Secondly, the IWMs facilitate the immediate wheel torque sign change,

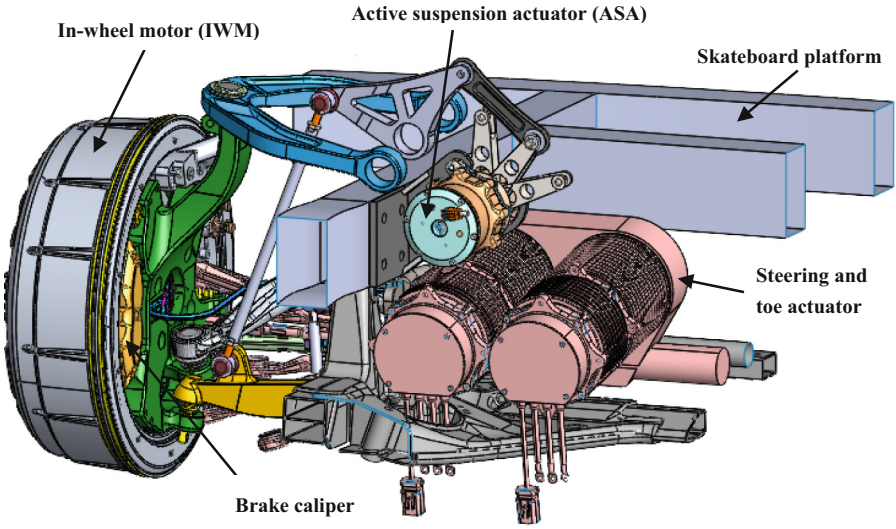


Fig. 1. Smart Corner System (SCS)

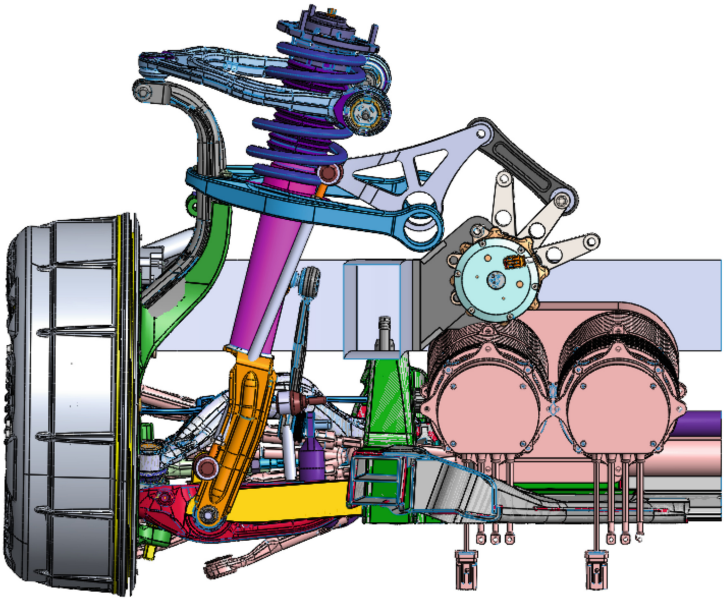


Fig. 2. Comparison between the normal production front suspension and the proposed SCS

enhancing agility and the control capabilities of the EVs, being crucial for functions that require high frequency torque oscillations. Another advantage from the SCS architecture is evolving from the synergy between IWM and the geometric characteristic of the suspension; by regulating the motor torque, the IWM not only generates a longitudinal

force, but also a vertical one, which can work in harmony with the one generated by the suspension system. With a controlled modulation of these forces, the IWM can actively increase passenger comfort, as shown at the top of Fig. 3 [6]. An additional advantage of using SCS on a 4-wheel drive layout, is the possibility to independently control the torque on the 4 wheels, implementing Torque Vectoring (TV) algorithms [7]. Several advantages are enabled by TV control strategies, and some examples are reported herewith. The difference between the wheel torques generates an additional yaw moment, which helps to counteract understeer and oversteer condition, improving safety even in critical condition. Moreover, with the application of differentiated torques, the vehicle behaves more agilely and responsively in cornering condition, e.g. by increasing the torques on the outer wheels, and reducing the torques on the inner wheel. TV algorithms are very effective at improving lateral dynamics, as shown at the bottom of Fig. 3, where the benefits of TV in terms of yaw rate reference tracking are compared between the performance of a benchmarking controller (proportional integrative—PI) with a nonlinear model predictive controller (NMPC). TV algorithms are also very effective for longitudinal dynamics control; in particular, they allow maximizing the traction force during acceleration when there are differences in grip between the wheels, sending the torque only to the wheel(s) with traction, reducing unnecessary wheel slip, and improving the ability to transfer torque to the ground. Thinking about the economy of the EV, which is a crucial aspect, the IWMs allow easy management of the regenerative braking, maximizing the energy recovery while driving and increasing vehicle autonomy. Another very effective application of the TV control algorithms is the emergency braking. In this case, usually the TV is not the primary braking system, but with independent wheel torque control, it can enhance longitudinal stability and safety during very strong braking. Specifically on split road friction coefficient surfaces, e.g., left wheels on asphalt, right wheels on ice, TV allows applying different braking forces on each side of the car that counteract the yaw unbalance generated from the road conditions. These strategies, combined with already existing safety logics (e.g., ABS, ESC), make EVs more stable and fun to drive.

The control algorithms that act on IWMs and active kinematic actuators, e.g., 4-wheel steering applications, allow a user-centric vehicle based on the driver's preferences, with the option of choosing between different driving modes (e.g., sport, comfort, and energy-efficient). Furthermore, with the independent control of the actuators, manoeuvres that require greater agility—such as on-the-spot steering and crab walking—can be done. In terms of vehicle dynamics control during extreme manoeuvres, predictive TV and active kinematics algorithms increase vehicle stability and safety by adjusting the vehicle's yaw moment during the manoeuvre. To enhance the innovation level of SCS control algorithms, the integration of an advanced sensor system enables the design of AI-based control architectures that learn, adapt, and react in real-time depending on variable vehicle and environmental conditions. These architectures are not only applicable to conventional vehicle but are also fully applicable to autonomous vehicles [8], where road preview, path tracking, and automatic thermal comfort control [9] become key components. The main advantages resulting from the utilization of AI-based control strategies are the following:

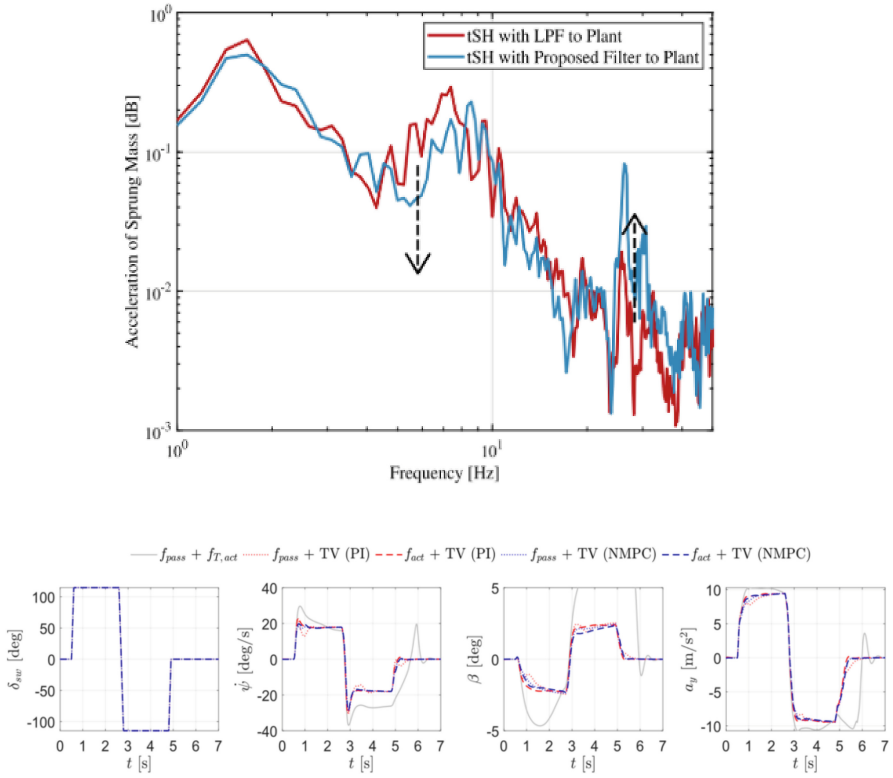


Fig. 3. Benefits coming from different IWM control applications: (top) Passenger comfort [6], (bottom) Vehicle's dynamics control [7]

- Compared to traditional controllers with fixed gain, AI algorithms can be trained on large datasets that include many extreme or rare conditions, allowing the system to better react to conditions not previously modelled, improving the robustness and safety of the control strategies.
- With respect to traditional predictive controllers, AI-based algorithms (such as Neural Network Model Predictive Controllers) have a reduced computational cost, which makes them real-time implementable for achieving high performance in terms of vehicle dynamics control.
- The real-time capability of the AI-based predictive algorithm, in combination with the advanced sensor system, allows the dynamic adaptation of the vehicle states to variable external conditions, e.g., changes in load, wear, road conditions, and temperature, to maintain a high level of passenger comfort.

At the same time, the design of energy-oriented controllers allows reducing the power lost during the manoeuvres, exploiting the possibility of having regenerated power from the IWMs during the braking phase, increasing the autonomy of the EV. In the end, the SCS introduces different degrees of global vehicle motion control.

3 Conclusion

Rigorous electrification on component-level and intelligent material selection led to the development of the presented modular and scalable SCS, which contains multiple vehicle functionalities and technological capabilities, namely (a) the IWM enabling traction and braking control, (b) the electro-mechanical brake-by-wire, supporting the IWM during hard braking manoeuvres, (c) the ASA providing optimal control of the vertical dynamics, (d) the steering actuator, ensuring precise control of the wheel toe angle, (e) AI/ML-based data-driven control strategies for the aforementioned functionalities, (f) digital twinning, supporting the SCS development, (g) virtual sensing, and (h) consideration of user-centric vehicle settings. These developments result in an SDV-ready SCS, able to boost the vehicle's performance, safety, and occupant's comfort, while simplifying EV development as well as the SCS repair, maintenance, and recycling processes. The SCS design presented in this paper is optimised to retrofit the Alfa Romeo Stelvio. Thus, SCS optimised for skateboard platforms will look different to achieve minimal packaging requirements, leading to increased passenger compartment space, greater cargo space, and more freedom in the design process of any kind of vehicle.

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