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# Active Front Steering (Part 2): Safety and Functionality

**Wolfgang Reinelt, Willy Klier, Gerd Reimann, Wolfgang Schuster, Reinhard Großheim**
ZF Lenksysteme GmbH, Schwäbisch Gmünd, Germany, wolfgang.reinelt@zf-lenksysteme.com



## ABSTRACT

Active Front Steering (AFS) is a newly developed technology for passenger cars that realises an electronically controlled superposition of an angle to the hand steering wheel angle that is prescribed by the driver. It enables functionalities such as (vehicle velocity) variable steering ratio, steering lead, as well as it provides an interface to support vehicle dynamics control systems. This paper focuses on application dependent safety functions and steering assistance functions. All functions described are model based, their accuracy is demonstrated.

## 1 INTRODUCTION AND MOTIVATION

Active Front Steering (AFS) is a newly developed technology for passenger cars that realises an electronically controlled superposition of an angle to the hand steering wheel angle that is prescribed by the driver. However, the permanent mechanical connection between steering wheel and road wheels remains.

This paper is the second in a series of two papers. The first one Klier and Reinelt (2004) gives a detailed description of the system itself, whereas this one focuses on safety and functionality of the system.

Although AFS is not a steer-by-wire system, a great deal of measures is required in order to ensure the overall safety of the system, which has been recognised widely in the literature by Harter et al (2000), Knoop et al (1999). In fact, the electronic components, the actuator dynamics and the signals used to achieve AFS functionality are continuously monitored in order to ensure correct and safe operation of the system. Many types of so-called safety and monitorings functions are implemented. However, this paper will focus on the *application dependent safety and monitoring algorithms*, such as plausibility check of the angles involved (hand steering wheel angle, road wheel angle, motor angle), plausibility check of (open and closed loop) dynamics etc. Since all of the above mentioned algorithms are model based, their models are derived first. Most of these models base on vehicle or actuator physics or geometry, possibly accompanied by black box error terms that account for variations arising from mass production of the components. Some examples are given to illustrate the detection of sensor failures and to demonstrate the accuracy that is currently achieved.

The *steering assistance functions* that can be immediately experienced by the driver are for instance a variable steering ratio and a steering lead. Moreover, AFS provides an interface to support vehicle dynamics control systems. Here, the variable steering ratio is described and some measurements are presented to show the benefit of these functions.

## 2 SYSTEM DESCRIPTION AND NOTATION

The complete system setup including mathematical modelling and parameter estimation is described in great detail in Klier and Reinelt (2004). In order to make this paper self-contained, the basic relations are given here as well. Fig. 1 shows the AFS principle: The driver controls the vehicles course via the hand

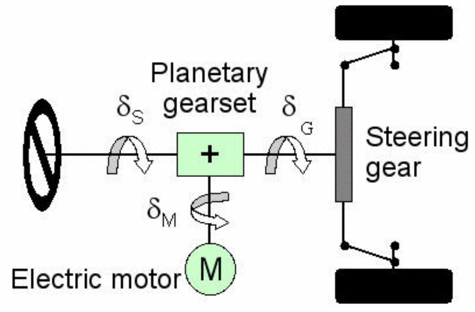


Figure 1: Schematic view of AFS system. The electric motor superimposes an angle $\delta_M$ to the hand steering wheel angle $\delta_S$. The result is the steering gear's pinion angle $\delta_G$.

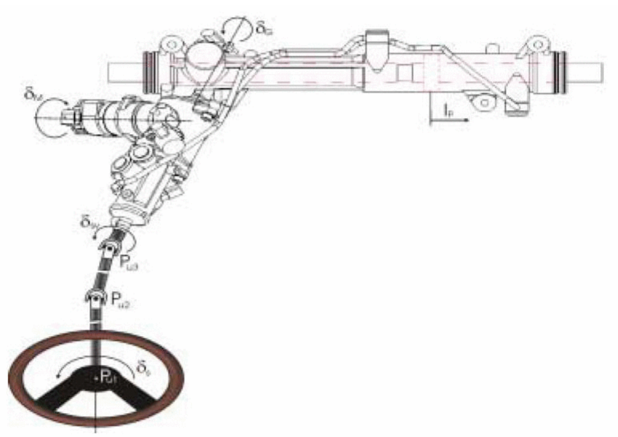

Figure 2: AFS system including (top-down) steering rack, actuator (motor and planetary gear), steering column and hand steering wheel.

steering wheel; the resulting steering wheel angle is denoted by $\delta_S$. AFS actuates an additional angle $\delta_M$ using its electric motor. Both angles result in an pinion angle $\delta_G$ down at the steering rack. All three angles relate as given in eqn.(1) below (also accounting for the respective ratios $i_M, i_D$). Fig. 2 shows the AFS system including actuator (motor and planetary gear box), steering column, steering rack and hand steering wheel. The resulting (average) road wheel angle can then be calculated via the pinion angle and a static nonlinearity$F_{SG}(\cdot)$ that accounts for the relation between pinion angle and rack displacement as well as for the steering geometry, cf. (2). Finally, the overall ratio between hand wheel to road wheel is defined in (3).

$$\delta_G(t) = \frac{1}{i_M} \cdot \delta_M(t) + \frac{1}{i_D} \cdot \delta_S(t) \tag{1}$$

$$\delta_G(t) = F_{SG}\left(\delta_F(t)\right) \tag{2}$$

$$\delta_F(t) = \frac{1}{i_V} \cdot \delta_S(t) \tag{3}$$

Having this basic framework at hand, we can start looking at functions that manipulate the motor angle $\delta_M(t)$ in order to e.g. achieve a desired overall steering ratio $i_V$. This desired motor angle $\delta_{Md}(t)$ will then be passed to the motor's feedback control algorithm. However, before designing such functions, the plausibility of all signals discussed so far has to be ensured, to ensure the safety of the AFS system. This is part of the AFS Functional Safety, described next.

## 3 FUNCTIONAL SAFETY

Fig. 3 gives a simplified view of the core signals that are needed in order to get steering assistance functions in place. The signals come with a basic diagnostics that is carried out by the sensor itself. The first check to be carried out by AFS then is a simple range and gradient check (RGC). These checks belong to the category of *electronics dependent safety functions*, since these can be set up whenever ECU and/ or sensors are in place. The more interesting category (from a modelling and control point of view), however, are the *application dependent safety functions*. These safety functions monitor e.g. sensor signals as well, but are based on application dependent relations. The information obtained from both types of safety functions is collected, the current state of the signals and the system is assessed and assistance functions are configured in an appropriate way.

In the case of AFS, examples for application dependent safety functions are monitoring of the pinion angle (PAP), monitoring of the kinematic relation (1) (AMA) and monitoring of the actuator dynamics, see also Fig. 3. These safety functions are discussed in the next sections. They all, however, share a generic structure that is depicted in Fig. 4 and already well established in literature, cf. Schwarte and Isermann (2002). The signal, to be monitored, is compared

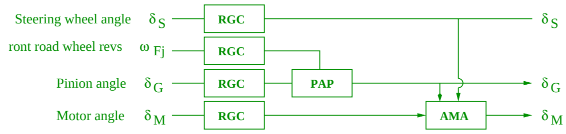


Figure 3: Simplified signal flow of all signals, to used for AFS functions, and their plausibility checks.

to its estimate, generated for instance by a model. Most importantly, the model has to use signals that are independent of the signal to be estimated. The difference between signal and its estimate is called *residuum*. A dead-zone assesses whether the residuum is acceptable or not. After this one has to decide whether the model is valid (in this very driving situation) or not, a decision, which produces the so-called *symptom*. A counter finally alerts a warning whenever the symptom appears a certain amount of instances (either in total, in a row etc.). In summary, this approach of monitoring a signal generates a "virtual" second signal channel, where both signals are compared then. For general approaches to change detection in signals, we refer to Basseville and Nikiforov (1993) and Gustafsson (2000). This contribu-

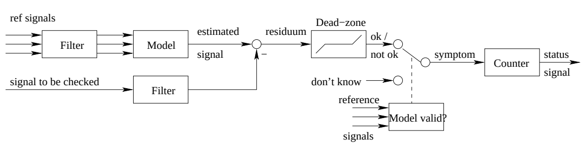


Figure 4: Generic structure of a model based safety function.

tion will focus on the model used within the safety function and demonstrate the accuracy that is currently achieved. The structure of the model will be derived. Since the models contain a lot of physical parameters plus some error terms, these have to be estimated and validated from data. The procedure of parameter estimation follows the same route in all examples. Data from test drives with prototype vehicles are collected and preprocessed. The parameters then are estimated with e.g. prediction error methods, see Ljung (1999) or unknown-but-bounded approaches, cf. Milanese et al (1996), including parameter validation on validation data and a final assessment of the parameter quality. An overview and comparison of recent methods is given by Reinelt et al (2002).

## 4 PINION ANGLE PLAUSIBILITY CHECK

### Function Description and Design

The purpose of the Pinion Angle Plausibility Check (PAP) is to monitor the pinion angle sensor signal for possible failures using the road wheel revolutions. The following analytic expression can be easily derived from the steering geometry, see Wong (2001, ch.5) and Fig. 5:

$$\tan \delta_i = \frac{-I(\omega_i^2 - \omega_o^2)}{S_L\omega_i^2 + \sqrt{S_L^2\omega_i^2\omega_o^2 - I^2(\omega_i^2 - \omega_o^2)^2}} \qquad (4)$$

where $I$ and $S_L$ denote the vehicle's wheelbase and track respectively, $\delta_i$ the angle of the inner (with respect to the curve) road wheel, and finally $\omega_i, \omega_o$ the revolutions of the inner and outer road wheel. $\delta_i$ is then mapped onto the pinion angle $\delta_G$ exploiting (2)[1]. Hence, the model used for estimation of the pinion angle uses the two front wheel revolutions as input signals and the steering geometry (represented by the parameters $I, S_L$ in (4) and the static nonlinearity $F_{SG}(\cdot)$ in (2)). The parameter identification basically follows a two stage procedure. Firstly, the vehicle's wheelbase and track are measured. Secondly, the static nonlinearity $F_{SG}(\cdot)$ is estimated, this step essentially being the estimation of a Wiener model. For methods of estimating these and assessing their quality, see Bauer and Ninness (2002).

### Results from a Testdrive

Fig. 6 shows sample results from a handling course maneuver for the pinion angle estimation, when no sensor failure is present. One should, however, take into account that a decision whether the pinion sensor signal is faulty or not cannot be made on the result of this safety function alone; the basic equation derived above may not be valid because of particular driving situations such as sliding, swimming or brake interventions by an ESP system an one wheel. To assess the state of the pinion angle sensor signal, the full information of all safety funcions (electronic dependent and application dependent) is neccessary.

[1] The static non-linearity $F_{SG}$ has to be adapted in a straightforward way to account for the angle of the inner wheel in-

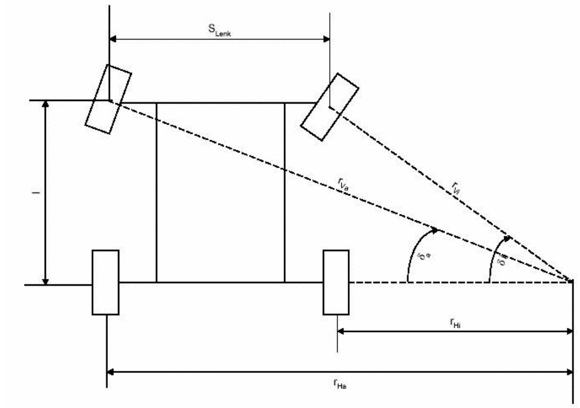


Figure 5: Vehicle geometry using the front wheel revolutions $\omega_i, \omega_o$ to calculate the average road wheel angle $\delta_F$.

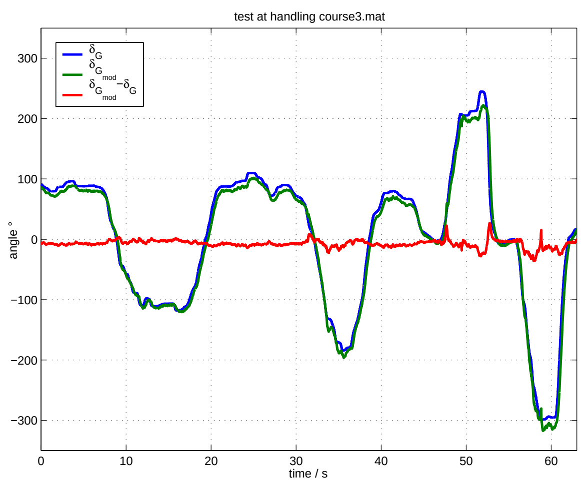


Figure 6: Data collected at a handling course maneuver for the pinion angle estimation, when no sensor failure is present: estimated angle (green), measured angle (blue), and difference between estimated and measured angle (red).

## 5 ANGLE MONITORING ALGORITHM

### Function Description and Design

The purpose of the Angle Monitoring Algorithm (AMA) is to monitor the kinematic constraint (1) between the three angles in order to detect possible sensor failures or mechanical failures. Although (1) looks quite simple, preliminary investigations show that it cannot be modelled in an acceptable accuracy as a linear black box model. The basic problem that prevents us from this approach is that the hand steering wheel sensor, measuring $\delta_S(t)$ is located in the top of the steering column, while the motor and pinion angle sensors are situated in the lower part of the steering column, see Fig. 2. A full multi-body model of the actuator is derived in Klier and Reinelt (2004) and could contribute to overcome this problem. However, this model is not suited for implementation on an ECU. Consequently, a simple solution has to be looked for: effects such as torsion of the steering column (which can be modelled in a linear fashion quite accurately) and effects of the universal joints in the steering column (which must be modelled using non-linear models) have been taken into account. All this leads us to a linear black box model and a trailing static non-linearity, i.e. the following Wiener model:

$$\dot{x}(t) = Ax(t) + b(\delta_G^{\#}(t) - \delta_M^{\#}(t));\ x(0) = x_0 \quad (5)$$

$$\hat{\delta}_S(t) = J\left(Cx(t)\right) \quad (6)$$

where $\delta_G^{\#}(t), \delta_M^{\#}(t)$ are pinion and motor angle respectively, normalised to the hand steering wheel angle using (1). The LTI system $(A, B, C)$ accounts for the linear torsion dynamics in (1) (basically using the steering velocity of the driver), and the static non-linearity $J(\cdot)$ accounts for possible effects given by universal joints in the steering column. Although an analytical expression for $J(\cdot)$ is at hand, it will not be possible to run is on the ECU (from a computational point of view). Hence, a simplified version has been applied.

As in the case of the pinion angle plausibility check, the linear and the non-linear part are estimated in two stages, based on data collected in the vehicle. The data, however, has to cover driving situations where both effects (torsion and universal joints) are present to ensure sufficiently much excitiation in the inputs signals.

### Results from a Testdrive

Fig. 7 shows the estimation of the steering wheel angle during a vehicle dynamics maneuver, a circle drive with changing vehicle velocity. A drift in the pinion angle sensor has been injected (starting at $3.7s$) which results in an increasing deviation between estimated and measured steering wheel angle. How

stead of the averaged front wheel angle.

much deviation is allowed before a failure is assumed, is to be applied in the safety function's dead-zone, see Fig. 4. Figs. 8 and 9 show the estimation of the steering wheel angle during a slalom drive with constant vehicle velocity. An impulse in the pinion angle sensor has been injected (at $5.14s$ of the experiment) which results in a "punctual" deviation between estimated and measured steering wheel angle. How long this deviation is allowed to appear before a failure is assumed, is to be applied in the safety function's counter, see Fig. 4.

Note, however, that a decision which of the three sensor signals is faulty cannot be made on the results alone; to assess this, the full information of all safety funcions (electronic dependent and application dependent) is neccessary, see also the "model valid" block in Fig. 4.

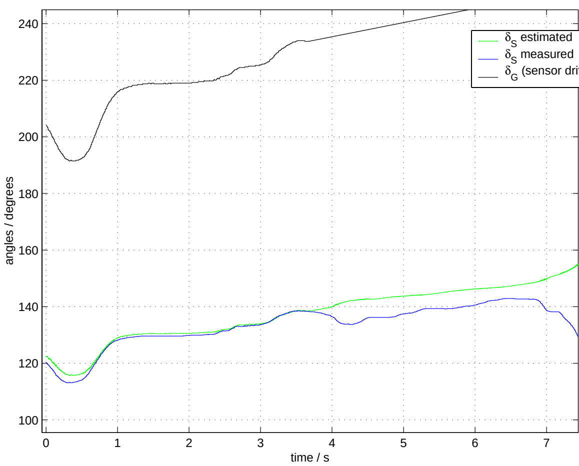


Figure 7: Data collected during a maneuver on the vehicle dynamics area demonstrating the angle monitoring algorithm dealing with a drift in pinion angle sensor, starting at $3.7s$. Measured steering wheel angle (blue), estimated steering wheel angle (green) and drifting pinion angle signal (black).

## 6 VARIABLE STEERING RATIO

### Function Description and Design

The purpose of the variable steering ratio (VSR) is to adapt the overall ratio between hand wheel angle $\delta_S(t)$ and (averaged) road wheel angle $\delta_F(t)$, cf. (3) to the current driving situation. The driving situation

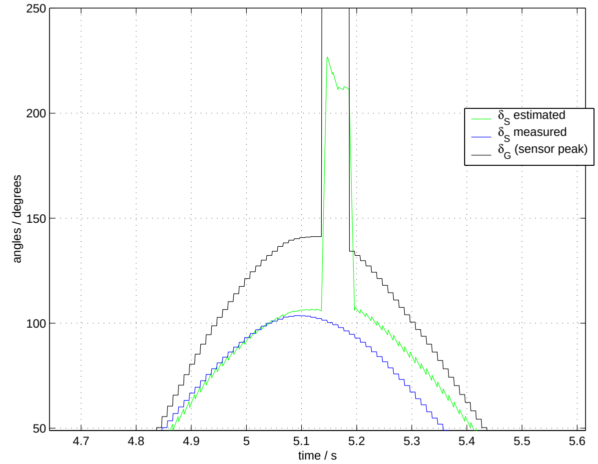


Figure 8: Data collected during a maneuver on the vehicle dynamics area demonstrating the angle monitoring algorithm dealing with a peak in the pinion angle sensor signal around $5.14s$. Measured steering wheel angle (blue), estimated steering wheel angle (green) and pinion angle signal with peak (black). Zoomed version of Fig. 9.

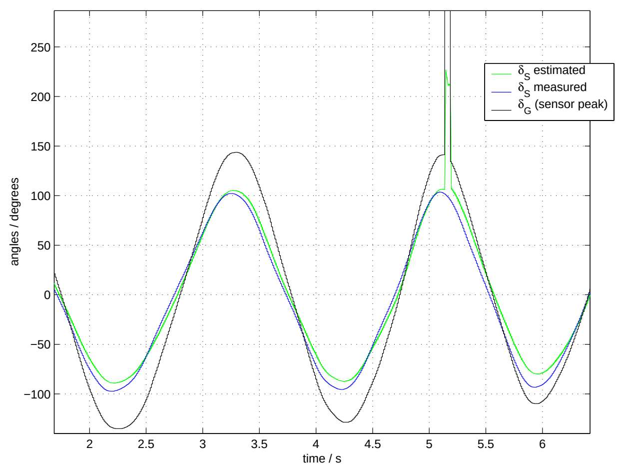


Figure 9: Data collected during a maneuver on the vehicle dynamics area demonstrating the angle monitoring algorithm dealing with a peak in the pinion angle sensor signal around $5.14s$. Measured steering wheel angle (blue), estimated steering wheel angle (green) and pinion angle signal with peak (black).

can, for instance, be determined by the vehicle's velocity $v_X(t)$ and pinion angle $\delta_G(t)$. Hence, $i_V$ in (3) becomes a function of velocity and pinion angle. The point in varying the ratio dependent on velocity is to decrease it (compared to the mechanical ratio) when driving at very low velocities, which is of particular use for example during parking maneuvers. Then the driver only has a small steering effort (in terms of turning the hand wheel) due to this direct steering ratio in order to maneuver the car smoothly into the parking space. At higher vehicle velocities the steering ratio becomes increasingly indirect up to the level of a conventional steering system (or even beyond). The principle of varying the overall ratio over the vehicle velocity is shown in Fig. 10. Moreover, AFS can be used to vary the ratio with respect to pinion angle, so that the functionality of a (mechanical) variable rack can be achieved. The desired overall ratio can be specified quite conveniently by the vehicle manufacturer for example in terms of a look-up table. An example for such a look-up table is given in Fig. 11. The means of realising the above de-

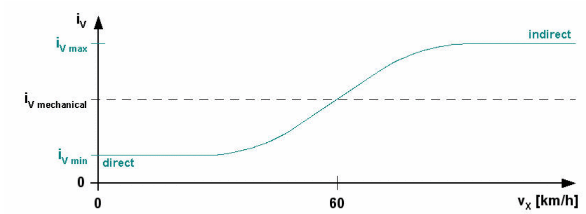


Figure 10: Example for velocity dependent ratio $i_V(v_X, \cdot)$.

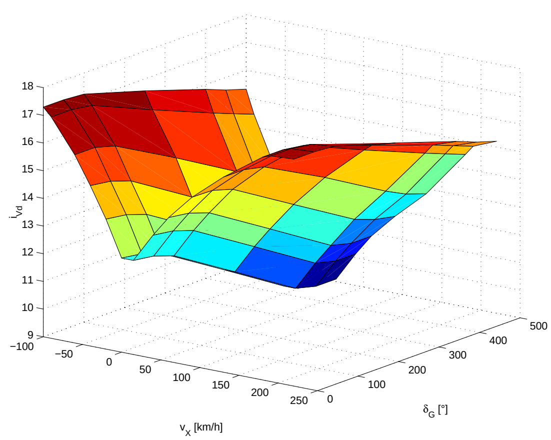


Figure 11: Example for velocity and pinion angle dependent ratio $i_V(v_X, \delta_G)$.

scribed functionality is the control the position of the AFS motor in order to achieve the desired ratio. We therefore insert (2,3) into (1), which yields the motor angle:

$$\delta_M(t) = i_M \cdot F_{SG}\left(\frac{\delta_S(t)}{i_V}\right) - \frac{i_M}{i_D} \cdot \delta_S(t) \quad (7)$$

Now, *given* the desired ratio at a certain time instant:

$$i_V = i_V(v_X, \delta_G) \quad (8)$$

the respective motor angle can be calculated using (7) and will then be passed on to the motor's feedback controller as reference signal.

### Results from a Testdrive

Fig. 12 shows the overall ratio $i_V$ that has been applied during a circle drive accelerating first and the braking. Quite obviously, other ratios have been applied for braking and for accelerating. This is due to the fact that the ratio is filtered during braking actions, which is a comfort feature for the driver. It is generally not appreciated when the ratio decreases as fast during (hard) braking as it increases when accelerating quickly.

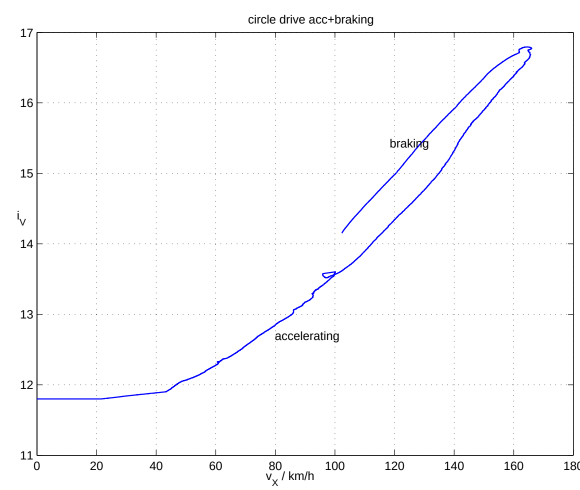


Figure 12: Example for velocity dependent ratio $i_V(v_X, \cdot)$ driving a circle accelerating and braking. Different rations being applied when accelerating and braking.

## 7 CONCLUSIONS AND FUTURE WORK

The Active Front Steering (AFS) System has been described, from a plain functional point of view, though (i.e. a electronically controlled superposition of an angle to the hand steering wheel angle that is prescribed by the driver). The need for installing model based safety functions, additionallly to the basis sensor diagnostics and range and gradient checks, has been motivated and some of the application dependent safety functions have been described, in particular the pinion angle plausibility check and the monitoring of the kinematic relation between the three angles, important for AFS. This list is far from being complete. A function, that can be directly experienced by the driver has been described as well: the (speed and pinion angle) variable steering ratio. All descriptions have been accompanied by measurements from AFS vehicles. Another function that can be experienced by the driver is the so-called steering lead, that essentially enhances the vehicle reaction during quick steering maneuvers. This function will be described in future works, also some more details on particular model based safety functions. Future work with respect to the safety functions will focus on more advanced monitoring strategies such as observer based approaches.

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