Proceeding of the 2004 American Control Conference
Boston, Massachusetts June 30 - July 2, 2004

WeP07.3

Observer Based Diagnosis of Roll Rate Sensor

M. Arndt, Phone: ++49 209 9596 448, Fax: ++49 209 9596 514, Email: marc.arndt@fh-gelsenkirchen.de
E. L. Ding, Phone: ++49 209 9596 392, Fax: ++49 209 9596 514, Email: eve.ding@fh-gelsenkirchen.de
T. Massel, Phone: ++49 209 9596 455, Fax: ++49 209 9596 514, Email: thomas.massel@fh-gelsenkirchen.de

Department of Physical Engineering, University of Applied Sciences Gelsenkirchen
Neidenburger Strasse 43, D-45877 Gelsenkirchen, Germany

Abstract: In the area of passive safety, the vehicle roll dynamic plays a very important role, especially when the vehicle tends to roll over. The danger of rolling over can early be recognized by the rollover sensing sensors. The Rollover Sensing System (ROSE) only works successfully, if all these sensors are faultless. One of these essential sensors is the roll rate sensor. Aim of this contribution is to present a new concept for monitoring the roll rate sensor signal. Investigations of the developed concept are carried out in a virtual vehicle. Finally, the car test results are demonstrated and discussed.

Keywords: vehicle roll dynamic, vehicle dynamic model, steady cornering, road with lateral inclination, sensor monitoring, fault detection, vehicle state estimation, linear observer, fuzzy logic.

1 Introduction

Active and passive safety describe the overall safety of an automobile. The aim of active safety is to avoid accidents. For example, the electronic stability program (ESP) provides assistance for braking, accelerating and steering in difficult driving situations. In other words, using the electronic stability program (ESP) is mainly to improve active safety of vehicles [1], [2]. In contrast to active safety, until now, passive safety only comes into operation, when an accident occurs. For frontal, rear, side and rollover crash protection, the Restraint System (RS) is designed mainly based on analysis of vehicle rollover, occupant motions and types of occupant injuries. In this area, lots of investigations are carried out and a very high level is achieved by developing advanced concepts [3], [4], [5], [6]. Such advanced concepts request information about the actual system state, the vehicle dynamic and behavior. Normally, two sensors are installed in the rollover sensing system (ROSE). The vertical accelerometer is used to detect the rollover type, while the most important sensor, the roll rate sensor, provides a signal closely related to the orientation of the vehicle in space [11]. A successful passive safety strongly depends on the performance of the sensors. For this reason, an on-line sensor monitoring and early warning system is a basic component also integrated in the electronic vehicle system for detecting faults in the sensors as early as possible, like the sensor monitoring system in the ESP [8].

Goal of the work presented here is to present a new concept for monitoring one of the ROSE-sensors, namely the roll rate sensor. In chapter 2, a linear observer for monitoring the roll rate sensor is developed by using the yaw rate sensor and the lateral accelerometer. Therefore, the localization of the roll rate sensor fault is very important. To guarantee that this monitoring works faultless and furthermore effectively, the availability of the model has to be investigated and a method to compute the adaptive threshold has to be developed. These are described in chapter 3. Finally, the car tests via a virtual vehicle are carried out and the results are demonstrated.

2 Linear observer design

2.1 State space model

Fig. 1 shows the simplified model for the vehicle roll motion on a road with the lateral inclination χ.

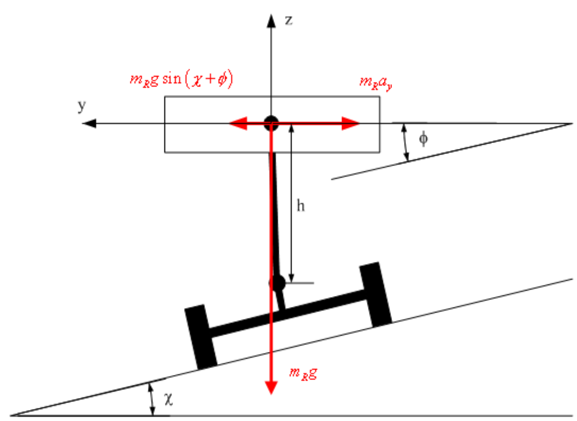


Fig. 1: Schematic of the roll motion

The symbols in Fig. 1 are defined as follows:

g: acceleration of gravity,
χ: lateral inclination angle of the road,
a_y: lateral acceleration of the vehicle body center,
ϕ: roll angle of the vehicle body in relation to the road,
m_R: sprung mass of the vehicle,

h: center height of gravity of the vehicle body in relation to the roll axis.

Denote $(\chi + \phi)$ with $\varphi_{x,M}$, where $\varphi_{x,M}$ signifies the roll angle of the vehicle body in relation to the earth-fixed coordinate system. Then, we have:

$$\phi = \varphi_{x,M} - \chi \,. \tag{1}$$

The derivative of $\varphi_{x,M}$ corresponds to the roll rate signal $\omega_{x,S}$, which is delivered by the roll rate sensor installed in the vehicle:

$$\dot{\varphi}_{x,M} = \omega_{x,M} \mathrel{\hat{=}} \omega_{x,S} \,.$$

The signal, which the lateral accelerometer senses, is formulated by the following equation according to functionality of accelerometers:

$$a_{y,S} = a_y + g\sin(\chi + \phi), \tag{2}$$

where the lateral acceleration a_y can be calculated by using the yaw rate sensor signal $\omega_{z,S}$ and the vehicle velocity v:

$$a_y = v\omega_{z,S} \,. \tag{3}$$

Inserting Equation (3) into Equation (2), the following equation holds:

$$\sin(\chi + \phi) = \frac{a_{y,S} - v\omega_{z,S}}{g}. \tag{4}$$

According to the torque balance in the roll axis (see Fig. 1), the roll dynamic of the vehicle body can be described by the following differential equation [10]:

$$\begin{aligned} &I_{xx}\ddot{\phi} + C_R\dot{\phi} + K_R\phi \\ &= m_R a_y h + m_R g h \sin(\chi + \phi), \end{aligned} \tag{5}$$

where the new symbols used in Equation (5) are defined as follows:

I_{xx}: moment of inertia in the roll axis,

C_R: damping coefficient of the roll motion system of the vehicle,

K_R: spring coefficient of the roll motion system of the vehicle,

$\dot{\phi} = \omega_x$: roll rate in relation to the road,

$\ddot{\phi}$: roll acceleration in relation to the road.

According to Equation (4), the angle $(\chi+\phi)$ can be computed by using the vehicle velocity v, the yaw rate sensor signal $\omega_{z,S}$ and the lateral accelerometer signal $a_{y,S}$. Applying Equation (4) to Equation (5) the following equation is achieved:

$$\begin{aligned} &I_{xx}\ddot{\phi} + C_R\dot{\phi} + K_R\phi \\ &= m_R a_y h - m_R h v_{ref}\omega_{z,S} + m_R h a_{y,S}. \end{aligned} \tag{6}$$

Now, we insert Equation (1) and Equation (3) into Equation (6) and obtain the new equation:

$$\begin{aligned} &I_{xx}\ddot{\varphi}_{x,M} + C_R\dot{\varphi}_{x,M} + K_R\varphi_{x,M} \\ &= m_R a_{y,S} h + I_{xx}\ddot{\chi} + C_R\dot{\chi} + K_R\chi. \end{aligned} \tag{7}$$

It is assumed again, that the first derivative and the second derivative of the road inclination angle χ are very small, so that $\ddot{\chi} \approx \dot{\chi} \approx 0$. Then, we have:

$$\begin{aligned} &I_{xx}\ddot{\varphi}_{x,M} + C_R\dot{\varphi}_{x,M} + K_R\varphi_{x,M} \\ &= m_R a_{y,S} h + K_R\chi. \end{aligned} \tag{8}$$

We define the state variables:

$$x_1 = \varphi_{x,M}$$

$$\dot{x}_1 = x_2 = \dot{\varphi}_{x,M}$$

$$\dot{x}_2 = \ddot{\varphi}_{x,M} = \frac{1}{I_{xx}}\left(-K_R x_1 - C_R x_2 + K_R\chi + m_R h a_{y,S}\right)$$

and formulate the above three equations in a state space:

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ \dfrac{-K_R}{I_{xx}} & \dfrac{-C_R}{I_{xx}}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}0 & 0\\ \dfrac{K_R}{I_{xx}} & \dfrac{m_R h}{I_{xx}}\end{bmatrix}\begin{bmatrix}\chi\\ a_{y,S}\end{bmatrix}$$

$$y = \begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix},$$

whose state variables are the roll angle and the roll rate, inputs are the lateral inclination angle of the road and the lateral accelerometer signal, and output is the roll rate. Based on this state space model, a linear observer can be designed. The advantage of the concept is, that the observer to be designed cannot only estimate the roll rate, but also the roll angle related to the earth-fixed coordinate system. This means, that using the linear observer, on the one side, the roll rate sensor signal can be monitored and on the other side, the roll angle can be estimated, if no fault in the sensors occurs. The state space model can be reformulated by the standard form for linear state space descriptions:

$$\begin{aligned} &\underline{\dot{x}}(t) = \underline{A}\underline{x}(t) + \underline{B}\underline{u}(t) \\ &y(t) = \underline{c}^T \underline{x}(t). \end{aligned} \tag{9}$$

2.2 Preparation of the first input signal

The observer is designed based on the pre-condition, that all of the input signals are known. However, The first input signal χ of the state space model is unknown. This problem can be solved as follows. According to Equation (4), the lateral road inclination angle χ can be calculated by:

$$\chi = \arcsin\frac{a_{y,S} - v\omega_{z,S}}{g} - \phi. \tag{10}$$

The unknown angle ϕ in Equation (10) can be estimated with the help of the torque balance in steady cornering state. Neglecting $\ddot{\varphi}_{x;M}$, $\dot{\varphi}_{x,M}$ and using Equation (1), the following equation is derived from Equation (8):

$$\phi = \frac{m_R a_{y,S} h}{K_R}. \qquad (11)$$

Inserting Equation (11) into Equation (10), we have:

$$\chi = \arcsin \frac{a_{y,S} - v\omega_{z,S}}{g} - \frac{m_R a_{y,S} h}{K_R}. \qquad (12)$$

2.3 Observer design

Based on the state space model developed above, a linear observer can be designed according to the well-known structure [9]:

$$\begin{aligned} \dot{\hat{\underline{x}}}(t) &= \underline{A}\hat{\underline{x}}(t) + \underline{B}\underline{u}(t) + \underline{k}\left(y(t) - \hat{y}(t)\right) \\ \hat{y}(t) &= \underline{c}^T \hat{\underline{x}}(t). \end{aligned} \qquad (13)$$

Subtracting Equation (13) from Equation (9), the error dynamics of the observer system results:

$$\dot{\underline{x}}(t) - \dot{\hat{\underline{x}}}(t) = \left(\underline{A} - \underline{k}\underline{c}^T\right)\left(\underline{x}(t) - \hat{\underline{x}}(t)\right). \qquad (14)$$

This observer system is asymptotically stable, if and only if the real components of all eigenvalues of the system matrix $\left(\underline{A} - \underline{k}\underline{c}^T\right)$ are negative. This means, that we have to select the vector $\underline{k}$ in such a way, so that the stability condition is fulfilled [9].

3 Monitoring strategy

3.1 Problem description and basic ideas

The basic idea of the model based fault detection scheme consists in the construction of the so-called analytical redundancy using system models which are in fact mathematical descriptions of known physical laws. On this basis, one can generate residual signals. A fault detection then follows by an evaluation of residual signals and a logic decision [7]. It is well-known that the main difficulty of using the model based fault detection schemes lies in the model uncertainty [15]. This problem becomes much more serious by dealing with the sensor fault detection for electronic control systems, since the process "car driving" is strongly influenced by lots of unknown factors, which can only be partly modeled or even, in some cases, cannot be mathematically described.

Regarding the observer developed in chapter 2, the model uncertainty has to be considered, too. To solve this problem, the model availability will be investigated. In driving situations, where the model is available, monitoring the roll rate sensor operates, otherwise this function has to be switched off. Furthermore, if the model is available, an adaptive fault threshold is used to avoid false messages, on the one hand, and to monitor the sensor effectively, on the other hand. Fig. 2 shows a flow chart that visualizes the consideration described above.

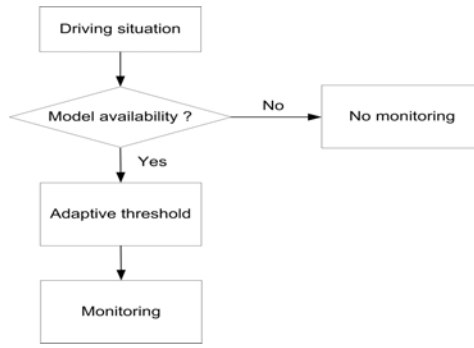


Fig. 2: Monitoring strategy

A possibility for defining model availability and for generating an adaptive threshold is presented in the next 2 subchapters.

3.2 Investigation of model availability

As lots of car tests using a virtual vehicle show, the linear observer presented above delivers satisfying results in quasi steady driving situations. In these situations the sensor monitoring is performed. Due to the model uncertainty in extremely high dynamic driving situations and possible faults in the yaw rate sensor and the lateral accelerometer, the observer cannot work very well, hence the monitoring has to be switched off. A combinational logic considering three conditions decides, whether a monitoring is turned on or not. This logic will be explained below with the help of Fig. 3.

First of all we make use of the three static models developed recently for estimating the lateral accelerometer signal [12]:

$$a_{y,M1} = \frac{v_{ch}^2}{l}\left(\delta_V - \frac{l\omega_{z,S}}{v}\right), \qquad (15)$$

$$a_{y,M2} = \frac{v_{ch}^2}{l}\left(\delta_V - \frac{l}{v}\left(\frac{v_{fr} - v_{fl}}{S_f}\right)\right), \qquad (16)$$

$$a_{y,M3} = \frac{v_{ch}^2}{l}\left(\delta_V - \frac{l}{v}\left(\frac{v_{rr} - v_{rl}}{S_r}\right)\right). \qquad (17)$$

with the new symbols:

v_{ch}:	characteristic velocity,
l:	distance between front and rear axle,
δ_V:	front wheel angle,
v_{fr}:	front right wheel speed,
v_{fl}:	front left wheel speed,
v_{rr}:	rear right wheel speed,
v_{rl}:	rear left wheel speed,
S_f:	front wheel track,

S_r: rear wheel track.

Results of lots of driving simulations suggest, that the absolute value of the derivative of the maximal difference between these models and the lateral accelerometer signal $|\Delta\dot{a}_y|_{\max}$ may not exceed its threshold $|\Delta\dot{a}_y|_{Threshold}$, if the model is available. This leads us to the first condition:

1. $|\Delta\dot{a}_y|_{\max} \le |\Delta\dot{a}_y|_{Threshold} = 15m/s^3$.

This fact is also theoretically explicable, since the large changes of the deviations between the models and the sensor signal indicate an extremely high dynamic driving behavior or a stepwise sensor fault in the yaw rate sensor or in the accelerometer.

Furthermore, the model is available, if:

2. $|a_{y,S}| \le |a_{y,S}|_{Threshold} = 6m/s^2$ and
3. $|\omega_{z,S}| \le |\omega_{z,S}|_{Threshold} = 60°/s$.

Applying a NOR gate, a combinational logic for the model availability is generated. This means, the model is available, if and only if these three conditions are fulfilled.

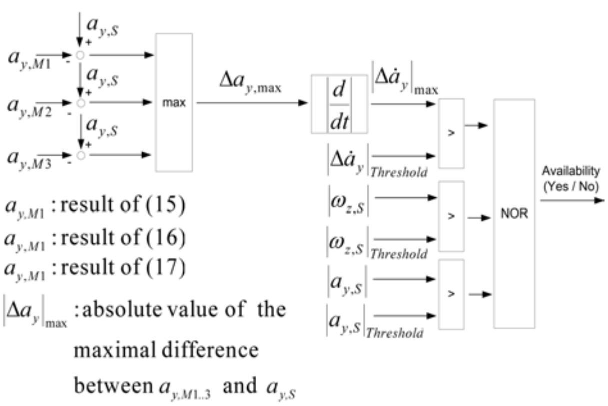


Fig. 3: Model availability

3.3 Computing the adaptive threshold

The first input of the state space model developed in chapter 2.1 is the road inclination angle which is calculated by (12). Due to the neglect of $\dot{\varphi}_{x,M}$ and $\ddot{\varphi}_{x,M}$, equation (12) cannot deliver satisfying results during dynamic driving situations. That means, a large change of the calculated road inclination angle χ points to a high dynamic of the vehicle and therefore to a worse monitoring performance. In order to figure out this performance in dependence of the dynamic behavior, and furthermore to generate an adaptive fault threshold, the fuzzy logic [13] is used.

Input of the fuzzy logic is the derivative of the calculated road inclination angle $\dot{\chi}$. Output of the fuzzy logic is the adaptive fault threshold $\dot{\varphi}_{x,Threshold}$. Fig. 4 shows this fuzzy logic with its input and output variable.

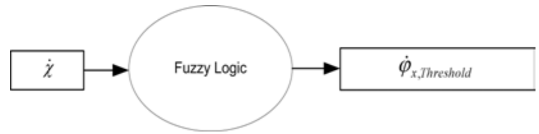
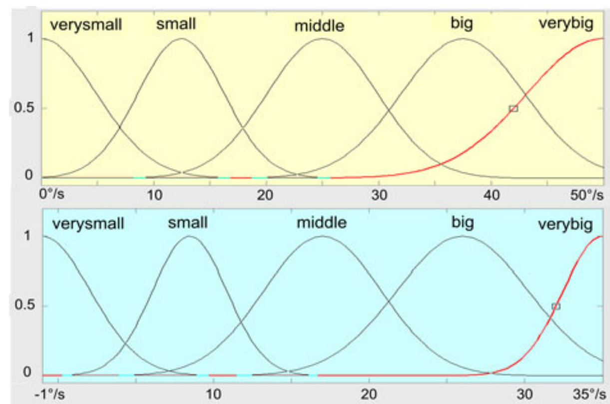


Fig. 4: The fuzzy logic

The used membership functions for the input and the output of the fuzzy logic and the fuzzy rules are shown in Fig. 5:



1. „If input is very small, then output is very small",
2. „if input is small, then output is small",
3. „if input is middle, then output is middle",
4. „if input is big, then output is big" and
5. „if input is very big, then output is very big".

Fig. 5: Membership functions and fuzzy rules

To present the corresponding fuzzification and defuzzification, $\dot{\chi} = 35°/s$ as input is selected. Fig. 6 shows the result. Applying the aggregation method and furthermore the centroid defuzzification, the single output is obtained: $\dot{\varphi}_{x,Threshold} = 22°/s$.

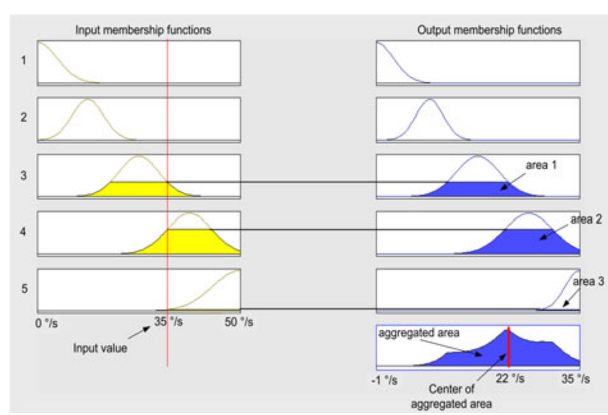


Fig. 6: Example of the principle of the fuzzy logic

Applying this fuzzy logic, satisfying results concerning an adaptive fault threshold are delivered, as simulation results using a virtual vehicle present in the next chapter.

4 Car tests using a virtual vehicle

For the car tests a simulation environment is defined for both simulating the vehicle motions on different roads and implementing the sensor monitoring algorithm. This simulation environment consists of the software MATLAB and the professional vehicle simulation software CARSIM [14]. In other words, CARSIM is a virtual vehicle, based on complex models involving thousands of calculations and tens of degrees of freedom, that can be used for car tests. In CARSIM, different driving maneuvers, types of vehicles and any kinds of driving environments can be defined and combined with each other. During the simulation, data exchange between MATLAB and CARSIM is carried out.

In this chapter simulation results of four different driving maneuvers are presented. These are:

1. A double lane change maneuver with a velocity of 50km/h on dry asphalt (μ = 0.85) and a simulated stepwise roll rate sensor fault of 8°/s at t = 5.3s,
2. a drive into a lateral inclined curve of 20° and 100m radius with a velocity of 80km/h on dry asphalt (μ = 0.85) and a simulated stepwise roll rate sensor fault of 8°/s at t = 10.0s,
3. a double lane change maneuver with a velocity of 60km/h on a road with μ = 0.3 and
4. a double lane change maneuver with a velocity of 50km/h on dry asphalt (μ = 0.85) and a simulated stepwise yaw rate sensor fault of 10°/s at t = 4.0s.

In each of the following figures the first diagram shows the lateral accelerometer signal, the second the yaw rate sensor signal, the third the roll rate sensor signal and the estimated roll rate, the fourth the roll rate residual and the adaptive threshold, and the fifth the sensor fault message and the model availability. If a fault is detected, the fault message signal is logic 1, otherwise it is logic 0. The model availability signal is logic 1 in case of availability, otherwise logic 0.

The result of the double lane change maneuver, shown in Fig. 7, indicates, that the functionality of generating the adaptive threshold works satisfactorily, since this threshold is raised and reduced almost parallel to the roll rate residual until t = 5.3s. After that, the fault is signalized by the fault message which changes its value from logic 0 to logic 1, since the adaptive threshold is crossed by the roll rate residual at t = 5.3s.

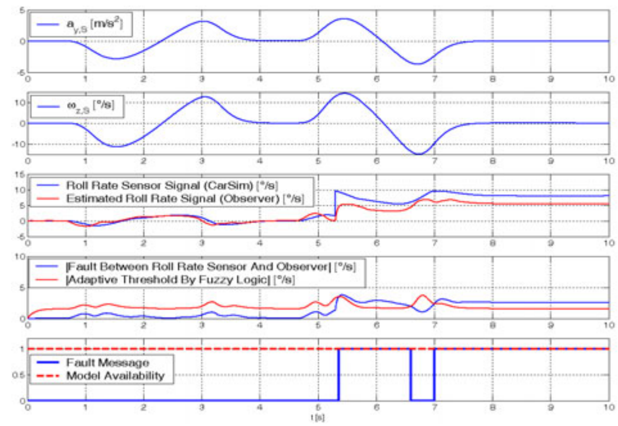


Fig. 7: Double lane change maneuver (μ = 0.85)

In Fig. 8 the result of the drive into a lateral inclined curve is presented. Also here it is signalized by the fault message immediately, that the simulated roll rate sensor fault is detected, since the adaptive threshold is crossed by the roll rate residual at t = 10.0s.

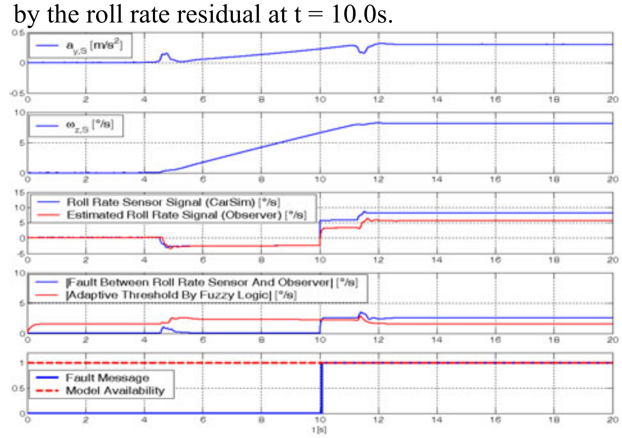


Fig. 8: Drive into a curve with lateral inclination

Fig. 9 presents, that the monitoring strategy also works on roads with low friction. In the forth diagram it can be seen, that the threshold is crossed by the residual in the interval from 6.5s to 9.0s and in the interval from 11.0s to 12.0s. But due to the decision of the model availability, the monitoring is switched off in these intervals, which are signalized by the red, dashed line in the fifth diagram, so that a false message is avoided.

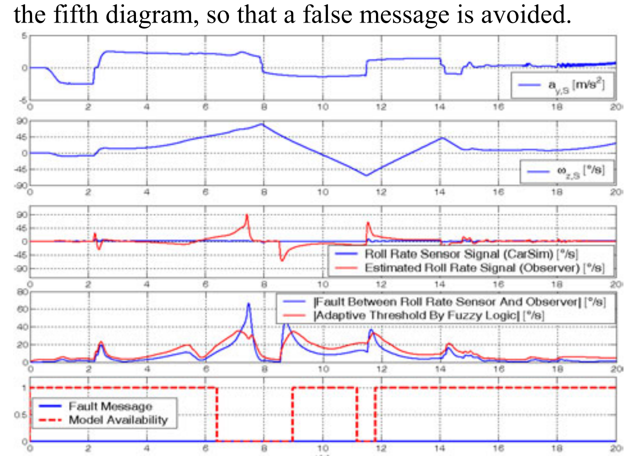


Fig. 9: Double lane change maneuver (μ = 0.3)

In Fig. 10 the simulation result of the double lane change maneuver with the simulated yaw rate sensor fault is shown. Also by this example the functionality concerning the decision of the model availability is presented. At the time, when the yaw rate sensor fault occurs, the threshold is crossed by the residual. But, the monitoring is switched off immediately by the decision of the model availability, so that a false message about the roll rate sensor fault can be avoided. One can see, that thanks to the performance of the model availability, a localization of the roll rate sensor fault can be realized.

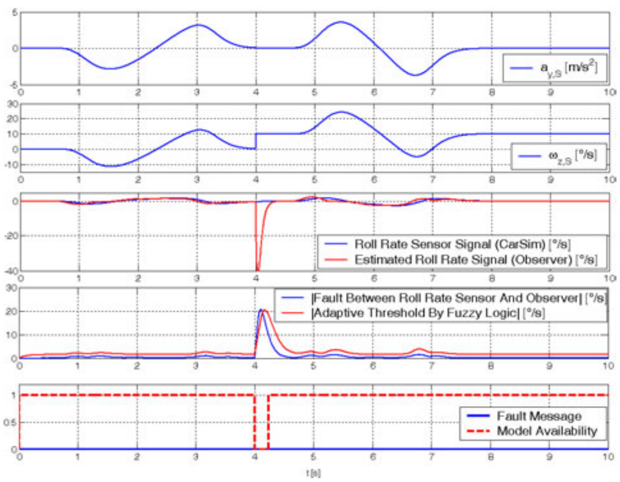


Fig. 10: Double lane change maneuver (μ = 0.85)

5 Conclusion

In this paper a possibility for monitoring the roll rate sensor is presented. According to the physical law of the vehicle roll motion, a state space model is derived, on which a linear observer is designed. In addition to the observer design, a concept for detecting sensor faults, that consists of start conditions of the monitoring and of generating an adaptive fault threshold with the help of fuzzy logic, is developed. The reason for having chosen the fuzzy logic firstly is, that this technique allows generating a smooth adaptive threshold and secondly, that the implementation expenditure is relative low.

The concept is tested in the virtual vehicle CARSIM. The tests show, that the concept produces very good results for monitoring the roll rate sensor. Using this concept the monitoring is turned-off automatically in case of model unavailability, so that false messages about a sensor fault are avoided. Thanks to the adaptive threshold, even small sensor faults can be detected quickly. Since the concept is now proved in a simulation environment, the next step is to check the concept in real cars. In order to complete the field of roll rate sensor monitoring, a strategy for a reliable evaluation of the detected faults has to be worked out in the further research and development.

6 Acknowledgement

The authors would like to acknowledge the support of The Ministry for School, Science and Research NRW in Germany.

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