ALTERNATÍV HAJTÁSLÁNCÚ AUTONÓM JÁRMŰVEK SZABÁLYZÁSI KIHÍVÁSAI

CONTROL CHALLENGES IN AUTOMATED VEHICLES WITH ALTERNATIVE POWERTRAIN SOLUTIONS

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ABSTRACT: The automotive industry has gone through rapid changes in the past decade, which is partially driven by technological advancement, including the ever-growing palette of alternative powertrain solutions and autonomous features. While the two development areas are seemingly independent of each other, many synergies can be found in the underlying technologies. This paper collects the most important aspects of autonomous vehicle controller design with respect to the powertrain solution employed, primarily focusing on the differences between traditional combustion engines and fully electric driven vehicles. It aims to identify the major trends along which todays automotive industry is evolving.

1. INTRODUCION

The development of Autonomous Vehicle (AV) technology embraces diverse fields of research and applied science. As of today, quite a few car manufacturers (Original Equipment Manufacturers, OEMs) already offer a limited stack of automated driving assistant features in production vehicles, the efficient implementation of higher levels of automation is an actively discussed topic among research communities, automotive suppliers and software companies [1].

In less than 5 years, the number of companies working on self-driving vehicle prototypes grew above 100, yet the diversity of the vehicle platforms is significantly lower. Development history indicates that some platforms/vehicle models are more suitable for prototyping or production purposes than others, which defines a set of criteria that such platforms need to adhere to. These criteria may be affected by the comfort, spaciousness, power(-capacity), powertrain or physical dimensions of the vehicle, which needs to satisfy the basic requirements of the unique hardware and software of automated vehicles [2].

This paper discusses the challenges and requirements of automated vehicle control with respect to the powertrain solution used for development/production.

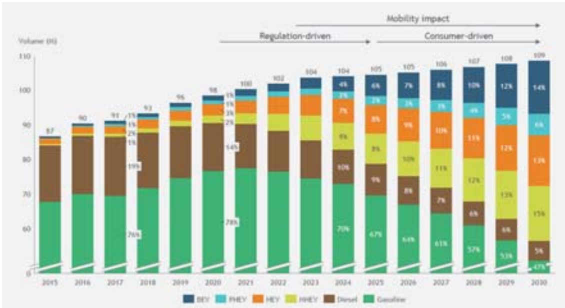

Figure 1 The Boston Consulting Group's market forecast of the share of alternative powertrain vehicles [3]. The tendency suggests that the share of hybrid and electric vehicles will significantly increase in the next decade.

2. POWERTRAIN SOLUTIONS

Today, more than 90% of all production vehicles are equipped with internal combustion engines (ICEs), and the ratio of gasoline and diesel powered engines is 5:1, respectively. Fig. 1 indicates that the share of (plug-in) hybrid vehicles (HEV/PHEV) remains at 5%, although hybrid technologies have evolved a lot in terms of efficiency in the past years, increasing their reliance on electric power. The fully electric or battery powered electric vehicles (BEVs, including hydrogen fuel cell solutions) have gained popularity this decade, however, their global volume percentage has barely reached 1% in 2019.

Autonomous Electric Vehicles (A-EVs) is a commonly misinterpreted umbrella term for future automotive technology. From the technology point of view, an autonomous vehicle does not need to be neither electric, nor hybrid to ensure safe and efficient operation, while most BEVs lack any form of autonomous features today. There are, however, numerous synergies with the two technologies. However, as algorithm development, computational capacity and safety regulations pose a bottleneck in AV development today, these synergies are less frequently addressed in the literature.

There is no consensus among OEMs and developer communities on the optimal powertrain solution for autonomy. Some OEMs (Tesla: BEV, GM: ICE, Daimler: PHEV) implement autonomous features on mass-produced vehicles, seemingly independent from the powertrain itself. Software companies and automotive suppliers prefer globally available and integration-ready models (Ford Focus, Toyota Prius/Camry) or they are bound by partnerships (Waymo-FCA, Argo.ai-Ford). However, PHEV and BEV solutions are dominantly preferred among OEM-independent developers and suppliers, which, besides the positive marketing impact due to environmental-friendliness, highlights the technological advantages over traditional ICE assemblies.

The next section discusses the potential advantages of using alternative powertrain solutions in self-driving vehicle prototypes from control engineering aspects.

3. CONTROL ASPECTS OF SELF-DRIVING VEHICLES

With the growing number of autonomous vehicle prototypes, the focus of development has shifted from hardware to software, which contradicts with the traditional motor vehicle design. Software algorithms are responsible for perception, prediction, decision making and control. They mostly rely on sensor data from cameras, radars and other automotive sensors, which are later fused together to create an environmental and dynamic model to aid decision making, path planning, and eventually motion control.

Vehicle control relies on a robust trajectory, which consists of parametrized curves defined by a curvature center and radius. Regardless the control paradigm or vehicle dynamics, one can select 3 parameters to define this trajectory:

1. The road curvature center, which the vehicle aims to turns about at a given time instant
2. Kinematic rotation center, which is bound to the vehicle. It is found by taking the intersection of all the lines perpendicular to the wheels
3. Dynamic turning point, which refers to the actual point in space the vehicle turns about.

When designing a trajectory, one needs to consider the geometry of the feasible road surface, the temporal changes in the environment and the kinematic and kinetic constrains of the vehicle. Due to the nonlinear dynamics of motion and rapid trajectory changes, a large number of different control approaches can be found today using linearization, LQ-optimal control or Model Predictive Control / Model Predictive Path Integral Control [4].

For autonomous vehicles there are two dynamically coupled, yet often separately addressed fields of control: longitudinal control and lateral control. The embedded software responsible for signal generation receives data from a high-level prediction and decision making module, using either formal logic, artificial intelligence or both. This module usually defines high level actions to be taken based on the dynamic environment and the current vehicle state.

Longitudinal control utilizes information from various sources in order to correctly function [5]. These are attributes of objects surrounding the ego-vehicle, such as relative position, speed and acceleration. The self-motion or *egomotion* of the controlled vehicle is also used by the software to create efficient predictions on in time. Position, speed and acceleration data can be directly measured by conventional vehicle-mounded sensors (radar, LIDAR, ultrasonic) or indirectly by supporting algorithms (stereo depth, distance estimation from detection size). In longitudinal control, most scenarios are related to automatic cruise control (ACC), where the ego vehicle maintains a cruising speed limited by the presence of potentially slower vehicles. At high speeds, the time delay of gaining information of the preceding vehicles is crucial, the sensor input may become noisy. This affects the performance of the control algorithms, and it is highly dependent on the powertrain method.

Lateral control is responsible for lane keeping, obstacle avoidance and route changing maneuvers. In the case of state machines and formal logic-based systems, the robust functioning of this module strongly depends on the quality of trajectory planning and state prediction. The comfort threshold for humans is considerably lower for lateral motion compared to that of the longitudinal, therefore the smoothness, applied acceleration and jerk (first time-derivative of the acceleration) should be carefully selected and may pose a challenge for vehicles with alternative powertrains.

From the control strategy point of view, lateral control may be treated as a tracking control problem following a temporarily changing spatial trajectory. On the other hand, a unified lateral guidance approach can be used to guide the vehicle by specified yaw and yaw rate values. These values are taken as a reference from predefined motion patterns and high-level maneuvers, all depending on the environmental conditions and the vehicle state.

4. INDIVIDUAL REQUIREMENTS WITH ALTERNATIVE POWERTRAINS

Today, purely internal combustion engines dominate the automotive market, while hybrid and fully electric cars take up most of the remaining market share with respect to unit numbers. From the powertrain design point of view, ICE and BEV vehicles represent the two extremes, while hybrid vehicles soften this boundary by providing a balance between the two significantly different approaches.

With the rising number of limited autonomous features, new design criteria have been defined by automakers to increase cruising comfort, and to address design methods and power efficiency of the vehicles.

4.1. Model-based control

In most autonomous vehicle control designs, both lateral and longitudinal control algorithms rely on a complex dynamic or simple kinematic model of the vehicle. Adaptive control methods and sliding-mode control approaches utilize a coarse system model to achieve robust operation. Model predictive control requires a more general knowledge about the system, including the predicted effect of known inputs (throttle, steering, braking). System identification and proper dimensionality reduction are also popular methods for finding optimal control architectures, which are often aided by AI-based identification methods and neural networks.

The dynamic behavior of ICEs is dominated by their nonlinear power and torque curves, indicating the correlation between engine rotation speed and available engine torque, as shown in Fig. 2. These curves are usually determined by standardized measurements under controlled conditions, but their highly nonlinear behavior and steep slopes, determining the current dynamic state of the vehicle is challenging. Local model linearization partly solves this issue in controller design, however, the uncertainty of the current working point in these curves result in noisy predictions and slow adaptation.

BEV systems on the other hand provide a smooth, virtually (piecewise) linear torque curve, allowing designers to make accurate predictions for the vehicle behavior as response to specific control inputs. Nevertheless, the true kinematic motion of the vehicle remains nonlinear, but from the controller design point of view, the mathematical model of the acting driving force on the wheels simplifies significantly.

4.2. Energy efficiency

ICEs present many idle cycles during the driving task, where fuel is burned only to maintain the continuous operation of the engine and keep the speed of rotation at a dynamically sensitive area of operation. This indicates that the longitudinal maneuverability of an ICE vehicle largely depends on the current state of the powertrain, where an inadequate choice of rotation speed and transmission state may increase response delay in the system.

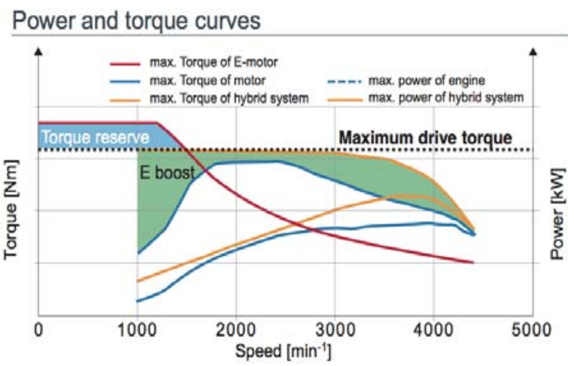

Figure 2: Power and torque curves of conventional ICE engines, hybrid systems and fully electric motors, according to a case study by Volkswagen [6]. Besides the considerably higher torque reserve of fully electric vehicles, the nearly constant torque available at lower speeds is favorable by autonomous vehicle design.

BEVs allow a rapid state change between fuel (battery) discharge and charge, the longitudinal maneuverability does not significantly depend on the current rotation speed and they are free of transmission-related issues. This makes these systems a preference for efficient trajectory design, where besides comfort and speed efficiency, power or consumption efficiency can also be implemented as a criteria for controller design.

This includes trajectory planning, control signal optimization to avoid saturation, and execution efficiency.

4.3. Control smoothness

Human drivers have various driving styles, ranging from cautious to often daring. Both their lateral and longitudinal control trajectories are smoothed over the course of driving path to increase control. This can be experienced in curved roads, where the width of the lane offers the driver a freedom of trajectory choice rather than restricting the vehicle position to the lane centerline. Similar phenomenon can experienced in longitudinal control situations, where the catching up pace to a vehicle from behind depends on the traffic conditions and the driving style of the human driver, and the resulting differential speed is not only the function of relative distance, like it would be a result of the naïve control law formulation [7].

Today, most autonomous vehicles follow formally defined rules on longitudinal and lateral control, creating strict boundaries for position and speed trajectory planning, where low tracking error is requested. However, it is important to note that these strict boundary conditions may be smoothed by fuzzy control or neural networks-based methods (such as reinforcement learning).

In the case of ICEs, closely following the planned trajectory may result in an often rapidly updated control signal input and thus a heavy oscillation on the fuel intake side. This increases the fuel consumption significantly and ultimately may lead to the early amortization of the engine and transmission units. BEVs, on the other hand, are not sensitive to the rapid changes in the magnetic field responsible for driving the electric motor, and due to the nearly constant torque available at different speeds, their control response is a lot faster than the response of ICEs.

4.4. Cruising stability

Most of today's vehicles are equipped with advanced electronic stability programs (ESP) to monitor the reduction or loss of traction. In the case of stability or traction loss, these systems aid the human driver to regain control of the vehicle. Advanced driver assistance functions (ADAS) also actively contribute to the improved maneuverability of the vehicles in critical situations. When the vehicle is controlled by a human driver, these functions are independently operating in the background and use complex vehicle dynamic models to assess system dynamic behavior. ESP systems collect data and predict values for tire *slip*, the vehicle stability boundaries under given environmental conditions and assess the system state with respect to the friction curve [8].

Due to the long system response time in the case of acceleration, ICE ESPs are operating by applying brake force on the wheels individually. Lateral control, however, remains in the hands of the human driver, therefore stabilization efficiency strongly depends on the driver capabilities and response time. Autonomous vehicles offer the advantage of lateral control applied *simultaneously* with the ESP's longitudinal assistance. However, in higher levels of automation, the combined and coordinated operation of lateral and longitudinal control, individual ESP systems will become obsolete as their functionalities will be included in the global vehicle control.

Many BEV constructions incorporate the electric motors in the wheels rather than distributing the torque through a differential unit. This allows the individual and immediate control of all wheels and thus braking-based stabilization can be enhanced by applying both positive and negative torque values to all wheels. This increases the overall stability of the system, allowing for more dynamic and/or efficient driving behavior.

5. DISCUSSION AND CONCLUSION

As autonomous features and alternative powertrain solutions are simultaneously getting integrated into production vehicles, software developers, control designers and mechanical engineers need to update and improve motor vehicle designs to address a new set of requirements. Autonomous vehicles are gradually taking over the control responsibilities from the human driver, and the previously quasi-independent control systems (longitudinal, lateral control, ESP and transmission) are getting merged in a unified, coordinated vehicle control unit. This paper listed several important design aspects that indicate that engineers are strongly recommended to take the limitations and advantages of different powertrain solutions into consideration when designing new systems. Vehicles with electric powertrain offer several advantages over traditional internal combustion engines from the trajectory control point of view. Most advantages can be derived from the faster response time and less model and construction complexity, although the aspects included in this paper can be discussed in the scope of hybrid, fuel-cell electric or other alternative powertrain solutions as well.

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DEAR READER,

The fourth Agria Conference on Innovative Pneumatic Vehicles - ACIPV 2020 has took place on 7th of May 2020, following a future forward, online format with regards to the global pandemic.

The initial goal of the Conference, founded in 2017, was to showcase the results of scientific researches conducted by university professors, PhD, Master and BSc students for their projects within the International AVENTICS Pneumobile Competition. By know its scope has been extended to control and automotive engineering researches too.

Business and academic world joined forces to organize the Conference series: Óbuda University's Institute of Mechatronics and Vehicle Engineering is responsible for the academic part while Emerson – representing its AVENTICS brand – is the host of the event. It is of great pleasure, that Ministry for Innovation and Technology is the patron of the Conference – here we would like to express our gratitude for their support.

This year we have welcomed twenty-two speakers during the Conference, whose studies could be read in this issue of the GÉP journal.

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