Single-Track Vehicle Dynamics Control: State of the Art and Perspective

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I. Introduction

AUTOMOTIVE control is one of the fields where automatic control theory has the greatest public visibility. Vehicle dynamics control (VDC) systems are a selling point for many manufacturers. In the automotive industry, automatic control is a little less a "hidden" technology than in other fields. The industry got to this point through a long process that started in 1971 with the antiskid Sure Brake system proposed by Chrysler and Bendix and from there, meeting alternate fate, got to today's advanced VDC.

The development of VDC systems for motorcycles started with some delay, but had a faster growth. The first automatic control system for motorcycles was, as for cars, the antilocking braking system introduced in 1983 by BMW. Now, the European Commission is mandating all motorcycles (over 125 cc) sold in Europe from 2016 to be equipped with ABS. The history of traction control (TC) is even more compelling. In 2008, only Ducati and BMW provided TC-equipped motorcycles; by the end of 2012, the list of brands sporting their own version of TC included: BMW, Ducati, Aprilia, MV-Agusta, Kawasaki, Honda, Yamaha, and basically all the other big players in the field [1].

The sudden success of motorcycle dynamics control is due to two related factors: On one hand, electromechanical actuators (electronic throttle bodies (ETB), semiactive suspensions, and actuated brakes) have become more cost-effective, reliable, lighter, and smaller; on the other hand, the success of advanced control techniques on the racing track has promoted the image of automatic control as a performance-enhancing technology, rather than a safety-oriented one. High-end motorcycles are recreational vehicles for the thrill seeking. Performance is a stronger selling point than safety. Once the initial investment had been faced by high-end motorcycles, the technology started to trickle down to more cost-effective vehicles, where safety plays an important role as they are often used as commuter vehicles.

The first VDC systems for motorcycles were adaptation of the systems already developed for cars, namely ABS and TC. Soon, the developers realized that the specific dynamic features of single-track vehicles called for ad hoc solutions. Also, the scientific literature developed its own community devoted to the study of single-track vehicles. In the scientific community, one can recognize two main subgroups (with some overlapping). A part of the community focuses on the modeling of single-track vehicles, whereas another part focuses on the design of control systems.

The aim of this paper is to describe the state of the art of motorcycle VDC. We will focus mainly on control systems, with some references to control-oriented modeling. The reader who is interested in the multibody modeling and analysis of single-track vehicle dynamics is referred to the excellent resources provided by Cossalter [2], Schwab and Meijaard [3], [4], Sharp [5], [6], and others [7].

This paper is an attempt to rationally organize the state of the art on motorcycle dynamics control. The available contributions are organized along two dimensions: the type of dynamics under control and the type of actuation. In other words, a methodological classification crosses technological considerations. The dynamics of single-track vehicles can be divided into two categories: the in-plane and the out-of-plane dynamics [2]. The in-plane dynamics refer to all those degrees of freedom that are excited when the vehicle moves on a straight line. These are longitudinal dynamics (traction and braking), heave, wheel hop, and pitch dynamics. The in-plane dynamics of PTW are similar to those of cars, albeit with some important differences in the relative importance of the phenomena. The out-of-plane dynamics, on the other hand, refer to those movements that force the vehicle to leave its vertical plane. These are the tilting dynamics, the lateral and yaw dynamics and the steering handle dynamics. They are unique to tilting vehicles and call for ad hoc solutions. The fact that the in-plane dynamics share some common features with automotive application, while out-of-plane dynamics do not, provides a useful watershed in the classification of the specific control problems.

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TABLE I
PAPER STRUCTURE

		Control variable		
		Wheel torque	Suspension force	Steer torque
Dynamics	in-plane	TC/ABS	Ride control	X
	out-of-plane	Racing TC/ABS Stability control	Ride control	Steer control

Table I graphically represents the classification adopted in this paper. Each cell is a different control problem that is described in a different section of the paper. In Section II, the general problem of straight running wheel-slip control is presented. Wheel-slip control takes the form of TC and braking control (loosely referred to as ABS). Section III details the extension of these methods to the out-of-plane dynamics. The racing TC and stability control systems are introduced. Section IV covers the main techniques and results regarding ride control through (semi)-active suspensions. As done for TC, the ride control ideas are extended to the out-of-plane dynamics in Section V. Despite the interesting results achievable in the out-of-plane dynamics control through wheel torque and suspension control, steer control is the most direct way of influencing such dynamics. Section VI details the main results in steer control. Section VII is devoted to narrow track titling vehicles (NTTV), i.e., vehicles that exhibit the same out-of-plane dynamics of motorcycles but have more than two wheels. NTTV are of particular interest to the control engineer because they share the main dynamic features with single-track vehicles, but add two additional control degrees of freedom: Differential wheel torque and direct roll control. Section VIII closes this paper with an outlook on future control development and challenges in the field.

II. IN-PLANE TRACTION AND BRAKING CONTROL

The traction and braking dynamics are mainly determined by wheel-slip. Wheel-slip is defined as the normalized difference between the longitudinal velocity of the vehicle and the peripheral velocity of a tire

$$\lambda = \frac{\omega\, r - v}{\max\,(v, \omega\, r)} \tag{1}$$

where r is the tire rolling radius, ω is the wheel angular velocity, and v is the longitudinal velocity of the center of gravity of the vehicle. The longitudinal tire force is a nonlinear function of wheel-slip, wheel sideslip, and vertical load: $F_x = \mu_x(\lambda, \alpha)F_z$, where F_z is the vertical load and μ_x is the longitudinal friction coefficient [8]. The sideslip angle, α, is the angle between a rolling wheel's actual direction of travel and the direction toward which it is pointing [8]. Fig. 1 shows a typical plot of the longitudinal and lateral friction coefficient characteristics. All characteristics have an ascending part, a peak (at λ^*) and a descending part. From figure, the importance of controlling wheel-slip is clear; an excessive slip determines a nonmaximal longitudinal force. Furthermore, for values of slip above the peak, the lateral force drops, and the dynamics become open-loop unstable [9]. As soon as the peak value is reached, if the wheel torque is not reduced, wheel-slip will rapidly diverge to 1. The drop of lateral force is particularly critical in single-track vehicles because the lateral force not only allows the vehicle to steer, but it keeps it upright and stable.

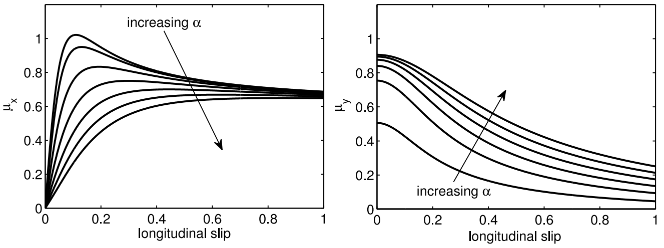

Fig. 1. Longitudinal and lateral friction coefficient dependency on wheel-slip and sideslip angle.

The problem of traction and braking control is a well-known problem in four-wheeled vehicles dynamics control; however, research shows that the methods devised for four-wheeled vehicles are not directly applicable. The literature identifies mainly two reasons as follows.

1) Motorcycles have a higher center of gravity with respect to the wheel-base than cars. This makes the load transfer phenomena more prevalent. The analysis in [10] and [11] present two approaches to the study of the effect of load transfer on braking performance. The former uses optimization techniques to design the suspension characteristics to minimize braking distance, whereas the latter proves that, in sport motorcycles, a controller based only on wheel-slip does not provide the optimal performance in terms of braking distance. The conclusion is that load transfer phenomena have to be explicitly accounted for in the design of the controller. The work initiated by these two papers is further developed in [12] and [13].
2) The tire lateral force plays a critical role in stabilizing the capsize mode of the motorcycle; the control performance requirements are, therefore, more stringent. An overshoot in wheel-slip that could only momentarily affect the trajectory of a car could cause the motorcycle to fall over. Furthermore, in order to provide yaw stability, the ABS system for cars are designed to lock the front tires before the rear tires. If this were to happen on a motorcycle, the motorcycle would fall [14].

Traction and braking dynamics are very similar; despite this fact, research has shown that they do require different methodologies. These differences are mainly due to differences in actuator dynamics. Several options are available to control the wheel torque. For traction torque, the choices are as follows.

1) ETB: The air in-take valve influences engine torque [15]. ETB's can be operated quite freely without concerns of exceeding the engine capabilities (overheating, partial combustion, and emission regulation); on the other hand, the dynamics from valve position and engine torque depends on the engine regime.
2) Engine spark advance: By changing the spark timing in spark ignited engines, the engine torque can be directly

modulated [16]. The dynamics from spark advance to engine torque is more direct than the air path dynamics. Moreover, this approach does not require additional electromechanical hardware. On the other hand, the spark advance dynamics are nonlinear and, more importantly, have considerable limitation in terms of engine capability. The spark advance cannot be kept far from its nominal condition for too long without affecting the engine temperature and combustion dynamics. This could eventually damage the engine.

3) Cylinder cutoff: By simply not injecting fuel and not igniting a cylinder, the engine torque can be reduced [17]. This technique is a very crude method that shares all the disadvantages of engine spark advance control along with the impossibility of precisely modulating the engine torque.
4) Electronic clutch: An electronically actuated clutch can be used to limit the engine torque transferred to the rear wheel [18]. Electronic clutches enable a very precise torque control, but with some limitations: They can only be employed during launch and for a limited amount of time. Clutches are wearable elements and their continuous actuation considerably limits their life.

Braking torque is more easily controlled by brakes; in particular, hydraulically actuated brakes and electrohydraulic brakes are the most common choices. In [19] and [20], the design of an electrohydraulic brake is discussed showing that a pressure control bandwidth of 20 Hz is easily achieved. Braking torque control is, therefore, more easily achieved, and the actuator dynamics are also more accurately modeled.

The different role played by the actuators in the overall dynamics calls for different methods and approaches to the development of the control system.

A. Braking Control

Reviewing the braking control literature, one can find two main approaches: Wheel deceleration and wheel-slip-based control.

Wheel deceleration control is very common in automotive ABS braking in virtue of its robustness and the need for relatively inaccurate (and thus inexpensive) actuation. Wheel deceleration-based (derived from classical ABS control) systems are based on letting the wheel-slip oscillate around the optimal value. The methodological difficulties associated to proving its safety and stability in the more complex motorcycle context and its intrinsic lower level of achievable performance are among the causes of the preference of the scientific community toward wheel-slip control. Nevertheless, most commercially available motorcycle ABS systems are developed by the same automotive suppliers and are probably based on adapted methodologies. No control system-oriented analysis of commercial ABS is available; however, some works assess and compare braking performance. In [21], Donovan compares the stopping distance of four different motorcycle makes. The results cover the comparison between ABS and no ABS on both wet and dry surfaces for a series of different load conditions. On dry surface, the average ABS stopping distance is 5% to 7% (depending on the load) shorter than the best manual braking performance. The performance further improves when wet surface is considered yielding a reduction of the stopping distance between 5% to 15%.

The cited analyses are very useful for policy makers but do not provide information on how the current ABS system can be improved. This information is provided by the detailed analysis of the technical literature, which, very precisely points toward wheel-slip control. Matter-of-factly, there are no scientific publications that address the design of a wheel deceleration-based control for PTW. Conversely, the literature devoted to wheel-slip control is rich and diverse. The design of a wheel-slip controller can be done either based on models or completely model free. The model-based approach is applicable as the braking actuator dynamics is easily modeled and the torque is precisely controlled.

Among the model-based approaches, we will consider performance-oriented systems [11], [12] and safety-oriented systems [22]. The objective of a performance-oriented system is optimizing the braking distance, usually in racing settings, and thus, the robustness issue is somewhat neglected. Neglecting the robustness issues has two advantages: On one hand, the controller can achieve better performance; on the other hand, there is no need to develop a control-oriented model, but the controller can be tuned directly on the complete multibody dynamics. In [11], Bikesim (a multibody motorcycle simulator) is used to tune an optimal braking controller. The resulting controller uses a combined wheel-slip control and load control on the front wheel, whereas a slip control suffices for the rear wheel. The proposed approach is capable of detecting and keeping the motorcycle braking on the maximum deceleration limit without pitching over; furthermore, the paper quantifies the contribution of the rear wheel braking in sport motorcycles. On high-friction surfaces, the rear wheel brake contributes only minimally to the overall braking deceleration (if only the in-plane dynamics are considered). The results of [11] are picked up by Sharp in [12] where the tuning of the controller is discussed in more details and a feedforward control action (termed preplanned control) is added. The tuning of the closed-loop controller is, however, carried out by trial-and-error in simulation.

The performance-oriented methods described above are useful to quantify the roles of different motorcycle parameters but are not robust enough to provide consistent performance when used on roads. In order to guarantee robustness, a control-oriented model is required that account for the varying parameters and guide the design of robust closed-loop controllers. In the context of this review, this approach is called safety oriented. The analysis in [22] shows that the classical single-corner model does not capture the load transfer dynamics accurately enough. The authors, thus, propose a linear parameter varying model (LPV) derived from the Jacobian linearization of the complete vehicle dynamics. This step considerably simplifies the model-reduction task and provides a system that is amenable to advanced control system design tools. The LPV framework has the capacity of describing nonlinear systems while maintaining some of the linear systems properties. LPV models, roughly speaking, can be defined as linear systems where

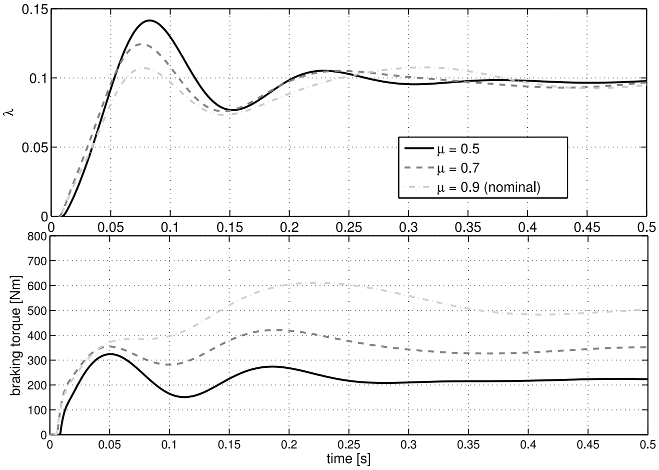

Fig. 2. Robustness validation of the LPV-based wheel-slip control method. Adapted from [22].

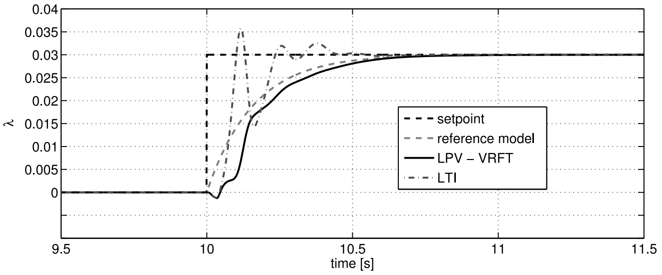

Fig. 3. LPV and LTI slip controller during a panic brake maneuver.

either the matrices of the state equations or the coefficients of the input–output relation depend on one or more time-varying parameters. In the case at hand, the chosen time-varying parameters are velocity and wheel-slip itself, resulting in a 2-D family of seventh-order system accounting for the wheel-slip, wheel hop, bounce, and pitch dynamics. Only the fully scheduled controller (accounting for both velocity and wheel-slip) achieves the required level of performance and robustness. The method discussed in [22], thanks to the availability of the LPV model, can be shown to be robust in face of unknown tire characteristics. Fig. 2 plots a braking maneuver performed on three different surfaces.

The model-based approaches yield good control performance but need an accurate model, which can be expensive to get. This drawback can be edged by recurring to model-free approaches (see [23]–[26]). Model-free approaches are based on the idea of designing the controller without any explicit model of the system dynamics. The systems and controls community has developed a plethora of methods for model-free control. Among the available choices, sliding-mode control, fuzzy control, and direct control synthesis approaches have been successfully applied. Lu's contribution in [23] describes a complete ABS system for a light motorcycle. The system is composed of 1) an electric motor-driven pressure actuator, 2) a pressure control, and 3) an ABS controller. The braking pressure actuator architecture guarantees a smooth braking pressure modulation. The ABS controller is based on a sliding-mode control approach. The sliding surface is defined according to a desired wheel-slip. Simulation and experimental results compare the proposed ABS system against an automotive derived ABS controller (based on the wheel deceleration); the wheel-slip-based control achieves slightly shorter braking distances: The stopping distance from 65 km/h for the wheel-slip-based control on dry slippery surface was measured at 11.63 m, whereas the wheel deceleration approach yielded 12.60 m. This paper reports braking distances but lacks a thorough discussion of the tuning process. The authors explain that the sliding-mode control approach enhances the robustness of the ABS braking system, but do not provide any supporting evidence. This line of reasoning is also argued for by Tanelli and Ferrara [25]. This paper formally proves the robustness of the controller. Sliding-mode controllers achieve their high level of robustness in virtue of a persistent switching around an ideal sliding surface. The resulting oscillations in the control variable and wheel-slip may affect the drivability.

This issue is addressed either by fuzzyfication or direct control design. Huang in [27] uses the same hardware as in [23] to implement a fuzzy controller. The fuzzy controller generates the reference pressure for the brakes based on a heuristic. A methodological analysis of the controller is not given, but an extensive experimental validation is discussed. Of particular interests, the tests are performed on a three-phase pavement road: The light motorcycle starts braking on a dry road, transitions onto a wet road, and finally returns to the dry road. Experiments show that the control system is stable and the desired braking performance is achieved without high frequency excitation of the braking torque.

Another possibility is direct control design. In [24] and [28], a direct LPV controller is designed. The method is a noniterative direct data-driven technique, i.e., a gain-scheduled fixed order controller is derived from a finite number of experiments, without need of explicitly identifying the plant dynamics. This yields an easy and efficient design procedure. The method employs instrumental variables and optimal data prefiltering to deal with measurement noise and underparameterization of the controller. The method results in a gain-scheduled controller with the vertical load as the scheduling parameter. Fig. 3 shows the performance of the LPV controller, compared to that of an LTI controller. Clearly, the LPV controller yields a better response. Note that, overall, a slower response is achieved with respect to the model-based method.

In general, model-based methods have two advantages over model-free ones. On the one hand, model-based methods can better exploit the accurate knowledge of the dynamics and provide better performance. On the other hand, model-based methods enable the formal proof of performance and robustness and are, thus, better suited for safety critical systems. For some of the above methods, the analysis could be carried out also for model-free methods, but a model would still be required and this would cancel out a part of the advantages of adopting a model-free design.

B. Traction Control

TC, despite having similar dynamic features as braking control, is more challenging. Accurate first-principle models of the engine torque generation are obtained with difficulty. The engine characteristics are accurately modeled in steady state with statics maps, but the dynamic behavior is more difficult. Historically, the difficulties brought by the time-varying engine dynamics were addressed with heuristics that yield rather crude results. Subsequently, the introduction of rigorous system identification techniques provided the required model to perform model-based design.

The work by Cardinale *et al.* in [29] is, to the best of the authors, the first publicly available contribution on the subject. Commercial TC systems were available before the publication of that paper, but company policies have limited the availability of information. Cardinale and collaborators propose a spark-based control; the spark advance is controlled based on the difference between the front- and rear-wheel velocities. Although not explicitly stated, the control algorithm is a second-order sliding-mode controller where the sliding surface is represented by null rear wheel-slip. The controller activates when the difference between the front- and rear-wheel velocity is above a threshold. Defining $e(k) = \omega_f(k) - \omega_r(k)$, if $e(k) > \epsilon$ then the spark advance is determined by

$$c(k) = c(k-1) + \text{sign}(e(k-1) - e(k))\delta. \tag{2}$$

The two control parameters, the activation threshold ϵ and the cutoff advance increment/decrement step δ are empirically tuned. Experimental results show that the rear wheel-slip is limited during sudden accelerations, but a thorough quantitative analysis is lacking.

The lack of a dynamics model prevents any methodological analysis or tuning of the controller. The authors' work in [30] first addressed this issue. The authors propose an identification protocol that enables a quick and accurate modeling of the engine-to-slip dynamics from experimental data. The method is based on the open-loop excitation of the control variable (in the original paper, sine-sweep and step inputs were employed) and a frequency-based system identification. The method yields control-oriented models that, although not useful to understand the role of each mechanical component, are useful for control system design. The method can also be employed to compare different motorcycles and different actuation solutions. The analysis leads to the following conclusions:

1) Both throttle-to-slip and spark-to-slop dynamics exhibit a resonance at 8 Hz.
2) Spark advance is "faster" than throttle action. At 10 Hz, there is a 60° difference in phase: Half of this loss is due to the servo loop. This observation proves that slip control through throttle control is achievable.
3) Although spark advance provides a slightly faster actuation, the response of the system is less linear and, therefore, more difficult to model and control.

The method is further discussed in [31] comparing different motorcycle makes. Formentin *et al.* provides a further contribution in [32] addressing the issue of optimizing the identification experiment, through design of experiments.

Massaro and collaborators take on the experimental identification method in [33] extending it with a detailed discussion of the dynamics. Combining the experimental data with their multibody simulator, they are able to provide a physical interpretation of the dynamics. Among other comments, they argue that a stiffer sprocket absorber (and, in general, a stiffer transmission) would make the design of the control system easier.

The availability of an accurate model opens the possibility of more advanced control systems. Chapter 8 in [31] gives a complete overview of the design process of a TC system for a motorcycle. Several aspects are considered: Reference generation, activation strategy, and controller tuning among the most important ones. The TC system is wheel-slip-based, and implements a novel approach for the reference generation. This sets the proposed method aside from the classical threshold-based TC systems. Fixed wheel-slip thresholds systems deprive the driver of any control when the TC is active. In the authors' approach, the activation threshold is fixed, but once it is crossed, the driver can modulate the wheel-slip reference through the throttle grip. The rider controls the reference slip by opening or closing the throttle; when the throttle is fully open, the rider is requesting the maximum allowed slip. This mechanism guarantees better safety, robustness, and controllability than the single-threshold logic. The second important element is the controller itself. The controller is tuned via classical control theory on the identified model. The resulting controller is a gain-scheduled controller. The scheduling is based on the online identification of the friction surface. The design is supported by an extensive experimental validation; the proposed method is compared against a commercial system from several standpoints: Acceleration time, wheel-slip, and lateral stability.

As for the ABS problem, model-free approaches have also been investigated. For example, in [34], a second-order sliding-model control is proposed, analyzed, and validated in simulation.

The literature draws a clear picture; from the performance point of view, wheel-slip-based traction and braking control are superior to wheel deceleration.

In order to be effectively employed, wheel-slip methods require the knowledge of the vehicle velocity, which cannot be directly measured. Vehicle velocity estimation is a critical problem on car; on motorcycle, it is made even more difficult by having fewer wheels to rely upon and by the possibility of wheelies and stoppies. Estimation problems are out of scope of this review, the interested reader is, however, encouraged to consult [35].

III. OUT-OF-PLANE TRACTION AND BRAKING CONTROL

Longitudinal wheel-slip has an effect on the lateral tire force; this in fact couples the longitudinal dynamics of the motorcycle with the out-of-plane dynamics. The systems presented in the previous section rely on the consideration that if the longitudinal wheel-slip is limited and stabilized then the out-of-plane dynamics are easier to control for the rider. This consideration is sound for "normal" road driving. If more aggressive race riding is considered, this hypothesis may lead to crashes.

The lateral force required to safely negotiate the corner depends on the roll angle (see Fig. 4). The longitudinal force used to slow/accelerate the vehicle must be controlled so that the tire

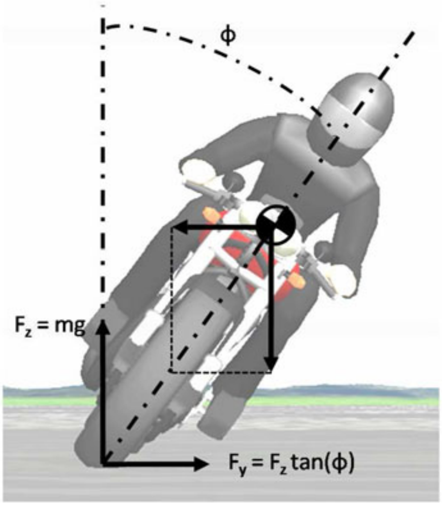

Fig. 4. Lateral force required to negotiate a corner with a roll angle ϕ.

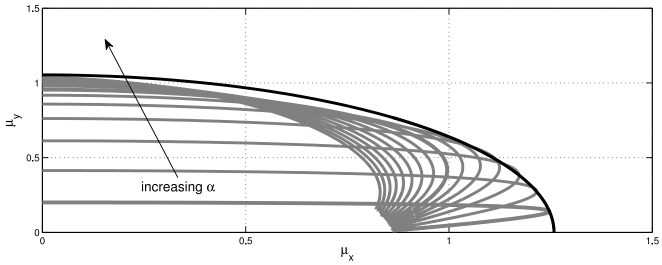

Fig. 5. $(\mu_x - \mu_y)$ relationship for different α as a function of λ for a given ϕ.

can still exert the needed lateral force to compensate for the centrifugal acceleration. This force is given by

$$F_y = F_z \tan(\phi). \tag{3}$$

In the literature, the coupling between the longitudinal and out-of-plane dynamics is addressed in three different ways: Curve-safe ABS and TC systems and genuine stability control.

A. Curve-safe ABS and TC Systems

These systems are evolution of the in-plane ABS and TC systems. They are augmented with roll angle sensing/estimation and adapt the wheel-slip reference accordingly. The basic idea, initially proposed in [36] for braking applications, is that of considering the lateral and longitudinal force characteristics that can be expressed as

$$\mu_x = \mu_x(\lambda, \alpha, \phi, F_z), \quad \mu_y = \mu_y(\lambda, \alpha, \phi, F_z). \tag{4}$$

If the roll angle ϕ is known, for each sideslip α, the longitudinal and lateral frictions can be expressed as a function of the longitudinal slip λ. Fig. 5 depicts the $\mu_x - \mu_y$ relationship for different α as a function of λ. The envelope of all the $(\mu_x - \mu_y)$ maps (usually referred to as the *traction ellipsoid*) represents the maximum friction that the tire can express for a given roll angle. Given a point in the (μ_x, μ_y) plane, two cases arise:

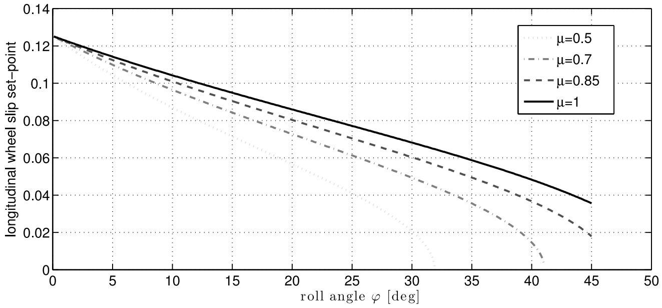

Fig. 6. Plot of the set-point value $\overline{\lambda}$ as a function of the roll angle for different road surfaces and $F_z = 1800\,N$: $\mu = 1$ (solid line), $\mu = 0.85$ (dashed line), $\mu = 0.7$ (dash-dotted line), and $\mu = 0.5$ (dotted line).

1) the point is outside the envelope. The requested (μ_x, μ_y) is not physically achievable;
2) the point is inside the envelope. There is at least one combination of (λ, α) that achieves the required (μ_x, μ_y).

In Fig. 5, condition (3) is represented by a line parallel to the *x*-axis. The values of λ for which the line intersects the $(\mu_x - \mu_y)$ maps represent admissible slip. If only the traction envelope is used to determine if a curve can be negotiated, it may return values of α that are physically feasible but not "ridable." The motorcyclist may not be proficient enough to ride the bike with the required sideslip. Therefore, a further condition is needed; a possible solution is to discard sideslip greater than the current sideslip angle estimated through a reference model.

Accordingly, based on the Pacejka model equations, the current set-point value $\overline{\lambda}$ is computed as

$$\begin{aligned} &\overline{\lambda} = \text{arg max}_{\lambda} \mu_x(\lambda, \alpha(\phi), \phi, F_z) \\ &\text{subject to} \\ &\mu_y(\overline{\lambda}) \geq \tan(\phi). \end{aligned} \tag{5}$$

As the current value of the vertical load F_z is not known, a conservative choice is made. Fig. 6 shows the set-point values $\overline{\lambda}$ computed by means of (5) as a function of the roll angle ϕ for different road surfaces and $F_z = 1800\,\text{N}$. The road friction coefficient μ acts only as a scaling factor on the longitudinal and lateral forces, the set-point value $\overline{\lambda}$ obtained for null longitudinal wheel-slip $\lambda = 0$ is the same on all road surfaces.

The adopted strategy correctly takes into account the tradeoff between longitudinal and lateral forces to determine the maximum braking torque that might be applied when braking on a curve.

The set-point is then fed to any of the wheel-slip-based control strategies presented in the previous section. In [36] and[37], the idea is applied to braking, whereas in [38], similar ideas are applied to TC. Several curve safe traction and braking systems are now becoming available for high-end sport motorcycle makes.

B. Stability Control

The basic idea of curve-safe slip control is that of avoiding exceeding safe wheel-slip. Although some manufactures market this kind of systems as stability control, it cannot be considered a genuine stability control, as intended for cars.

In cars, stability control systems rely on the application of differential braking to impart a yaw momentum that helps controlling the lateral dynamics of the vehicle. A similar line of reasoning can be applied to motorcycles, with some critical differences. Motorcycles do not have right and left wheels, and it is not possible to impart a yaw moment when going straight. Nevertheless, it is possible to influence the roll dynamics by applying differential front–rear traction or braking torques. This idea is investigated in [37], [39], and [40].

The model-based design, analysis, and validation of an electronic stability control system for PTW is addressed in [39]. The initial analysis shows that the best controlled variable for motorcycle stability is the roll angle. The system is, therefore, designed as a roll angle control system. First-principle dynamic models are too complex for control system design. A control-oriented model is, thus, obtained through frequency-based system identification: A seventh-order multiple-input multiple-output model is shown to capture the main out-of-plane dynamics. The authors propose different control strategies to enhance the safety of two-wheeled vehicles and to comply with the rider's intention during braking or traction maneuvers. The design results in a hierarchical control system whose highest priority objective is to stabilize the roll dynamics, when that objective is achieved the desired acceleration or decelerations are tracked. This is achieved through a time-varying saturation of the control variables. Several simulation tests performed on a multibody motorcycle simulator show that the proposed control strategies can cope with disturbances that are both of the same nature of the control variable and also external disturbances, such as road unevennesses. The robustness of the control systems with respect to the working condition and to the measurement noise has been investigated. Moreover, the performance of the control strategies are satisfactory also in critical situations, such as on straight running, when the capabilities of the actuators are limited, or during a high side. On average, a 50% to 60% improvement of the stability (measured as RMS of roll rate) is obtained.

IV. IN-PLANE RIDE CONTROL

In land vehicles, suspensions play a critical role in determining both the vehicle occupants' comfort and their safety [41]. From the VDC point of view, one can differentiate between passive, adaptive, load-leveling, semiactive, and active suspensions. Passive suspensions do not offer any level of controllability. Adaptive and load-leveling suspensions enable some controllability of both damping and preload at low frequency [42]. This makes them suitable for automatic control of road clearance depending on the load, for example. Semiactive suspensions are capable of modulating the damping coefficient at high frequency, enabling closed-loop ride control. Finally, active suspensions are linear force actuators that can exert active vertical forces. The reader is pointed to [43] for a more detailed discussion on suspension technology.

From the performance point of view, active suspensions surpass all other solutions (see for example [44], [45]). They are, however costly, and poses serious safety issues. Some of these issues have been solved for automotive applications, but the use of active suspensions in motorcycles is still far-fetched. For this reason, in the remainder of the section, the focus will be on semiactive suspensions. Semiactive suspensions are recognized as the best tradeoff between performance, complexity, cost, and power requirements.

Over the years, several general control strategies have been developed for semiactive suspensions. The development of these strategies is based on the so-called quarter car model and, thus, are applicable to motorcycles as well. See [46] for a comparative overview of the most used approaches.

Compared to the case of longitudinal dynamics control, the portability of semiactive control strategies developed for cars to motorcycle is greater. Despite this fact, there is a margin to tailor some of those approaches to the specifics of in-plane motorcycle ride control.

The first problem that one encounters when porting a suspension strategy to a motorcycle is noise. In automotive applications, a lot of effort has been devoted to the sensor reduction problem; this resulted in strategies that only need one sensor [47]. However, when applied to motorcycles, the use of only the chassis accelerometer can be problematic. Due to the mechanical layout, engine vibrations are usually transmitted to the body and the correct measure of its movements is deeply affected. Consequently, the performance achievable by a suspension algorithm, based on body dynamics, may degrade. The work in [48] discusses the design of a single-sensor control strategy that only employees the stroke sensor. The strategy is termed *Mix-1-Stroke* and is able to inherit the theoretical optimality of the solution employing only a body accelerometer. The proposed algorithm is compared against several benchmark algorithms in both simulation and experimental tests. Further experimental results on semiactive suspension tuning for motorcycles are presented in [49].

The second differentiating issue is related to the more prominent load transfer. As cited in Section II, some researchers have looked into the issue of how the load transfer affects braking and traction, but to this day, the issue of devising a centralized suspension control that accounts for the pitch dynamics is open for research. Some manufactures are marketing antidive systems based on semiactive suspensions. The underlining idea is to improve controllability during braking, but no scientific study is available on the topic from a control standpoint. Limebeer [50] addresses the effect of braking on the stability but does not address the control problem.

V. OUT-OF-PLANE RIDE CONTROL

When out-of-plane dynamics are considered, motorcycles once again require ad hoc solutions. The topic of out-of-plane ride control is relatively new and only a few contributions are available. Among the most interesting ones, [51] and [52] are worth of note.

In [51], Evangelou proposes a rear suspension control system to minimize unwanted chassis oscillations during steady-state cornering, in particular weave (see Section VI). Evangelou's solution is based on a variable geometry suspension, actuated by an electric motor. This active system, acting as a displacement controller, varies the geometry of the rear monoshock absorber. The geometry has an effect on the suspension equivalent stiffness. As such the actuator can be classified as a sort of preload control; however, the fact that a closed-loop control system is designed to minimize yaw rate oscillation make the system an out-of-plane ride control system. The controller is designed using Nyquist plot techniques applied to the linearized model of a steady-state cornering motorcycle. The resulting controller is a bandpass controller with a peak at around 1.6 Hz. In this way, the controller only acts when the oscillations are triggered and not at low frequency. A linear closed-loop analysis confirms that only the targeted oscillations are affected and no other dynamic modes. The control system is validated in simulation; during high-speed maneuvers ($v > 75$ m/s), the system yields a 36% improvement in the duration of the oscillations after a road disturbance. This requires an average of 250 W of actuation power. The power requirements are considerably higher that of a semiactive suspension, but are feasible. In this paper, the idea of energy recuperation is also preliminarily explored.

In some patented and yet-to-be-published results [52], the possibility of semiactive out-of-plane ride control is investigated. In this preliminary work, a control algorithm that generates a desired value for the rear suspension force is designed. Dissimilarly from the previous work, here the objective is that of minimizing roll rate, rather than yaw rate. The force $F_{s,1}$ generated by the front suspension is estimated using a model of the suspension and the suspension stroke measurement. $F_{s,1}$ is then employed, along with the mathematical model of the motorcycle, to compute the reference force for the rear suspension $F_{s,2}$. The force is generated to create a roll momentum that opposes the movement of the vehicle. The reference force is then actuated using a clamping algorithm as it is usually done in two state skyhook or groundhook strategies [43]. The resulting logic has some similarities with the skyhook concept: Instead of attaching a virtual damper to the sky, the virtual rotational damper is connected to the locally vertical plane. In his Ph.D. thesis, De Filippi analyses the performance of his semiactive algorithm on a catalogue of different maneuvers; simulation results indicate that the semiactive stability algorithm improves the damping of the motorcycle oscillations. On average, an improvement from 5% to 20% is registered. This should be compared with the 36% improvement cited above with an active rear wheel suspension and the 50% to 60% improvement of the stability control system discussed in Section III. The improvement is marginal with respect to other solutions, but the hardware required is entirely off-the-shelf and currently available on the market.

VI. STEER CONTROL

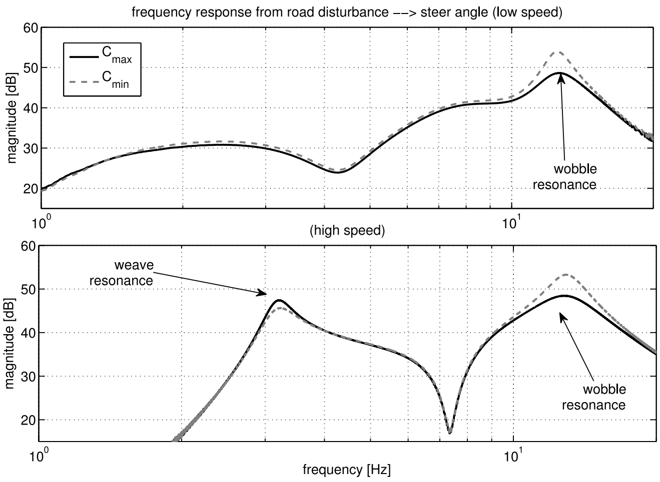

Fig. 7. Plot of the magnitude of the frequency response with roll angle $\varphi = 30°$ and (a) speed $v = 50$ km/h and (b) speed $v = 140$ km/h; maximum (dashed line) and minimum (solid line) steer damper value.

Motorcycles are subject to three out-of-plane modes: Capsize, weave, and wobble (see [2], [53]–[55]). The capsize mode is a nonoscillatory mode that describes the motorcycle tendency to lean in and out of a corner (see Section III). Weave and wobble are oscillatory modes. Weave is a low-frequency oscillation of the entire motorcycle. Wobble is a higher frequency oscillation of the steering handle around its axis (see Fig. 7). These modes can become lightly damped or even unstable under certain conditions. Many accidents (see for example [56]), several resulting in serious injuries and deaths, have been attributed to unstable weave or wobble modes.

Several approaches have been proposed to improve the damping of these modes. The available approaches can be classified into passive, semiactive, and active.

The weave and wobble damping can be passively improved by redesign the geometry of the motorcycle or by adding ad hoc components. In [2], a sensitivity analysis of several frame and steering-assembly parameters is proposed. These methods, however, cannot be properly classified as control; they are rather vehicle redesign considerations. Passive control solutions are on the other hand based on the introduction of specific components.

A passive steering damper is a device that generates a moment opposite to the angular velocity of the steering assembly relative to the vehicle frame. It can improve vehicle stability but its tuning is not straightforward. The issue is summarized by Fig. 7, which shows the steering angle frequency response of the dynamic relationship between a road disturbance and the steering angle for a sport motorbike at low and high speed as functions of the steering damping coefficient. A passive steering damper has an opposite effect: It can improve weave or wobble but has a negative effect on the others.

The steering inerter was introduced in [57]. Specifically, this contribution discusses the design of a passive mechanical compensator tailored to control weave and wobble modes. This passive mechanical compensator is composed of a spring, a damper, and an inerter. The inerter is a component which exerts a force proportional to the relative acceleration of its terminal ends, see also [58]. The authors use design techniques based on loop shaping, Nyquist plot, and sequential quadratic programming optimization to design and optimize the mechanical network. The approach has been tested in simulation, obtaining excellent results, simultaneously damping weave and wobble. However, the passive mechanical network is technologically complex and has been manufactured exclusively as a prototype, thus yielding a solution not yet mature for mass production. More details on the component are also presented in [59].

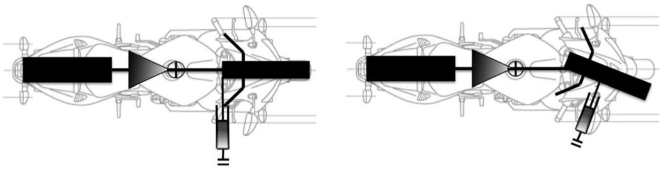

Fig. 8. Schematic view of the ideal skyhook (left hand) and groundhook (right hand) damping schemes.

Semiactive systems, on the other hand, are more industrially viable. These solutions augment the currently employed steering dampers.

Passive steering dampers can be made semiactive by using proven and off-the-shelf components; this enables the real time control of the damping coefficient. Depending on the reaction time of the component, they are classified as either semiactive damper (if the damping coefficient can be modified with time constants of the order of milliseconds) or adaptive (for slower systems). Both types of actuators have been explored.

Adaptive systems are not fast enough to be employed in a closed loop. The best way to employ them is to schedule the damping coefficient according to some vehicle state. For example, in [60], the damping coefficient is scheduled with respect to vehicle velocity and acceleration. A three-dimensional, empirically tuned, map hardens the damping as the velocity and acceleration increase. In this way, it is possible to avoid excessive wobble when the motorcycle is accelerating and the front tire unloads. This approach has limitations; the steering damper behavior is predetermined and it, thus, is incapable of responding and adapt to what the vehicle is currently doing. In order to avoid this limitation, a genuinely closed-loop approach has to be implemented. This needs fast semiactive technology.

The approach presented in [61]–[63] employs a semiactive steering damper to reduce both weave and wobble. A control-oriented model reveals a parallelism with the ride control problem. This is exploited to develop three strategies: A rotational skyhook which aims at damping weave, a rotational groundhook aimed at damping wobble, and a frequency mix of the two that damps both modes according to the current excitation (see Fig. 8). The strategies are based on yaw rate, roll angle, and steer rate measurements. The tuning of the controller is supported by an LPV-based methodological analysis of the closed-loop dynamics, and an extensive simulation and experimental validation campaign shows the effectiveness of the proposed approach. The mixed approach is capable of improving the damping of the modes of 50%.

Also, active steering systems have been investigated. Most of the contributions regarding steer control with active systems revolve around the design of automatic steering and path following and/or optimization [64]. Trajectory control for motorcycle is a vast field with many methodological contributions. Motorcycle dynamics, with their complexity, are ideal to test and develop advanced nonlinear control techniques, but given the current technology state, the development of an autonomous motorcycle is still years ahead.

The approach proposed in [65] is the only one focusing on the control of steering instability with an active steering compensator. The analysis is mainly methodological and applies an $\mathcal{H}_\infty$ controller. The controller, when compared with a passive steering damper and the passive compensator of [57], substantially improves the damping of the wobble mode. The weave-mode damping improves for high-speed low-lean-angle conditions. On the other hand, the active compensator yields a small degradation in the weave-mode damping under high-roll angle conditions.

All the closed-loop control systems presented above need a measurement of the motorcycle yaw rate and steering angle. Measuring yaw rate is effectively achieved using MEMS gyrometers; the use of steering angle sensors in motorcycle is still limited. The issue of estimating the steer angle, therefore, arises and is addressed in [66] and [67].

VII. NARROW TRACK TILTING VEHICLES

Recently, the market has witnessed the introduction of a new kind of vehicles: NTTV's. NTTV's are not, properly speaking, single-track vehicles as they have at least an axle with two wheels. There exist NTTV's with four wheels, or three wheels (either front or rear). However, the fact that their mechanical design allows them to lean into the corner (as opposed to out the corner as a four-wheeled vehicle would do) makes them to exhibit the same dynamic properties of single-track vehicles. A historical perspective of NTTV is offered in [68].

Thanks to their features, they are a potential solution to urban traffic congestion and pollution. NTTV are highly maneuverable, lightweight, and with small footprint (as motorcycles) but, having multiple wheels, they can be made statically stable (as cars) and, thus, safer.

Besides all the control systems described above, the specific architecture of NTTV's yields more controllability in terms of roll angle. In particular, the research community proposes three different approaches: Direct tilting control (DTC) [69], steering tilting control (STC) [70], or torque vectoring [71].

STC [70] is based on the idea of controlling the vehicle tilt via manipulation of the steering angle, in the same way as an experienced rider does on a single-track vehicle. It requires a certain level of control on the steering angle, which can be achieved through active steering actuators. The results, both in simulation and experimental, shown in [70] prove proper performance of the electronic stability control. Despite the documented success, STC has some inherent drawbacks. The vehicle cannot be automatically balanced at low speed, nor on slippery roads. Furthermore, since the actuation happens through the steering handle, the rider could be startled by a sudden application of steering torque.

DTC tries and addresses the main drawbacks of STC. DTC exploits the fact that the vehicle can be designed so that only a part of the vehicle tilts; thus, an actuator can be placed between the titling and the non-titling sections, allowing for the direct application of roll torque. This is the most direct way of controlling the vehicle roll. Some early work on DTC [69] shows that it is possible to control the tilt of the vehicle, stably tracking a desired reference. The reference should be generated to achieve a perfectly coordinated turn i.e., the net moment acting at the center of gravity of the vehicle should be equal to zero without using any external actuator torque. Normally, the desired reference is computed according to a reference model; this can introduce errors. An additional drawback is the delayed vehicle response as it tracks the desired reference. In [72], instead of a reference tilt angle, the controller is designed to minimize the lateral acceleration measured on the vehicle. In a steady-state coordinated turn, the lateral acceleration should be null. This approach lightens the computational burden. Experimental results prove the validity of the approach.

A possible solution is presented in [73], where the steering torque is employed to directly generate an open-loop tilting torque on the vehicle. This avoids the need for a reference model and the inevitable delay associated to lean-angle-based closed-loop systems. The stability is guaranteed by the self-stabilizing dynamics of the vehicle; however, a closer analysis of the method reveals that during cornering the vehicle does not reach a coordinated cornering condition. Residual tilting torques of up to 100 N·m are registered. This, as noted in [68], will not cancel out the lateral acceleration acting on the rider and is not energy efficient.

With time, the community got to the consensus that the best choice is to use a combination of the two approaches: The integrated STC and DTC, either termed STDC [68] or dual-mode controller [74]. The basic idea is to ensure the stability of the vehicle with DTC at low speed when the STC is ineffective and use the STC at higher speeds where the torque required to the DTC actuator would be too high. An implementation based only on a velocity threshold is proposed in [74] and [75]; the proposed switching algorithm exhibits a nonsmooth behavior around the switching velocity. Better smoothness is obtained in [68] and [76] use of velocity-dependent weighting functions.

The literature shows that the integrated approach yields the best performance. Unfortunately, it is also the most complex actuator-wise: It needs a way of exerting a tilting torque and active steering (in some cases, an actual steer-by-wire system is required). This may considerably affect the cost of the vehicle. Torque vectoring is a possible solution, especially when dealing with electric vehicles. Electric vehicles are often equipped with motor-in-the-hub technology; this enables the differential torque control without any additional cost. In [71], the idea is applied to a prototype four-wheeled NTTV. The controller is designed starting from a control-oriented model of the vehicle dynamics. Simulations show that torque vectoring can improve roll dynamics; in particular, an obstacle avoidance maneuver is taken as a reference.

VIII. CONCLUSIONS AND PERSPECTIVE

In this review paper, we did our best to represent the state-of-the-art in motorcycle dynamics control. In choosing the relevant contributions, we were driven by two considerations: 1) The contribution needs to be on control system design, analysis, and validation. 2) The contribution ought to be currently (or in short-term) industrially relevant.

This forced us to leave out a plethora of interesting contributions. The community working on other aspects of motorcycle dynamics is considerably larger than the one summarized here. In the introduction, we mentioned a few works on important aspects of motorcycle dynamics modeling that are necessary to understand the importance and features of the control system.

Despite this, for focus' sake, we neglected several contributions. In particular, it is worth citing the researches looking into the human factors in motorcycle riding; those evaluating the real-world effect of active safety systems and the one looking into the future with braver ideas.

Motorcycle (or bicycle) dynamics are extremely complex and multifaceted. Furthermore, one should consider that rarely it is a matter of motorcycle dynamics only, rather we should refer to motorcycle and rider dynamics. The rider mass is not negligible with respect to the motorcycle one; moreover, the rider tends to lean with the motorcycle. Several researchers are considering the role of the rider in the attempt to learn more not only on motorcycles but also on human muscular control. The interested reader should consult [77] the Bicycle Rider track of the 2013 International Symposium on Dynamics and Control of Single-Track Vehicle.

In this paper, we draw a very optimistic picture. Technically speaking, there are numerous ways to improve the safety of single-track vehicles without negatively affecting performance, as control system engineers; however, we oftentimes focus too much on track-test results, forgetting that these vehicles will be driven by normal people on roads. It is, thus, important to evaluate the real world effects of active safety systems. The fact that high-end motorcycles are often employed as leisure machines rather than means of transportation makes this analysis even more important. Several reports and analyses have been prepared by transportation departments and research institutes [78]. For example, in [79], the rate of fatal crashes in the period 2003 to 2008 is analyzed. Data show that the rate of fatal motorcycle crashes was 37% lower for ABS models than for their non-ABS versions. Further analysis based on real usage can be found in [80].

Finally, we would like to end this contribution looking into the future. The scientific (and industrial) community is very active in researching more far-fetched solutions. The most important research directions in single-track VDC that have not been cited in this paper are:

1) Fully autonomous motorcycles: The first motorcycle entry into the DARPA challenge dates back to 2005, since then a number of contributions have been published.
2) New personal mobility vehicles: The dynamics of small indoor or outdoor new personal mobility vehicles can be conducted to those of a single-track vehicle. In the past few years, many exciting new vehicles have been proposed.
3) New actuators: With the advancement of mechatronic systems, new ideas for actuation are becoming more realistic. The most interesting ones are: rear-wheel steering [81] and gyro-stabilization [82].

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