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Control of a Scaled Vehicle in and Beyond Stable Limit Handling

Mart Baars[1,2], Hans Hellendoorn[1], and Mohsen Alirezaei[2](✉)

[1] Delft University of Technology, Delft, The Netherlands
[2] Department of Integrated Vehicle Safety, TNO, Helmond, The Netherlands
mohsen.alirezaei@tno.nl

Abstract. In this research a controller is developed that can control path-tracking both within and beyond stable limit handling. A controller is developed, based on the equations of motion of the nonlinear bicycle model. The performance of the controller is evaluated in both simulation and on a 1/10 scale radio controlled car. The controller is able to track a path in typical cornering conditions and let the vehicle enter and maintain a drift while remaining close to the desired path.

Keywords: Autonomous · Drifting · Limit handling · Scaled car

1 Introduction

An autonomous driving system should be able to control the vehicle in all driving situations to ensure safety of the passengers. Especially controlling unstable behaviour, like drifting, is important since inappropriate control could have disastrous consequences. Being able to control this behaviour, however, does not only ensure safety but could also improve agility of the vehicle [1].

During typical cornering, the lateral motion of the vehicle is controlled by only the steering input. During drifting, however, also the throttle input (on a rear-wheel driven car) has an influence on the lateral motion of the vehicle. For this reason, a different control approach is required during drifting. In [2], a control approach is proposed that switches between two drift controllers; a steering focussed controller that controls the drift by steering while keeping the rear longitudinal wheel slip constant and a throttle controller that keeps a constant steering input. Switching between those two controllers can prevent the vehicle from both spinning and exiting the drift in a many situations. In [3] a Nonlinear Model Predictive Controller (NMPC) is used to find the steering and throttle input corresponding to a found combination of tyre forces, that maintain the drift. By comparing predicted responses of different control inputs, an optimal input sequence can be estimated. A different control approach is presented in [4], where the steering controller is equal for both typical cornering as for drift control. A path-tracking controller determines the steering input in both situations. The throttle input is based on longitudinal velocity for typical

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cornering and based on yaw rate, sideslip angle and longitudinal velocity during drifting. A State-Dependent Riccati Equation (SDRE) controller is used to find the optimal controller gains.

Where the NMPC and SDRE controller show promising results, the complexity and the required computational resources for real-time application are a large drawback. The controller gains in [2] are mainly based on vehicle dynamics, this results in a simple and insightful controller that, in the basis, uses on proportional control only. Unlike the other two, this controller is unable to follow a path. The main contribution of this research is the development of a drift controller with path-tracking capabilities both within and beyond stable limit handling, as an extension to the work of Hindiyeh [2]. This means including path-tracking capabilities to the drift controller and implement the transition from typical cornering to drifting.

The research is structured as follows; In Sect. 2 the problem will be formulated. Next, the path-tracking and drifting errors will be defined in Sect. 3. The design of the controller will be discussed in Sect. 4. Finally, the results based on simulations and implementation in a 1/10 scaled RC car will be analysed in Sect. 5.

2 Problem Formulation

In normal driving conditions, a path can be tracked by using only the steering input. To maintain a drift, however, control of the yaw motion and body sideslip angle of the vehicle is required, which additionally requires control of the throttle input. Since the throttle input influences both the lateral and longitudinal motion of the vehicle, path-tracking and drifting cannot be approached as separate problems. A controller that combines both is therefore required.

3 Error Definition

Drifting is a steady-state cornering condition, albeit an unstable one. This means that a drift can be maintained by controlling the vehicle to one of its equilibria. Based on an equilibrium analysis, equilibria of a simulation model of the scaled RC car are found. By controlling the vehicle to the equilibrium velocity, yaw rate and body sideslip angle, a drift can be maintained. The errors that are to be minimised to maintain a drift are, therefore, defined as

$$\begin{aligned} e_r &= r - r^{eq}, \\ e_\beta &= \beta - \beta^{eq}, \\ e_{v_x} &= v_x - v_x^{eq}. \end{aligned} \tag{1}$$

Path-tracking requires different errors to control the position and heading of the vehicle with respect to the path. The error definition for path tracking as used in this research, is based on a widely used method based on a look-ahead point [5,6], but adapted to work with high sideslip manoeuvres. In the original method the distance to the path is calculated orthogonal to the vehicle axis. At a high body sideslip, however, this distance is not representative for the actual distance to the path. Therefore, the distance to the closest point on the path is used. The error definition as used in this research, is shown in Fig. 1. The look-ahead error, e_{la}, is calculated, based on the lateral error, e_y, and the heading error, ψ_e, and body sideslip angle, β, with the following equation

$$e_{la} = e_y + x_{la} \sin(\psi_e \beta_{ss}). \tag{2}$$

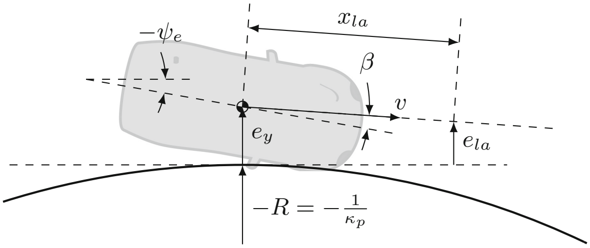

Fig. 1. Path-tracking error definition as used in this research, with the look-ahead error e_{la}, the lateral error, e_y, the heading error, ψ_e, the body sideslip angle, β, the look-ahead distance, x_{la}, the velocity, v, and the path curvature, κ_p.

4 Controller Design

The response of a vehicle to a steering and throttle input differs in typical cornering conditions and for large body sideslip manoeuvres. For that reason, a separate controller for both conditions is developed. The output of both controllers is a steering input and a desired longitudinal wheel slip factor for the rear wheels. The reference generator uses path information (curvature and path-tracking errors) from the positioning system and the vehicle states, $\mathbf{x}$, to select a controller and define the state references, $\mathbf{r}$. The controller structure is shown in Fig. 2.

4.1 Typical Cornering Controller

The steering controller that is used in typical cornering conditions is proposed in [7]. A combination of feedforward and feedback is used to minimise the path-tracking errors. The feedforward steering angle is defined as follows:

$$\delta_{FF} = \left(\ell + \frac{K_{us} v_x^2}{g} \right) \kappa_p, \tag{3}$$

where $K_{us} = \frac{F_{zf}}{C_{\alpha,f}} - \frac{F_{zr}}{C_{\alpha,r}}$ is the understeer gradient, ℓ is the wheelbase of the vehicle, v_x is the longitudinal velocity, g is the gravitational acceleration and κ

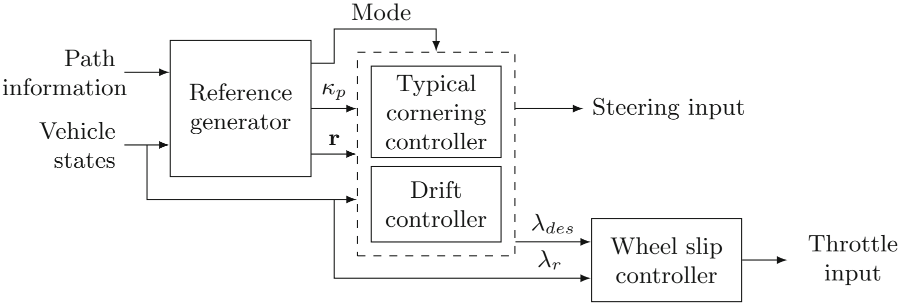

Fig. 2. Schematic of the controller structure

is the curvature of the path. The feedback steering angle is calculated with the same equation, but with a curvature based on the path-tracking errors instead of the path-curvature. A Sagitta is used to define the curve back to the path, based on the path-tracking errors. The curvature of the Sagitta is defined by

$$\kappa_{FB} = -\frac{2e_{la}}{e_{la}^2 + x_{la}^2} \approx -\frac{2e_{la}}{x_{la}^2}. \tag{4}$$

The throttle input in typical cornering conditions is used to follow the longitudinal velocity reference.

4.2 Drift Control

During high body sideslip manoeuvres, the vehicles lateral and yaw motion are controlled by the steering and throttle input simultaneously. Based on the equations of motion and feedback linearisation, the controller defined by Hindiyeh is described as follows:

$$\begin{aligned}\left(\frac{a}{I_z} - \frac{K_\beta}{mv_x}\right) F_{y,f} - \left(\frac{b}{I_z} + \frac{K_\beta}{mv_x}\right) F_{y,r}& \\ = -(K_\beta + K_r)r + K_r r^{eq} + K_\beta K_r(\beta - \beta^{eq}).&\end{aligned} \tag{5}$$

Based on the vehicle and equilibrium states, a combination of front and rear lateral tyre forces is found to keep the vehicle in a drift. These front and rear lateral tyre forces can be translated to a steering and throttle input via a coordination scheme, discussed later in this section. As reference for this controller, the equilibrium yaw rate, r^{eq}, and body sideslip angle, β^{eq}, are used to keep the vehicle at a certain equilibrium drift. By defining these to constants based on the path-tracking errors, path-tracking can be added to this controller. From a desired curvature and velocity, a desired vehicle yaw rate can be obtained via

$$r_{des} = \kappa_{des} v_{des}. \tag{6}$$

In Sect. 4.1 it was shown that the path-tracking errors can be transformed into a feedback curvature by calculating the Sagitta. Combined with the path curvature and Eq. 6, the path tracking errors and the vehicle velocity can be transformed into a desired yaw rate. With that yaw rate and the velocity an equilibrium body sideslip angle can be found. Plugging these into Eq. 5 results into a combination of lateral tyre forces that keeps the vehicle on a path, while drifting. To transform these forces to a steering and throttle input, an input coordination scheme is used. Initially the controller will be in steering mode, this means that the throttle input is controlled to maintain a desired velocity. Based on this throttle input and the vehicle states, the rear lateral tyre force can be calculated. This lateral tyre force results, with Eq. 5, in a desired front lateral tyre force. Via an inverse tyre model, the steering angle corresponding to that lateral tyre force will be calculated. It is possible that the calculated front lateral tyre force is not reachable within the limits of the tyre force, the tyre is saturated. In that case, the controller goes into throttle mode. This means that a steering angle will be chosen near the maximum of the front lateral tyre force and new rear lateral tyre force will be calculated with Eq. 5. An inverse tyre model is used to find the throttle input corresponding to that lateral tyre force.

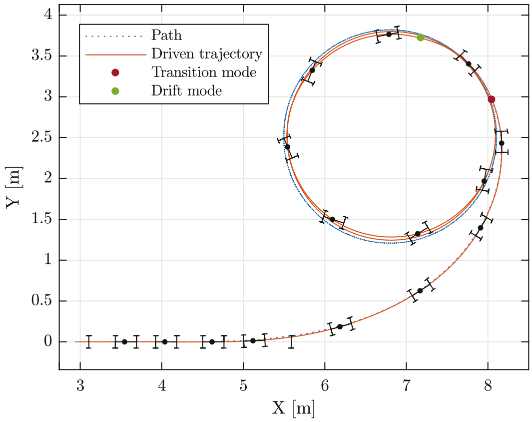

Fig. 3. Trajectory of the DSV entering and maintaining a drift while tracking a path in simulation.

5 Results

The controller is implemented in a simulation environment on a seven degrees-of-freedom vehicle model (longitudinal, lateral and yaw motion and four wheel rotations) of the scaled vehicle that is used for implementation (The Delft Scaled Vehicle, DSV). A sensitivity analysis shows that the controller is able to maintain a drift while tracking a path for severe state perturbations, initial path deviations and for a range of path curvatures. In simulation the controller is able to track a path from typical cornering conditions up to a sustained drift. The transition from typical cornering to drifting is induced by increasing the

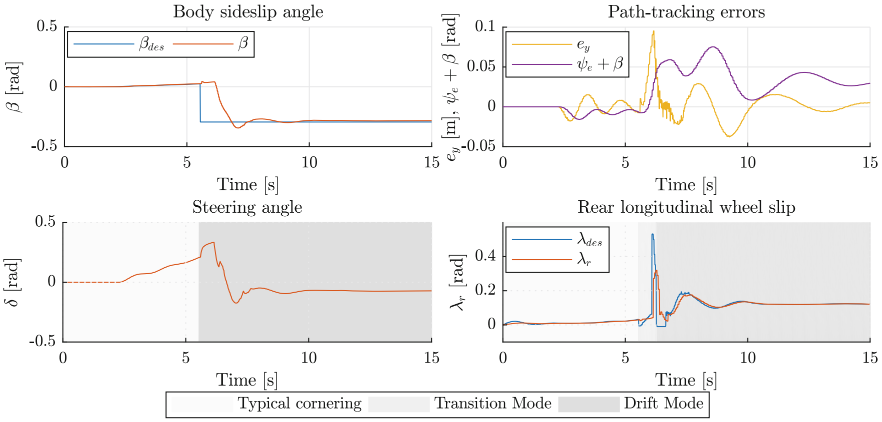

Fig. 4. States of the DSV entering and maintaining a drift while tracking a path in simulation.

steering angle to let the vehicle cut the corner slightly and increase the vehicle yaw rate. Subsequently, the throttle is increased to reduce the rear lateral tyre forces and let the rear of the vehicle slide to the outside of the curve. After this action the drift controller is used to keep the vehicle on the path. In Figs. 3 and 4 the response of a vehicle entering a drift in simulation is shown. The final step of this research is the implementation of the controller in a 1/10 scale radio controlled car, the Delft Scaled Vehicle (DSV), as shown in Fig. 6. The DSV is equipped with sensors for the measurement of wheel speeds, acceleration and location and can be controlled via the Robotic Operating System (ROS). On the DSV, the controller is able to follow a path in typical cornering conditions[1] and during drifting[2]. Figures 5 and 7 show the response for the DSV tracking a path while drifting. The controller is able to maintain the drift for at least 40 s, with the body sideslip angle close to its reference value. The lateral and course error show large oscillations with a period of approximately 5 s. An explanation for these oscillations can be found in the trajectory plot. The circular path in which the DSV settles is slightly bigger than the tracked path and translated in the positive Y direction. From the body sideslip angle plot, it becomes apparent that the body sideslip angle is not at the desired value. This shows that the DSV settles in a different equilibrium than is used from the path information. This results from discrepancies between the model and the actual vehicle, due to model simplifications and uncertainties. The high frequency oscillations that can be seen in the wheel slip measurement are a result of various lags in the system. So although the controller is able to maintain a drift close to the path, further tuning is required to increase the performance of the controller.

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[1] A video of the implemented controller in typical cornering conditions can be found at: https://youtu.be/aU6xPavFe4Q.

[2] A video of the implemented controller in high sideslip conditions can be found at: https://youtu.be/VWgdd5jgyuk.

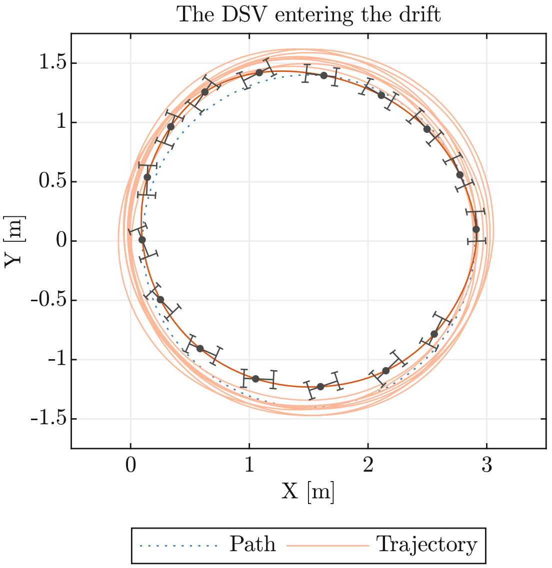

Fig. 5. DSV entering a drift

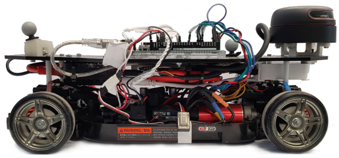

Fig. 6. The Delft Scaled Vehicle (DSV)

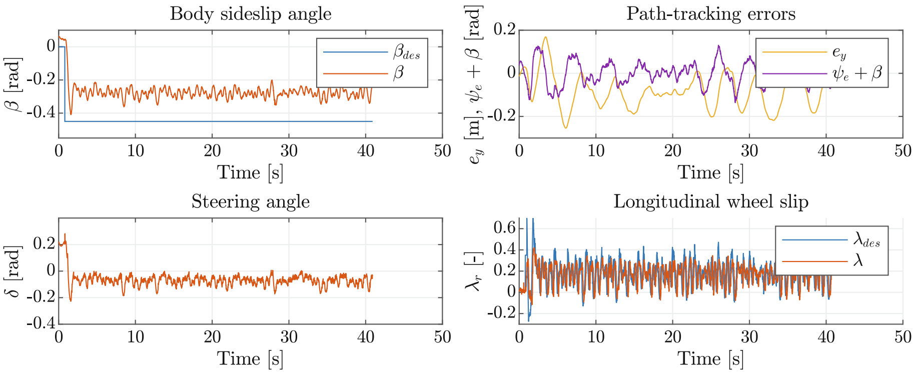

Fig. 7. States of the DSV entering a drift

6 Conclusion

In this research a controller is developed that can follow a feasible path in both typical cornering and unstable high body side slip angle conditions. A sensitivity analysis shows that the controller can stabilise the drifting vehicle around the path for various curvatures and velocities. Additionally, it showed the controller can stabilise the vehicle from significant state perturbations. Furthermore, the controller is able to enter a drift from typical cornering conditions. By steering into the corner, before saturating the rear tyres, the deviation from the path during the transition can be minimised. Implementation of the typical cornering controller in the DSV showed the controller is able to track a desired trajectory accurately. Furthermore, the drift controller achieved to bring the DSV into a drift and sustain it, while remaining close to the path.

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