Actuator Fault-Tolerant Vehicle Motion Control: A Survey
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Abstract—The advent of automated vehicles operating at SAE levels 4 and 5 poses high fault tolerance demands for all functions contributing to the driving task. At the actuator level, fault-tolerant vehicle motion control, which exploits functional redundancies among the actuators, is one means to achieve the required degree of fault tolerance. Therefore, we give a comprehensive overview of the state of the art in actuator fault-tolerant vehicle motion control with a focus on drive, brake, and steering degradations, as well as tire blowouts. This review shows that actuator fault-tolerant vehicle motion is a widely studied field; yet, the presented approaches differ with respect to many aspects. To provide a starting point for future research, we survey the employed actuator topologies, the tolerated degradations, the presented control approaches, as well as the experiments conducted for validation. Overall, and despite the large number of different approaches, the covered literature reveals the potential of increasing fault tolerance by fault-tolerant vehicle motion control. Thus, besides developing novel approaches or demonstrating real-time applicability, future research should aim at investigating limitations and enabling comparison of fault-tolerant motion control approaches in order to allow for a thorough safety argumentation.

I. INTRODUCTION

Fault-tolerant vehicle systems, which have been the subject of intensive research for more than two decades, continue to gain importance with the advent of automated driving technology. While the required safety level for the operation of automated vehicles according to SAE levels 4 and 5 [2] is yet to be defined, it is indisputable that automated vehicles demand a high degree of fault tolerance throughout the automated driving system. On the part of vehicle actuators, redundant implementations are one way to compensate for the missing human fallback layer in SAE levels 4 and 5. However, redundancy is usually accompanied by increased costs caused by, i. a., additional weight and installation space complexity. These drawbacks become even more important for novel over-actuated topologies proposed in several automated vehicle prototypes, for instance those featuring wheel-individual drive, brake, and steering actuators.

Also in modern series production vehicles, there is a trend towards over-actuation in order to improve the vehicles’ handling, ride comfort, and safety. For instance, electronic stability control leverages wheel-individual brakes, and premium class vehicles feature chassis control systems that use torque vectoring and by-wire rear-axle steering.

The over-actuation offers additional opportunities for realizing fault-tolerant automated vehicles. Since drive, brake, and steering actuators generally impact both, the longitudinal and lateral vehicle motion, the resulting functional redundancies could be exploited either for avoiding physical redundancy at the actuator level or as a secondary fallback layer if the currently accepted single fault assumption for vehicle systems [3] does not hold true for automated vehicles.

In either case, the impact of the degraded actuators must be handled by fault-tolerant system layers superimposed on the actuator layer in order to obtain safe vehicle behavior.

Focusing on the automotive domain, Wanner et al. [7] review fault-tolerant vehicle design in general in their 2012 study. With respect to fault-tolerant control in the presence of actuator degradations, the authors present general considerations as well as requirements and introduce a few selected publications on the topic. Vivas-López et al. [8] as well as Shyrokaу [9] survey approaches towards global chassis control in their studies from 2013 and 2014, respectively. Yet, the authors give only a few selected examples of fault-tolerant control approaches addressing

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actuator faults. The same applies to the more recent works of Kissai et al. [10], Huang et al. [11], and Shet et al. [12], which are from 2017, 2019, and 2020, respectively. As Vivas-López et al. and Shyrokau, Kissai et al. present a survey on integrated vehicle motion control. Again, only one approach is mentioned that targets actuator fault-tolerant vehicle motion control. The work of Huang et al. focuses on steer-by-wire systems. While giving an extensive overview of steering-internal fault-tolerant control, it mentions only a few publications that present approaches to overcome steering degradations by means of other healthy actuators. Finally, also the recent survey of Shet et al. contains only a small selection of publications outlining fault-tolerant vehicle motion control approaches.

This survey is meant to serve as a starting point for future research in the field of fault-tolerant vehicle motion control. Hence, after refining the focus in Section II, the subsequent sections are structured by the different ways in which researchers and practitioners can approach fault-tolerant vehicle motion control. On the one hand, they can look for approaches to handle selected actuator degradations; therefore, Section III provides an overview of the different degradation types addressed in the literature. On the other hand, researchers and practitioners can search for fault-tolerant vehicle motion control approaches for a given set of drive, brake, and steering actuators. Actuator topologies are hence reviewed in Section IV. To compare novel control approaches to the state of the art, Section V considers the different control targets, the employed control techniques, and the related control structures. Last but not least, Section VI gives an overview of the experiments that are used to evaluate fault-tolerant vehicle motion control approaches.

II. FOCUS OF THE SURVEY

Within in the field of automated driving, we concentrate on road vehicles. Fault-tolerant control approaches for off-road vehicles, e.g., [13, 14], omnidirectional robots [15–18], as well as other mobile robots [19–21] are not further discussed as their specific application domain poses different requirements from a safety perspective compared to road vehicles. The same applies to fault-tolerant motion control of special purpose vehicles and vehicles with more than four wheels, for instance [22–28]. Specifically, we focus on drive, brake, and steering actuators as these are present in every road vehicle. Moreover, tires are arguably the most critical mechanical components with regard to motion safety as they transfer all forces generated by actuators. Transfer characteristics as well as vehicle dynamics change significantly after tire blowouts and therefore impact vehicle motion critically. Thus, we include publications that target vehicle motion control after tire blowouts. In contrast, active suspension systems as optional components are not further considered. As a consequence, we purely highlight planar vehicle motion aspects, although vertical motion is partially considered in the covered literature, too.

All publications surveyed in Sections III–VI introduce approaches to exploit the over-actuation of a vehicle. Therefore, publications showing fault tolerance at the actuator level are not considered. Moreover, we focus on publications that outline the specific control approach for reaching fault tolerance. Publications that only show results are neglected, e.g., [237–244]. The same applies to publications that only state that an approach is potentially fault-tolerant without demonstrating the implementation or presenting experimental results.

Some publications that appear relevant based on their titles and abstracts unfortunately cannot be included in this survey because they are only available to us in Chinese [245–258], Japanese [259], or not at all [260–264].

Within this focus, a total of 172 publications forms the core of this survey. Hence, without claiming to be exhaustive, the survey provides a representative picture of the current state of the art in fault-tolerant vehicle motion control research. An overview of the contained publications is presented in Table I, which summarizes employed actuator topology, covered degradations, control approaches, as well as conducted experiments for each publication.

The literature covered in this survey indicates that actuator fault-tolerant vehicle motion control has been the subject of research for roughly a quarter of a century as illustrated in Fig. 1. After the potential of fault-tolerant vehicle motion control had already been recognized earlier (1989 at the latest, cf. [267]), there were a few publications in the mid-1990s. However, it was not until the beginning of the 21st century that fault-tolerant vehicle motion control

\[\text{Fault-tolerant control approaches for active suspension systems are presented, e.g., in [114, 118, 121, 201–236].}\]
came more into the attention of researchers, with research intensifying significantly over the past decade.

III. Degradations

For implementing fault-tolerant control systems, an understanding of how components degrade due to internal faults is key. Hence, in this section, we highlight and unify the different ways of how researchers model degradations. Based on the unified understanding, we distinguish nine degradation categories, each posing comparable requirements on fault-tolerant vehicle motion control approaches.

The ways researchers model degradations can be described by means of the general fault-tolerant control problem without feed-through, which also neglects disturbances and uncertainties:

\[ \dot{x}(t) = f_i(x(t), u_i(t)), \quad y(t) = g(x(t)), \]

where \( x \in \mathbb{R}^n \) denotes the system state vector and \( y \) the measurement output. \( f_i \) describes the system dynamic potentially subject to faults. Here, the system dynamic \( f_i \) changes in the presence of tire blowouts, which form the first category and are considered in 23 publications [178–200].

The remaining categories comprise actuator degradations and can be explained by means of the potentially degraded system input \( u_i(t) \in \mathbb{R}^m \) with \( u_i = (u_{i,1}, \ldots, u_{i,m})^\top \), where \( m \) equals the number of control inputs. With \( u_i(t) \), two ways of describing actuator degradations can be distinguished. On the one hand, researchers take a set-based perspective, which concentrates on the usable range of \( u_i \). For the fault-free case, the usable range of control inputs is \( \underline{u} \leq u_i \leq \bar{u} \), where \( \underline{u} \) and \( \bar{u} \) are the minimum and the maximum value of the control inputs. In case of faults, the usable range for one or multiple \( u_i \in u \), with \( i \) indicating the \( i \)-th actuator, deteriorates such that the intended input, \( u_{f,i} = (u_{f,i,1}, \ldots, u_{f,i,m})^\top \), where \( u_{f,i} \) and \( \bar{u}_{f,i} \) denote the physical actuator limitations. Consequently, actuators are assumed to degrade by providing a reduced range. For the singleton \( u_{f,i} = u_{\bar{f},i} \) follows \( u_{f,i}(t) = \text{const.} \), which is a frequently encountered degradation in literature; in particular \( u_{f,i}(t) = 0 \) is often considered.

On the other hand, several researchers model actuator degradations by defining the system input \( u_i(t) \) as

\[ u_i(t) = \epsilon_i(t)u_i(t) + u_+(t), \]

where \( u_i(t) \) is the intended input, \( \epsilon_i(t) = \text{diag} \{ \epsilon_i \} \) a diagonal matrix with \( \epsilon_i \in [0, 1] \) denoting a time-varying effectiveness factor, and \( u_+(t) \) a time-varying additive fault. Common degradations from this perspective are a stuck-at fault \( (\epsilon_i(t) = 0, u_{+,i}(t) = \text{const.}) \) and especially a loss-of-effectiveness fault \( (\epsilon_i(t) \in (0, 1), u_{+,i}(t) = 0) \). Other degradations can be summarized as time-varying control inputs and can be expressed by means of \( u_{+,i}(t) \), too. Still, time-varying degradations are rarely encountered in the literature covered in this survey. For additive faults \( u_+(t) \neq 0 \), physical actuator limitations are mostly not taken into account explicitly. Limitations are implicitly addressed in the provided experimental examples by choosing fault values that result in an actuator usage that lies in a physically realistic range yielding \( u_{f,i}(t) \in [\underline{u}_{f,i} \bar{u}_{f,i}] \subset [\underline{u}_i \bar{u}_i] \).

It is quite obvious that both ways of describing degradations can be merged to a great extent: Both ways can easily model constant control inputs or stuck-at degradations. A reduced control input range can be related to the loss-of-effectiveness fault. The same applies to a constant offset if one explicitly considers physical actuator limitations that bound the actuator usage, which also results in a reduced control input range. Only time-varying control inputs are specific to the modeling of faults using loss-of-effectiveness and additive faults.

Based on these general considerations, we categorize the degradations tolerated by the control algorithms found in the covered literature. We summarize degradations of drive and brake actuators as both impact the wheel rotation and create four categories:

1) Zero torque,
2) Reduced torque range,
3) Unintended torque, and
4) Spinning or locking wheel.

In the third category, constant non-zero torques as well as time-varying torques are subsumed that are counteracting the intended vehicle motion. The fourth category addresses the special yet – in terms of vehicle dynamics – interesting case of unintended drive or brake torques that exceed the tire force limits such that the wheel starts spinning or locks when braking.

Also four steering degradation categories can be distinguished in literature:

1) Zero steering angle,
2) Reduced steering angle range,
3) Reduced steering rate, and
4) Zero steering torque.

The seventh category summarizes unintended steering angles, which can be either constant or time-varying. After a degradation according to the last category, the wheel’s motion around its z-axis is purely determined through the forces at the tire road contact patch, attenuated by friction and other effects in the steering system.

Fig. 2 depicts the number of publications that address each of the nine categories. With respect to brake and drive degradations, most publications – namely 66 – consider zero torque [29, 45, 48–50, 54, 55, 57, 58, 65, 66, 68, 70, 74, 76–80, 83–86, 88–93, 95, 97, 98, 101–110, 116, 122, 126, 128, 133–137, 141–143, 145, 147, 150, 155, 159–163, 167, 175, 177] followed by a reduced torque range with 54 publications [30–33, 38, 40, 43, 45, 51, 52, 64, 66–68, 74, 82, 94, 109, 114, 115, 117, 120, 121, 123, 124, 126, 127, 129–131, 138–142, 144–146, 149, 150, 152, 159, 162, 163, 165–168, 170, 172–176]. 15 publications assume a constant torque [39, 42, 67, 69, 70, 119, 126, 127, 142, 144, 146, 150, 156, 157, 176], whereas only six consider locking or spinning wheels [58, 103–105, 126, 158]. Last but not least, a sole publication addresses malfunctioning anti-lock and anti-spin control systems [126], which is not displayed in Table I.
| Author(s) (Year) | Actuator topology | Degradation | Control technique |
|------------------|-------------------|-------------|------------------|
| Ahmadi et al. (2020) | FA | AW | Path | PD&DCA |
| Allipour et al. (2011) | AW | Br | VeD | (FF+SF)&OCA |
| Almeida and Arraibo (2013) | AW | Steer. | VeD | (PT+SM)&OCA |
| Amato and Marino (2020) | AW | Br | VeD | PI&DCA |
| Bian et al. (2016) | AW | Steer. | VeD | SM/OCA |
| Bosche et al. (2009) | AW | Path | VeD | LT |
| Boudali et al. (2018) | AW | Path | VeD | (FF+SF)&OCA |
| Bünne and Andresson (2006) | AW | Path | VeD | PD&DCA |
| Chen et al. (2011) | AW | Path | VeD | LTI |
| Chen et al. (2017) | AW | Path | VeD | H∞ |
| Chen et al. (2018) | AW | Path | VeD | H∞ |
| Chen et al. (2019) | AW | Path | VeD | SM&ACA |
| Chen et al. (2019) | AW | Path | VeD | SM&ACA |
| Chen et al. (2020) | AW | Path | VeD | RB&OCA |
| Chen et al. (2020) | AW | Path | VeD | MP&C&SM |
| Chu et al. (2012) | AW | Path | LoD | OCA |
| Dominguez-Garcia et al. (2004) | AW | Path | LoD | OCA |
| Dumont et al. (2006) | AW | Path | LoD | OCA |
| Fu et al. (2020) | AW | Path | LoD | (FF+SM)&OCA |
| Gaspár et al. (2015) | AW | Path | LoD | LTI|DCA |
| Guo and Chen (2019) |AW | Path | LoD | FF&PI&DCA |
| Guo et al. (2020) | AW | Path | LoD | H∞&OCA |
| Guo et al. (2020) | AW | Path | LoD | H∞ |
| Hac et al. (2006) | AW | Path | LoD | OCA |
| Hac et al. (2019) | AW | Path | LoD | OCA |
| Haddad et al. (2013) | AW | Path | LoD | FB |
| Hiraoka et al. (2004) | AW | Path | LoD | LQR |
| Hoedt et al. (2013) | AW | Path | LoD | FB&ACA |
| Hu et al. (2015) | AW | Path | LoD | LQR&ACA |
| Hu et al. (2016) | AW | Path | LoD | SF+LT |
| Hu et al. (2017) | AW | Path | LoD | SF+LT+SM |
| Hu et al. (2018) | AW | Path | LoD | SF+LT+SM |
| Hu et al. (2019) | AW | Path | LoD | SF+LT+SM |
| in Park et al. (2013) | AW | Path | LoD | SM&ACA |
| Ito and Hayakawa (2013) | AW | Path | LoD | (RB+FF)&DCA |
| Jeon et al. (2013) | AW | Path | LoD | SM&ACA |
| Jing et al. (2015) | AW | Path | LoD | H∞ |
| Jing et al. (2018) | AW | Path | LoD | H∞&DCA |
| Jonasson and Wallmark (2007) | AW | Path | LoD | PI&DCA |
| Jonasson and Wallmark (2008) | AW | Path | LoD | PI&DCA |
| Jonasson and Thor (2016) | AW | Path | LoD | FF+PID |
| Jonasson and Thor (2017) | AW | Path | LoD | FF+PID |
| Khelladi et al. (2020) | AW | Path | LoD | FF+SF&ACA |
| Kim and Huh (2016) | AW | Path | LoD | SM |
| Kiri et al. (2017) | AW | Path | LoD | FF+PID |
| Kissai et al. (2016) | AW | Path | LoD | H∞&OCA |
| Knobel et al. (2009) | AW | Path | LoD | FB&ACA |
| Kou et al. (2010) | AW | Path | LoD | MP&C&OCA |
| Krüger et al. (2010) | AW | Path | LoD | MP&C&OCA |
| Lee and Lee (2020) | AW | Path | LoD | RB+P |
| Li et al. (2009) | AW | Path | LoD | FF&PI&DCA |
| Li et al. (2013) | AW | Path | LoD | MFA |
| Li et al. (2014) | AW | Path | LoD | MP&C&OCA |
| Li et al. (2014) | AW | Path | LoD | DCA |
| Li et al. (2016) | AW | Path | LoD | SM |
| Li et al. (2016) | AW | Path | LoD | SM |
| Liu et al. (2012) | AW | Path | LoD | RB+OCA |
| Liu et al. (2012) | AW | Path | LoD | RB |
| Liu et al. (2016) | AW | Path | LoD | MP&C&OCA |
| Liu et al. (2016) | AW | Path | LoD | MP&C&OCA |
| Liu et al. (2016) | AW | Path | LoD | OCA |

**Actuator topologies:** AW: All-wheel; FA: Front axle; RA: Rear axle; I: Wheel-individual; (): Not actively used.

**Degradations:** Dr.: Drive; Br.: Brake; Steer.: Steering; T.: Tire; TU: Unintended wheel torque; T0: Zero wheel torque; L: Locking or spinning wheel; TR: Reduced wheel torque range; SR: Reduced steering range; SD: Reduced steering dynamics; SU: Unintended steering angle; S0: Zero steering torque; BO: Tire blowout.

**Control targets:** LaD: Lateral dynamics; LoD: Longitudinal dynamics; Path: Path tracking; Pose: Temporal sequence of poses; VeD: Vehicle dynamics; YA: Yaw angle.

**Control techniques:** ACA: Analytical control allocation; D: Differential; DCA: Direct control allocation; FB: Flatness-based; FF: Feed forward; I: Integral; LQR: Linear-quadratic regulator; LT: Lyapunov theory-based; MFA: Model-free adaptive control; MPC: Model-predictive control; OCA: Optimal control allocation; PI: Proportional; RB: Rule-based reconfiguration; SF: State feedback control; SM: Sliding mode; k: Hierarchical control structure; +: Parallel control structure; /: Alternative control techniques.

**Experiments:** HiL: Hardware in the Loop; MiL: Model in the Loop; VeL: Vehicle in the Loop.

**Reference:** DLC: Double lane change; SLC: Single lane change; Crv.: Curved; Str.: Straight; Oth.: Other.
| Author(s) (Year) | Actuator topology | Degradation | Drive | Brake | Steering | Control | Technique | Type |
|------------------|-------------------|-------------|-------|-------|----------|---------|------------|------|
| Liu et al. (2017) | AW-I | TA | LaD | FF & DCA | MIL |
| Liu et al. (2021) | AW-I | TA | LaD | FF & DCA | MIL |
| Lu et al. (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Lu et al. (2016) | AW-I | TA | LaD | FF & DCA | MIL |
| Luo et al. (2019) | AW-I | TA | LaD | FF & DCA | MIL |
| Marino et al. (2007) | AW-I | TA | LaD | FF & DCA | MIL |
| Mi et al. (2015) | AW-I | TA | LaD | FF & DCA | MIL |
| Miyazaki and Ohmae (2005) | AW-I | TA | LaD | FF & DCA | MIL |
| Moseberg and Roppenecker (2015) | AW-I | TA | LaD | FF & DCA | MIL |
| Moseberg and Roppenecker (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Moseberg (2015) | AW-I | TA | LaD | FF & DCA | MIL |
| Mutoh and Tomita (2007) | AW-I | TA | LaD | FF & DCA | MIL |
| Mutoh (2009) | AW-I | TA | LaD | FF & DCA | MIL |
| Németh et al. (2012) | AW-I | TA | LaD | FF & DCA | MIL |
| Nguyen et al. (2017) | AW-I | TA | LaD | FF & DCA | MIL |
| Pathak et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Plumlee et al. (2004) | AW-I | TA | LaD | FF & DCA | MIL |
| Plumlee (2004) | AW-I | TA | LaD | FF & DCA | MIL |
| Polmans and Stradke (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Poussot-Vassal (2008) | AW-I | TA | LaD | FF & DCA | MIL |
| Poussot-Vassal et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Ramanathan Venkita et al. (2020) | AW-I | TA | LaD | FF & DCA | MIL |
| Raveendran et al. (2020) | AW-I | TA | LaD | FF & DCA | MIL |
| Reinold et al. (2019) | AW-I | TA | LaD | FF & DCA | MIL |
| Ringdorfer et al. (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Saktivel et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Sename et al. (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Sho et al. (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Song et al. (2003) | AW-I | TA | LaD | FF & DCA | MIL |
| Song and Hedrick (2005) | AW-I | TA | LaD | FF & DCA | MIL |
| Song et al. (2011) | AW-I | TA | LaD | FF & DCA | MIL |
| Stolte et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Subroto et al. (2012) | AW-I | TA | LaD | FF & DCA | MIL |
| Sun et al. (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Temiz et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Temiz et al. (2019) | AW-I | TA | LaD | FF & DCA | MIL |
| Temiz et al. (2020) | AW-I | TA | LaD | FF & DCA | MIL |
| Tian et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Wada et al. (2017) | AW-I | TA | LaD | FF & DCA | MIL |
| Wada et al. (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2007) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Longoria (2009) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Wang (2010) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Wang (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Wang (2011) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Wang (2012) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang and Wang (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2013) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2014) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2015) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2016) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2017) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2018) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2019) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2020) | AW-I | TA | LaD | FF & DCA | MIL |
| Wang et al. (2021) | AW-I | TA | LaD | FF & DCA | MIL |
| Wanner et al. (2012) | AW-I | TA | LaD | FF & DCA | MIL |

**Actuator topologies:** AW: All-wheel; FA: Front axle; RA: Rear axle; I: Wheel-individual; (•): Not actively used.

**Degradations:** Dr.: Drive; Br.: Brake; Steer.: Steering; T.: Tire; TU: Unintended wheel torque; TO: Zero wheel torque; L/S: Locking or spinning wheel; TR: Reduced wheel torque range; SR: Reduced steering angle range; SD: Reduced steering dynamics; SU: Unintended steering angle; S0: Zero steering torque; BO: Tire blowout.

**Control targets:** LaD: Lateral dynamics; LoD: Longitudinal dynamics; Path: Path tracking; Pose: Temporal sequence of poses; VeD: Vehicle dynamics; YA: Yaw angle.

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**Experiments:** HIL: Hardware in the Loop; MIL: Model in the Loop; VIL: Vehicle in the Loop.

**Reference:** DLC: Double lane change; SLC: Single lane change; Crv.: Curved; Str.: Straight; Oth.: Other.
Steering degradations are in general less often considered compared to drive and brake degradations. Fixed steering angles are covered in 35 publications [34–36, 41, 42, 47, 57, 58, 70, 73, 76, 77, 81, 96, 99, 103–105, 108, 110–112, 118, 126, 132–134, 136, 146, 150, 151, 153, 154, 164, 169]. 25 publications include a free-running steering [44, 46, 59–63, 65, 71, 72, 75, 85–87, 100, 113, 132, 145, 146, 148, 162, 163, 171]. Fewer publications consider a reduced steering angle range (20) [34, 37, 52, 53, 56, 67, 68, 82, 120, 125–127, 131, 133, 134, 145, 146, 150, 151, 153] or steering rates (5) [126, 130, 145, 162, 163]. Overall, researchers expect that there are more or less defined ways of how actuators degrade. That is, they implicitly assume certain actuator-internal mechanisms that lead to the defined behavior, e.g., a drive motor that is torque-free after a fault. In contrast to this general black box assumption, a few publications take into account the internal dynamics of an actuator and model the temporal behavior of the actuator during a degradation. For instance, Nguyen et al. [109] and Chen et al. [178] propose approaches to handle drive degradations caused by bearing faults deteriorating the available drive torque.

### TABLE I (continued)

| Author(s) (Year) | Actuator topology | Degradation | Control | Experiment |
|------------------|-------------------|-------------|---------|------------|
| Zhang and Cocquempot (2014) | AW-I | VeD | -Fuzzy (ACA/OCA) | HiL |
| Zhang and Cocquempot (2014) | AW-I | VeD | -Fuzzy (ACA/OCA) | MiL |
| Zhang et al. (2015) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang et al. (2016) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang et al. (2017) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang et al. (2018) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang et al. (2019) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang et al. (2020) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zhang and Lu (2020) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Zong et al. (2013) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Chen et al. (2014) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Fenyes et al. (2020) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Guo et al. (2012) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Haddad et al. (2012) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Jing and Liu (2019) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Li et al. (2013) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Li et al. (2014) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Liu et al. (2018) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Meng et al. (2019) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Mo et al. (2013) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Patwardhan et al. (2014) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Patwardhan et al. (2015) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Patwardhan et al. (2016) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Wang et al. (2015) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Wang et al. (2016) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Wang et al. (2017) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Wang et al. (2018) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Yang et al. (2019) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |
| Yu et al. (2014) | AW-I | VeD | -Fuzzy (RB+DCA) | MiL |

**Actuator topologies:** AW: All-wheel; FA: Front axle; RA: Rear axle; 4: Wheel individual; (): Not actively used.

**Degradations:** Dr.: Drive; Br.: Brake; Steer.: Steering; T.: Tire; TU: Unintended wheel torque; TR: Reduced wheel torque range; SU: Reduced steering angle range; SD: Reduced steering dynamics; SR: Reduced steering angle range; SO: Zero steering torque;

**Control targets:** LA: Lateral dynamics; LD: Longitudinal dynamics; Path: Path tracking; Pose: Temporal sequence of poses; VeD: Vehicle dynamics; YA: Yaw angle.

**Control techniques:** ACA: Analytical control allocation; DCA: Direct control allocation; FF: Feed forward; I: Integral;

**Experiments:** HiL: Hardware in the Loop; MiL: Model in the Loop; ViL: Vehicle in the Loop.

**Reference:** DLC: Double lane change; SLC: Single lane change; Crv.: Curved; Str.: Straight; Oth.: Other.
publications addressing actuator degradations; — publications addressing drive degradations; — publications addressing brake degradations; — publications addressing wheel degradations. Therefore, we focus on wheel hub or close-to-wheel motors in electric vehicles for wheel-individual all-wheel drive. This far the most widespread variant (107 publications). This implementation reveals that the most widely used actuator implementations in literature are more projecting into future, for wheel-individual all-wheel drive is by far the most widespread variant (107 publications). This implementation is frequently motivated by the potential for wheel hub or close-to-wheel motors in electric vehicles as well as the ease of implementation in simulation and control design.

The joint consideration of drive, brake, and steering implementations reveals that the most widely used actuator topology consists of wheel-individual all-wheel drive and front-axle steering [41, 42, 45, 50–52, 59–63, 67, 68, 75, 87, 96–98, 100, 101, 116, 120, 132, 135, 146, 148–154, 158, 159, 172–176, 187, 199]. Publications focusing on fault-tolerant control for wheel-individual all-wheel drive only [30–32, 38, 43, 49, 80, 84, 88, 93, 94, 109, 113, 128, 138–142, 144, 155, 160, 161] are considered second most in literature followed by wheel-individual all-wheel brake together with front-axle steering [41, 42, 45, 50–52, 59–63, 67, 68, 75, 87, 96–98, 100, 101, 116, 120, 132, 135, 146, 148–154, 158, 159, 172–176, 187, 199].

In general, the effects of degradations as well as the potential to overcome these effects are strongly linked to the available actuator topology. While compiling this survey it turned out that actuator implementations are not always designated clearly and unambiguously. For instance, the term “front steering” could refer to either one steering actuator that steers both wheels or to one steering actuator per wheel resulting in wheel-individual steering. Therefore, we distinguish between front-axle, rear-axle, and all-wheel topologies where all-wheel refers to separate front and rear-axle actuators. It is stated explicitly if wheels of an axle can be controlled individually, otherwise both wheels are affected by the same actuator. The abbreviation scheme used in Table I as well as in Fig. 3 is influenced by the work of Jonasson et al. [268].

Altogether, the available literature presents fault-tolerant control schemes for a wide range of different actuator topologies, which appear with different frequency as can be taken from Fig. 3. Concentrating on single actuator types, it can be observed that the most common brake and steering implementations reflect the state of the art in series production vehicles: 50 publications involve wheel-individual all-wheel braking and 76 front-axle steering. For steering implementations, all-wheel steering (28 publications) and wheel-individual all-wheel steering (22) are quite frequently encountered as well. In contrast, drive implementations found in literature are more projecting into future, for wheel-individual all-wheel drive is by far the most widespread variant (107 publications). This implementation is frequently motivated by the potential for wheel hub or close-to-wheel motors in electric vehicles as well as the ease of implementation in simulation and control design.
only a single actuator type. Topologies featuring three actuators are the most over-actuated topologies, i.e., combining wheel-individual all-wheel drive and wheel-individual all-wheel brakes with either wheel-individual all-wheel steering [106, 107] or the wheel-individual all-wheel drive topology mentioned above. A brake-only topology using wheel-individual brakes at all wheels is encountered as well [64, 72, 92, 122, 143, 147, 178, 185, 188, 200]. For these topologies, steering angles act as system parameters or as disturbance if a steering actuators are mentioned but not actively used, cf. Table I. Moreover, two different steering-only implementations are found which consist either of all-wheel steering [34, 37, 53, 99, 125, 181] or front-axle steering [180, 183, 184, 186, 191, 192, 194, 198]. Obviously, the approaches using solely front-axle steering are used for compensating effects of tire blowouts. For the steering-only approaches, vehicle speed serves as system parameter.

Last but not least, we would like to note that some dissertations show integrated vehicle motion control approaches applicable to different actuator topologies, which also investigate the approaches’ potential for fault tolerance [58, 77, 112, 192]. For these publications, Table I as well as Fig. 3 take into account those topologies that are explicitly investigated by the authors with regard to faulty actuators.

V. Control approaches

In addition to the diversity of actuator topologies and permissible actuator degradations, a plethora of fault-tolerant vehicle motion control approaches exists in the covered literature. In order to give an overview, we examine the approaches from three perspectives in the following subsections. In Subsection V-A, as a first perspective, we present the different control targets that researchers aim to achieve with their approaches. To attain the control targets, researchers use a variety of control techniques, which are summarized as a second perspective in Subsection V-B. The presented control approaches often combine different control techniques. Therefore, as a third perspective, we give an overview of the resulting control structures in Subsection V-C. Additionally, Subsection V-D highlights approaches that use brake or drive actuators to steer.

A. Control targets

Overall, we distinguish five different control targets. An overview of the number of available publications for the different control targets is given in Fig. 4. With 66 publications, the control of vehicle dynamics (comprising longitudinal as well as lateral vehicle motion) is the most common control target in the body of literature considered in this survey. These are primarily publications addressing actuator degradations [30–33, 36, 39, 43, 48, 50, 51, 54, 55, 58, 64, 69, 70, 74, 75, 77–79, 82–86, 88, 90–92, 94, 97, 101, 103–105, 109, 118, 127–131, 135–142, 144–146, 150–152, 156–158, 169, 170, 173, 175, 177], while only one publication targets the control of vehicle dynamics in presence of tire blowouts [200]. These publications are frequently motivated by human-driven cars where reference values for the vehicle dynamics are generated via the driver inputs on the steering wheel as well as the brake and the accelerator pedals.

Lateral vehicle dynamics – i.e., yaw and lateral motion – are the second most encountered control target in the surveyed literature. They are considered in 48 publications addressing actuator degradations [34, 38, 46, 49, 57, 59, 61, 62, 65–68, 71, 72, 76, 80, 81, 87, 89, 93, 95, 96, 99, 100, 108, 111–116, 119–122, 132–134, 147–149, 155, 159–161, 164, 165, 171] and six addressing tire blowouts [178, 183, 185–188]. In contrast, the reviewed approaches seldom target pure longitudinal dynamics [45, 106, 107, 123, 124, 143].

The remaining publications consider the vehicle motion in relation to an external reference. Among these, path tracking is the biggest group, to which publications considering tire blowouts contribute a significant number with 16 publications [179–182, 184, 189–199]. Still, those considering actuator degradations form the majority in this group (27 publications) [29, 35, 37, 40–42, 44, 47, 52, 53, 56, 60, 63, 73, 98, 110, 125, 153, 154, 162, 163, 166–168, 172, 174, 176]. Publications that target yaw angle [102, 117] control and pose tracking [126] are comparably rare.

B. Control techniques

To reach the control targets, researchers use various control techniques, often in combination. We categorize the techniques as displayed in Fig. 5, which reveals that different techniques are encountered with varying frequency. Of course, the techniques’ implementations differ in the publications, even within one category, which are influenced i.a. on the actuator topology, tolerated degradations, control target, and control structure.

Classic feedback control techniques are widely used. Among these, P, PI, PID, or PD controllers (summarized under PID in Fig. 5) form the biggest group [29, 31, 32, 36, 69–72, 75, 80, 81, 87, 94, 99, 102–105, 109, 110, 129–131,
145, 149, 150, 152, 155–159, 171, 173, 181, 183, 186, 195]. To explicitly address actuator degradations, linear quadratic regulators are also frequently used [38, 47, 57, 59, 112, 113, 162, 163, 169, 175, 185, 189, 190]. In comparison, standard state feedback control is encountered less often [35, 46, 60–62, 73, 144, 151, 154, 170, 187, 197, 199].

Moreover, advanced feedback control techniques are employed regularly. Here, sliding mode control is most widespread [30, 31, 33, 41, 42, 44, 47–49, 51, 61–64, 66, 74, 85, 86, 94–96, 119, 122–124, 127, 132, 135–138, 141, 142, 147, 164, 172–174, 188, 200]. Further regularly used are Lyapunov theory-based techniques [39, 40, 52, 53, 67, 68, 76, 100, 114, 115, 121, 133, 134, 146, 148, 153, 179, 182, 193], $\mathcal{H}_\infty$ control [39, 40, 52, 53, 67, 68, 76, 100, 114, 115, 121, 133, 134, 146, 148, 153, 179, 182, 193] as well as model-predictive control [44, 78, 83, 90, 91, 126, 165, 176, 177, 180, 194, 198, 199]. $\mathcal{H}_\infty$ control techniques are sometimes enhanced with other norm-optimal techniques, e.g., the $L_2$-norm is used for disturbance rejection in [146, 179]. A few publications also use fuzzy control [120, 160, 161, 186], flatness-based [56, 58, 77, 79], as well as model-free adaptive control techniques [82, 97, 98].

The remaining techniques can be summarized as non-feedback control techniques. Here, control allocation is the most often used control technique in order to distribute control inputs to the four wheels; sometimes employed as sole control technique, yet in most cases in hierarchical control structures as control layer underlying a feedback control technique. 44 publications solve the optimization problem underlying the control allocation online [31, 33, 35, 36, 43, 45, 49, 52, 54, 64, 70, 76, 78, 79, 83, 88, 90–92, 94, 96, 111, 118, 128, 133–138, 140, 141, 145, 147, 149, 155–157, 159, 173, 176, 177, 182, 200] and 22 analytically [38, 41, 42, 48, 58, 59, 66, 73, 77, 103–105, 127, 129–131, 152, 156–158, 164, 199]. Among the latter, solutions based on pseudo-inverses are frequently encountered [38, 48, 73, 77, 103–105, 127, 156–158, 164, 199]. Additionally, researchers use simpler control allocation techniques, which are subsumed as direct control allocation in Table I and Fig. 5. These techniques allocate forces either evenly among the wheels [32, 65, 68, 69, 93, 122, 160, 161] or proportionally to the tire normal force distribution [29, 50, 55, 81, 84, 116, 119, 143]. In case of tire blowouts, also uneven distributions are presented in order to account for the specific effects [187, 188]. Commonly, all direct control allocation techniques cannot directly take into account physical tire limits. Thus, sometimes rule-based redistribution is proposed if maximum tire forces are exceeded.

Other non-feedback control techniques are feed forward control and rule-based reconfiguration. Feed forward control comprise techniques that reduce control efforts of a parallel feedback controller in closed loop applications or control the desired vehicle motion in open-loop manner [35, 38, 49, 65, 71–73, 75, 81, 93, 103–105, 109, 139, 150–154, 190–192, 195–197]. In a broader sense, many of the control approaches can be described as rule-based since controller reconfiguration necessary for fault tolerance normally follows a certain set of rules. However, we summarize those approaches as rule-based where discrete and simple reconfiguration takes place [43, 65, 80, 88, 89, 102, 106, 107, 110, 147, 160, 161, 185, 200], e.g., in a four-wheel individual drive application, disabling the non-faulty drive of an axle when the axle’s other drive motor stops providing torque to a wheel.

C. Control structures

As stated, different control techniques are often combined to reach the control targets. The resulting control structures are either parallel or hierarchical, sometimes a combination of both. Hierarchical control structures with usually two control layers are found in 73 publications [29, 31, 32, 35, 36, 38, 41–44, 47–50, 52, 58, 59, 64, 66, 68–70, 73, 76–79, 81, 83, 90, 91, 93, 94, 96, 103–105, 119, 122, 127, 129–131, 133–138, 140, 141, 145, 147, 149, 152, 155–161, 164, 173, 176, 177, 182, 185, 187, 188, 190, 199, 200]. 35 publications feature parallel control structures [31, 35, 38, 49, 60–62, 65, 71–73, 75, 80, 88, 103–105, 109, 110, 139, 150–154, 160–163, 173, 181, 195–197, 199]. Here, either multiple controlled variables are addressed by distinct control laws or a single controlled variable is addressed by a combination of different control techniques. The remaining portion of the examined publications uses a sole control technique [30, 33, 34, 37, 39, 40, 45, 46, 51, 53–57, 63, 67, 74, 82, 84–87, 89, 92, 95, 97–102, 106–108, 111–118, 120, 121, 123–126, 128, 132, 142–144, 146, 148, 165–172, 174, 175, 178–180, 183, 184, 186, 189, 191–194, 198].

It is worth mentioning that some publications also present the control techniques used at the actuator level. As we focus purely on vehicle motion control (cf. Section II), these are neglected in the statements of this subsection and in the overviews of Table I. The same applies to fault estimation techniques, which are included in some publications. Last but not least, we would like to highlight that a
few publications feature alternative control techniques on selected control layers [33, 65, 102, 147, 156, 157, 200].

D. Steering redundancy through drive or brake actuation at front axle

In presence of degradations, the majority of control approaches controls the vehicle motion directly by means of the remaining healthy actuators. However, indirect approaches can be found too, primarily regarding degradations of front-axle steering whose actuator has stopped providing steering torque. Then, these approaches control the steering angle by either wheel-individual front-axle drives [44, 59–63, 75, 87, 100, 113, 132, 148] or brakes [46, 71, 72, 171] in order to gain the desired vehicle motion. The drive or brake actuation causes a moment around the tires’ vertical axis, which is used to induce the desired steering motion – given that certain prerequisites with regard to suspension kinematics such as a positive mechanical trail are fulfilled. These approaches are referred to as drive or brake assisted steering as well as steer-by-drive or steer-by-brake. Of course, using wheel torques as backup steering mechanism influences the overall vehicle dynamics as these are strongly coupled with the dynamics of the steering system. Consequently, Zhang et al. [171] investigate possible consequences of their steer-by-brake approach on longitudinal dynamics while Kirli et al. [75] focus on demonstrating limitations for a steer-by-drive approach.

VI. Experiments

For demonstrating the suitability of fault-tolerant control approaches, experimental validation is key. Just as with the perspectives presented in the previous sections, the experimental setups used for validation differ considerably in the covered literature and make comparisons between approaches difficult, even when similar topologies and degradations are used.

A. Type of experiments

A first distinguishing point is the type of experiments. Researchers use model-in-the-loop experiments in the vast majority of publications [29–44, 46–73, 75–78, 80–86, 88–90, 92–115, 118–141, 143, 145–157, 159–175, 177, 179–181, 183–190, 193–200]. Rare exceptions are publications showing hardware-in-the-loop [74, 117, 176, 182] or even vehicle-in-the-loop experiments [45, 79, 87, 91, 116, 142, 144, 158, 178, 191, 192].

For model-in-the-loop experiments, commercial simulation environments are quite frequently employed. Among these, CarSim is most often used [30–32, 38–42, 44, 49–51, 56, 57, 60–64, 66–68, 74, 78, 80, 92–94, 97, 98, 100, 108, 109, 122, 132, 135–141, 143, 145–149, 155, 159, 164, 165, 170–176, 181, 184–187, 200], followed by veDYNA [150–154, 180, 182, 193–198], CarMaker [73, 117, 179], ADAMS [52, 53], Cruise [43], Dyna4 [119], and AMESim [76]. Altogether, the vehicle models’ parameterizations are selected more or less individually in each publication and also depend strongly on the actuator topology as well as on the considered degradations.

B. Reference trajectories

In particular, the experiments differ in terms of the chosen reference trajectories, which are the second distinguishing point. Although often oriented towards standard vehicle testing maneuvers, the references are specific for each publication and vary widely in speed, yaw rate, lateral, as well as longitudinal acceleration. As a result, they pose different challenges for vehicle motion control, especially in the presence of degradations.

Based on the standard vehicle testing maneuvers, we divide the reference trajectories into five categories to give an overview. Reference trajectories oriented to lane change maneuvers are often used, either in terms of single lane changes [30, 31, 35, 41, 42, 51, 57, 59–61, 63, 67, 68, 77, 85, 86, 94, 96, 100, 110, 111, 120, 127, 129–131, 138–141, 146, 150–155, 170, 173, 174, 181] or double lane changes [38, 44, 49, 51, 53, 62, 74–76, 78, 79, 85–87, 99, 109, 112, 114–116, 126, 132, 136, 137, 146–148, 150–152, 159, 164, 165, 175, 176]. Moreover, reference trajectories that are curved in only one direction are found regularly [29, 33, 36, 37, 41, 42, 44, 45, 57, 60, 62, 63, 65, 68–72, 80, 81, 83, 85, 86, 90, 92, 96, 105, 106, 119, 122, 125, 127, 132, 138–142, 144, 146, 148, 150–152, 154, 156, 157, 160, 161, 171, 176, 177, 180, 183, 185, 187, 189], for instance J-turns or circular drives, which cannot be sharply distinguished in the literature.

Usually simpler to handle from a vehicle dynamics point of view, trajectories going straight are employed in [31, 32, 37, 39, 40, 48, 49, 54, 55, 64, 66, 69, 80, 83, 84, 88, 89, 92–95, 97, 98, 102–104, 106, 107, 110, 117–119, 122–125, 128, 135–137, 139, 141–143, 145, 149, 150, 153, 155, 158, 162, 163, 166–168, 170, 172–174, 177, 178, 180, 182–188, 193–198, 200]. Other trajectories are of arbitrary shape [34, 40, 43, 45–47, 50, 52, 56, 58, 73, 82, 91, 101, 108, 113, 133, 134, 155, 159, 169, 171, 179, 190–192, 195, 199]. Please note that the maneuvers overall are not sharply distinguishable, e. g., we categorize curved reference trajectories with large curvatures as straight since they evoke negligible lateral acceleration and yaw motion.

VII. Conclusion and outlook

Motivated by the need for a high degree of fault tolerance in SAE level 4+ automated vehicles, we survey fault-tolerant vehicle motion control approaches targeting drive, brake, steering, and tire degradations in this paper. Altogether, we are surprised by the plethora of available publications, which comes along with a huge variety of different control approaches.

Basically, the literature reveals that different actuator degradations can be handled in vehicles with varying actuator topologies even in dynamic driving situations. This implies a high potential for exploiting functional redundancies as part of safety concepts for future series production vehicles. However, further research is required to support the mandatory thorough safety argumentation.
First, advanced real world testing would increase the validity when arguing real-time capability and suitability since the majority of publications use simulation experiments.

Furthermore, explicitly highlighting the limits of an approach would contribute to the state of the art. While good case experiments basically show that an approach is working, investigating the limits would allow a statement under which conditions a fault-tolerant control approach fails. This would enable a comparison of the functional range that an approach can ensure with the functional range required by a specific application. For example, we introduce a first concept to investigate systematically whether fault-tolerant vehicle motion control is suitable under normal driving conditions for a given automated vehicle application in [269].

Investigating the functional limits could be one approach that would allow for a comparison of different fault-tolerant control approaches. However, a comparison based on the current state of the art, in general, is hardly possible due to the manifold of varying conditions used in the reviewed literature. Hence, a general framework to test different approaches under otherwise identical conditions (i.e., standardized vehicles as well as reference trajectories) would be of high value for researchers and practitioners. In this context, an approach for comparing trajectory tracking controllers for automated vehicles is presented by Calzolari et al. [270], though not considering actuator faults. The authors also introduce a scoring mechanism, which is based on the deviation from a reference trajectory and allows an easy comparison of different control approaches. Such an approach could be extended for comparing different fault-tolerant vehicle motion controllers.

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References

[1] T. Woopen et al., “UNICARagil – Disruptive Modular Architectures for Agile, Automated Vehicle Concepts,” in 27th Aachen Colloq., Aachen, Germany, 2018. doi: 10.18154/RWTU-2018-229009.

[2] Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, SAE Int. Standard J3016, 201806.

[3] R. Iserrmann, R. Schanz, and S. Stötzl, “Fault-tolerant drive-by-wire systems,” IEEE Control Syst. Mag., vol. 22, no. 5, pp. 64–81, 2002. doi: 10.1109/MCS.2002.1035218.

[4] R. Mattei and M. Maurer, “Autonomous driving – a top-down-approach,” Automatisierungstechnik, vol. 63, no. 3, pp. 155–167, 2015. doi: 10.1515/auto-2014-1136.

[5] Y. Zhang and J. Jiang, “Bibliographical review on reconfigurable fault-tolerant control systems,” Annu. Rev. Control, vol. 32, no. 2, pp. 229–252, 2008. doi: 10.1016/j.annrev.2008.03.008.

[6] T. A Johansen and T. I. Fossen, “Control Allocation – A Survey,” Automation, vol. 49, no. 5, pp. 1087–1103, 2013.

[7] D. Wanner, A. Trigell, L. Drugge, and J. Jerrelin, “Survey on Fault-Tolerant Vehicle Design,” World Electric Veh. J., vol. 5, no. 2, pp. 598–609, 2012. doi: 10.3390/wevj5020598.

[8] C. A. Vivas-López, D. Hernández-Alcantara, J. C. Tudón-Martínez, and R. Morales-Menendez, “Review on Global Chassis Control,” in 5th IFAC Symp. Syst. Struct. and Control, ser. IFAC Proc. Volumes, vol. 46, no. 2, Grenoble, France: IFAC, 2013, pp. 875–880. doi: 10.3182/20130204-3-FR-2033.00040.

[9] B. Shyrokau, “Coordinated control of multi-actuated electric vehicle,” Dissertation, Nanyang Technological Univ., Singapore, 2014. doi: 10.32657/10356/61979.

[10] M. Kissai, B. Monsuez, and A. Tapus, “Review of integrated vehicle dynamics control architectures,” in 2017 Eur. Conf. Mobile Robots (ECMR), Paris, France: IEEE, pp. 1–8. doi: 10.1109/ECMR.2017.8098687.

[11] C. Huang, F. Naghdyl, H. Du, and H. Huang, “Fault tolerant steer-by-wire systems: An overview,” Annu. Rev. Control, vol. 47, pp. 98–111, 2019. doi: 10.1016/j.arcontrol.2019.04.001.

[12] R. M. Shet, N. C. Iyer, and Y. Jeppe, “Fault Tolerant Control System for Autonomous Vehicle: A Survey,” J. Adv. Res. Dynamical and Control Syst., vol. 12, pp. 813–830, SP8 2020. doi: 10.5373/JARDCS/V12SP8/20202858.

[13] M. Proetzsch, T. Luksch, and K. Berns, “Fault-Tolerant Behavior-Based Motion Control for Offroad Navigation,” in Proc. 2005 IEEE Int. Conf. Robot. and Automat., Barcelona, Spain: IEEE, pp. 4697–4702. doi: 10.1109/ROBOT.2005.1570845.

[14] M. A. Djeziri, R. Merzouki, B. O. Bouamama, and M. Ouladsine, “Fault Diagnosis and Fault-Tolerant Control of an Electric Vehicle Overactuated [sic],” IEEE Trans. Veh. Technol., vol. 62, no. 3, pp. 986–994, 2013. doi: 10.1109/TVT.2012.2219150.

[15] D. Rotondo, V. Puig, F. Nejari, and J. Romera, “A Fault-Hiding Approach for the Switching Quasi-LPV Fault-Tolerant Control of a Four-Wheeled Omnidirectional Mobile Robot,” IEEE Trans. Ind. Electron., vol. 62, no. 6, pp. 3932–3944, 2015. doi: 10.1109/TIE.2014.2367002.

[16] R. Loureiro, S. Beumuassa, Y. Touati, R. Merzouki, and B. O. Bouamama, “Integration of Fault Diagnosis and Fault-Tolerant Control for Health Monitoring of a Class of MIMO Intelligent Autonomous Vehicles,” IEEE Trans. Veh. Technol., vol. 63, no. 1, pp. 30–39, 2014. doi: 10.1109/TVT.2013.2274289.

[17] N. Hacene and B. Mendil, “Fuzzy Behavior-based Control of Three Wheeled Omnidirectional Mobile Robot,” Int. J. Automat. and Computat., vol. 16, no. 2, pp. 163–185, 2019. doi: 10.1007/s11633-018-1135-x.

[18] Y. Lounici, Y. Touati, S. Adjerid, B. O. Bouamama, and D. Benazzouz, “Uncertain Bicausal Bond Graph and Adaptive Fuzzy PID Controller for Fault-Tolerant Control,” in 2020 Int. Conf. Elect. Eng. (ICEE), Istanbul, Turkey: IEEE, 2020. doi: 10.1109/ICEE49069.2020.9249839.

[19] X.-Z. Jin, Y.-X. Zhao, H. Wang, Z. Zhao, and X.-P. Dong, “Adaptive fault-tolerant control of mobile robots with actuator faults and unknown parameters,” IET Control Theory Appl., vol. 13, no. 11, pp. 1665–1672, 2019. doi: 10.1049/iet-cta.2018.5492.

[20] X. Zhang, Y. Xie, L. Jiang, G. Li, J. Meng, and Y. Huang, “Fault-Tolerant Dynamic Control of a Four-Wheel Redundantly-Actuated Mobile Robot,” IEEE Access, vol. 7, pp. 157909–157921, 2019. doi: 10.1109/ACCESS.2019.2949746.

[21] M. Doran, R. Sterritt, and G. Wilkie, “Autonomic architecture for fault handling in mobile robots,” Innov. Syst. and Softw. Eng., 2020. doi: 10.1007/s11334-020-00361-8.

[22] T. K. Bera, R. Merzouki, B. O. Bouamama, and A. K. Samantaray, “Design and validation of a reconfiguration strategy for a redundantly actuated intelligent autonomous vehicle,” Proc. Inst. Mech. Eng., Part F: J. Syst. and Control Eng., vol. 226, no. 8, pp. 1060–1076, 2012. doi: 10.1177/0959651812447486.

[23] J. Nah, W. Kim, K. Yi, D. Lee, and J. Lee, “Fault-tolerant driving control of a steer-by-wire system for six-wheel-driving six-wheel-steering vehicles,” Proc. Inst. Mech. Eng., Part D: J. Automob. Eng., vol. 227, no. 4, pp. 506–520, 2013. doi: 10.1177/0954407012457507.

[24] H. Liang, Y. Ma, J. Zhi, Y. Li, and Y. Peng, “Optimized torque allocation strategy on multi-vehicle wheels,” in 2017
J.-E. Moseberg, “Regelung der Horizontalbewegung eines überaktuierten Fahrzeugs unter Berücksichtigung von Realisierungsanforderungen,” (in German), Dissertation, Univ. Erlangen-Nürnberg, Erlangen, Germany, 2016.

N. Mutoh and Y. Tomita, “Fault-Safe Control Methods for EVs with the Fault-Safe Structure Driven by Front and Rear Wheels Independently,” World Electric Veh. Assoc. J., vol. 1, pp. 271–278, 2007.

N. Mutoh, “Front-and-Rear-Wheel-Independent-Drive-Type Electric Vehicle (FRID EV) with Compatible Driving Performance and Safety,” presented at the EVS24 Int. Battery, Hybrid and Fuel Cell Veh. Symp. Ser. World Electric Veh. J., Vol. 3, 2010, pp. 152–161. doi: 10.1109/ACCESS.2020.2983203.

B. Németh, P. Gáspár, J. Bokor, O. Sename, and L. Dugard, “Fault-tolerant control design for trajectory tracking in driver assistance systems,” in 8th IFAC Symp. Fault Detection Supervision and Saf. Tech. Procceses (SAFEPROCESS), ser. IFAC Proc. Volumes, vol. 45, no. 20, Mexico City, Mexico: IFAC, 2012, pp. 186–191. doi: 10.3182/20120829-3-MX-2028.00102.

T.-H. Nguyen, B.-C. Chen, D. Yin, and P.-S. Huynh, “Active fault tolerant torque distribution control of 4 in-wheel motors electric vehicles based on Kalman filter approach,” in 2017 Int. Conf. Syst. Control. Eng. (ICSCS), Ho Chi Minh City, Vietnam: IEEE, pp. 360–364. doi: 10.1109/ICCSSE.2017.8030897.

P. M. Pathak, R. Merzouki, A. K. Samantaray, and B. Ould-Bouamama, “Reconfiguration of Directional Handling of an Autonomous Vehicle,” in 2008 IEEE Region 10 and 3rd Int. Conf. Ind. Inf. Syst., Kharagpur, India: IEEE, doi: 10.1109/ICINF.2008.4798408.

J. H. Plumblee, D. M. Bevly, and A. S. Hodel, “Control of a ground vehicle using quadratic programming based control allocation techniques,” in Proc. 2004 Amer. Control Conf. (ACC), vol. 5, Boston, MA, USA: IEEE, pp. 4704–4709. doi: 10.1109/ACC.2004.1388555.

J. H. Plumblee, “Multi-input ground vehicle control using quadratic programming based control allocation techniques,” Master’s Thesis, Auburn Univ., Auburn, AL, USA, 2004.

K. Polmans and S. Stracke, “Torque vectoring as redundant steering for automated driving or steer-by-wire,” in 5th Int. Munich Chassis Symp. 2014, Munich, Germany: Springer Fachmedien Wiesbaden, pp. 163–177. doi: 10.1007/978-3-658-05978-1_13.

C. Poussot-Vassal, “Robust LPV multivariable Automotive Global Chassi Control,” Dissertation, Grenoble Institut Polytechnique, Grenoble, France, 2008.

C. Poussot-Vassal, O. Sename, and L. Dugard, “A LPV/H∞ Global Chassis Controller for handling improvements involving braking and steering systems,” in Proc. 74th IEEE Conf. Decis. and Control, Cancun, Mexico: IEEE, pp. 5366–5371. doi: 10.1109/CDC.2008.4738874.

S. Ramanathan Venkata, B. Bouikroune, A. Mishra, and E. Van Nuen, “A Fault Tolerant Lateral Control Strategy for an Autonomous Four Wheel Driven Electric Vehicle,” in 2020 IEEE Intell. Veh. Symp. (IV), Las Vegas, NV, USA: IEEE, pp. 1221–1226. doi: 10.1109/IV402020.9304740.

R. Raveendran, K. B. Devika, and S. C. Subramanian, “Brake Fault Identification and Fault-Tolerant Directional Stability Control of Heavy Road Vehicles,” IEEE Access, vol. 8, pp. 169 229–169 246, 2020. doi: 10.1109/ACCESS.2020.3024251.

P. Reinold, V. Nachtigal, and A. Trächtler, “An Advanced Electric Vehicle for Development and Test of New Vehicle-Dynamics Control Strategies,” in 6th IFAC Symp. Adv. Automot. Control (AAC), ser. IFAC Proc. Volumes, vol. 43, no. 7, Munich, Germany: IFAC, 2010, pp. 152–161. doi: 10.3182/20100712-3-DE-2013.00172.

M. Ringdorfer, “Integrated Vehicle Dynamics Controller for Electric Traction Drives and Mechatronic Drivetrain Components,” Dissertation, Tech. Univ. Graz, Graz, Austria, 2013.

R. Rathi, S. Mohanapriya, C. K. Ahn, and P. Selvaraj, “State Estimation and Dissipative-Based Control Design for Vehicle Lateral Dynamics With Probabilistic Faults,” IEEE
X. Du, G. Han, M. Yu, Y. Peng, X. Xu, and J. Fu, “Fault Detection and Fault-Tolerant Control of Vehicle Semi-Active Suspension System with Magneto-rheological Damper,” *Smart Mater. and Struct.*, 2020. doi: 10.1088/1361-665X/abbdf8.

S. Fergani, O. Sename, and L. Dugard, “A LPV/$H_\infty$ Fault Tolerant Control of Vehicle roll dynamics under semi-active damper malfunction,” in *Proc. 2014 Amer. Control Conf.* (ACC), Portland, OR, USA: IEEE, pp. 4482–4487. doi: 10.1109/ACC.2014.6859081.

P. Gáspár, Z. Szabó, and J. Bokor, “A Fault-Tolerant Vehicle Control Design,” in *17th IFAC World Congr.*, ser. IFAC Proc. Volumes, vol. 41, no. 2, Seoul, South Korea: IFAC, 2008, pp. 8540–8545. doi: 10.3182/20080706-5-KR-1001.01444.

P. Gáspár, “Model-Based Control Design of Integrated Vehicle Systems,” in *Towards Intell. Eng. and Inf. Technol. Ser. Stud. Comput. Intell.*, I. J. Rudas, J. Fodor, and J. Kacprzyk, Eds., vol. 243, Berlin, Heidelberg: Springer, pp. 103–119. doi: 10.1007/978-3-642-05737-5_8.

P. Gáspár, Z. Szabó, and J. Bokor, “LPV design of fault-tolerant control for road vehicles,” in *2010 Conf. Control and Fault-Tolerant Syst. (SysTol)*, Nice, France: IEEE, pp. 807–812. doi: 10.1109/SYSTOL.2010.5676060.

S. Fergani, O. Sename, and L. Dugard, “LPV Design of Fault-Tolerant Control for Road Vehicles,” *Int. J. Appl. Math. and Comput. Sci.*, vol. 22, no. 1, pp. 173–182, 2012. doi: 10.2478/v10006-012-0031-x.

H. Jing, R. Wang, H. R. Karimi, M. Chadli, C. Hu, and F. Yan, “Robust Output-Feedback Based Fault-Tolerant Control of Active Suspension with Finite-Frequency Constraint,” in *9th IFAC Symp. Fault Detection, Supervision and Saf. for Tech. Processes (SAFEPROCESS)*, D. Maquin, Ed., ser. IFAC-PapersOnLine, vol. 48, no. 21, Paris, France: IFAC, 2015, pp. 1173–1179. doi: 10.1016/j.ifacol.2015.09.685.

H. Jing, R. Wang, C. Li, J. Wang, and N. Chen, “Fault-tolerant control of active suspensions in-in-wheel motor driven electric vehicles,” *Int. J. Veh. Des.*, vol. 68, p. 2, 1/2/3 2015. doi: 10.1108/14680071511563780.

H. Li, H. Gao, H. Liu, and M. Liu, “Fault-tolerant $H_\infty$ control for active suspension vehicle systems with actuator faults,” *Proc. Inst. Mech. Eng., Part I: J. Syst. and Control Eng.*, vol. 226, no. 3, pp. 348–363, 2012. doi: 10.1177/0954407011414801.

H. Li, H. Liu, H. Gao, and P. Shi, “Reliable Fuzzy Control for Active Suspension Systems With Actuator Delay and Fault,” *IEEE Trans. Fuzzy Syst.*, vol. 20, no. 2, pp. 342–357, 2012. doi: 10.1109/TFUZZ.2011.2174244.

Q. Li, Y. Pan, and H. Liang, “A Switching Control Approach for Uncertain Vehicle Suspension Systems with Actuator Failure,” *Int. J. Fuzzy Syst.*, 2021. doi: 10.1007/s40815-020-00996-1-3.

B. Lin and X. Su, “Fault-tolerant Controller Design for Active Suspension System with Proportional Differential Sliding Mode Observer,” *Int. J. Control, Automat. and Syst.*, vol. 17, no. 7, pp. 1751–1761, 2019. doi: 10.1177/1532790618811440.

B. Liu, M. Saif, and H. Fan, “Adaptive Fault Tolerant Control of a Half-Car Active Suspension Systems Subject to Random Actuator Failures,” *IEEE/ASME Trans. Mechatronics*, vol. 21, no. 6, pp. 2847–2857, 2016. doi: 10.1109/TMECH.2016.2587159.

B. Liu, Q. Zeng, S. Tong, C. L. P. Chen, and L. Liu, “Actuator Failure Compensation-Based Adaptive Control of Active Suspension Systems With Prescribed Performance,” *IEEE Trans. Ind. Electron.*, vol. 67, no. 8, pp. 7044–7053, 2020. doi: 10.1109/TIE.2019.2937037.

M. Moradi and A. Fekih, “Adaptive PID-Sliding-Mode Fault-Tolerant Control of Automotive Suspension DAMPER,” in *Proc. 2015 Amer. Control Conf.* (ACC), Portland, OR, USA: IEEE, vol. 2, pp. 4882–4887. doi: 10.1109/ACC.2015.7170067.

M. Menezes Morato, O. Sename, and L. Dugard, “LPV-MPC Fault-Tolerant Control of Automotive Suspension Dampers,” in *2nd IFAC Workshop Linear Parameter Varying Syst.*
[257] S. Yu, Y. Liu, F. Wang, H. Chen, and H. Guo, “Simulation of Trajectory Control of Vehicles During a Tire Blowout,” *J. Beijing Univ. Technol.*, vol. 42, no. 8, pp. 1225–1232, 2016. doi: 10.11936/bjutxb2015110016.

[258] Y. Tao, “Dynamics and Active Safety Control of The Tire Blowout Vehicle,” Master Thesis, Jiangxi Univ. Tech-nology, Nanchang, China, 2018.

[259] A. Ito and Y. Hayakawa, “Design of Fault Tolerant Control System for Steer-by-Wire Depending on Drive System,” *Trans. Soc. Instrum. and Control Eng.*, vol. 48, no. 12, pp. 872–881, 2012. doi: 10.9746/sicetr.48.872.

[260] O. Wallmark and M. Jonasson, “Vehicles with autonomous corner modules: Control and fault handling aspects,” in *Proc. Program Rev. Meeting – MIT Industry Consortium Adv. Automot. Elect./Electron. Compon. and Syst.*, Seattle, WA, USA, 2007.

[261] N. Mutoh and Y. Tomita, “Failsafe control methods for EVs with the structure driven by front and rear wheels independently,” in *Proc. 22nd Int. Battery, Hybrid Fuel Cell Electric Veh. Symp. and Expo (EVS-22)*, Yokohama, Japan, 2006.

[262] K. Kawakami, S. Matsugaura, M. Onishi, and H. Shimizu, “Development of fail-safe technologies of ultra high performance EV “KAZ”,” in *Proc. 18th Int. Electric Veh. Symp. (EVS-18)*, Berlin, Germany, 2001.

[263] B. Li, “Optimal control allocation for trajectory and stability control of electric vehicle with in-wheel motors after a tire blowout,” in *Thesis Collection Proc. 19th Asia Pacific Automot. Eng. Conf. and SAE-China Congr.*, 2017, SAE of China Ed., Shanghai, China: Springer, Singap.

[264] Y. Liu, C. Zong, D. Zhang, H. Zheng, X. Han, and M. Sun, “Fault-tolerant control approach based on constraint control allocation for 4WIS/4WID vehicles,” *Proc. Inst. Mech. Eng., Part D: J. Automob. Eng.*, vol. 213, pp. 899–909, 2019. doi: 10.1177/0954407015617334.

[265] M. Jonasson, “Exploiting individual wheel actuators to enhance vehicle dynamics and safety in electric vehicles,” Dissertation, KTH Roy. Inst. Technol., Stockholm, Sweden, 2009.

[266] O. Wallmark and T. Stolte, “Your publication ‘Vehicles with autonomous corner modules: Control and fault handling aspects’,” E-mail communication, 2019.

[267] R. D. Fruechte, A. M. Karmel, J. H. Billings, N. A. Schilke, N. M. Boustany, and B. S. Repa, “Integrated vehicle control,” in *Proc. 19th Int. Autom. Control Conf.* (IFAC), vol. 5, San Francisco, CA, USA: IEEE, 1989, pp. 408–413. doi: 10.1109/IFAC.1989.40176.

[268] M. Jonasson, J. Andreasson, B. Jacobson, and A. S. Trigell, “Global force potential of over-actuated vehicles,” *Veh. Syst. Dyn.*, vol. 48, no. 9, pp. 983–998, 2010. doi: 10.1080/00423110903243232.

[269] T. Stolte, L. Qiu, and M. Maurer, “Reference Trajectories for Investigating Fault-Tolerant Trajectory Tracking Control Algorithms for Automated Vehicles,” in *9th IFAC Symp. Adv. Automot. Control (AAC)*, D. Nelson-Gruel, Ed., ser. IFAC-PapersOnLine, vol. 52, no. 5, Orléans, France: IFAC, 2019, pp. 354–360. doi: 10.1016/j.ifacol.2019.09.007.

[270] D. Calzolari, B. Schürmann, and M. Althoff, “Comparison of Trajectory Tracking Controllers for Autonomous Vehicles,” in *Proc. 20th Int. Conf. Intell. Transp. Syst. (ITSC)*, Yokohama, Japan: IEEE, 2017. doi: 10.1109/ITSC.2017.8317800.