

Sensor and Actuator Fault Detection in Connected Vehicles under a Packet Dropping Network

Z. Abdollahi Biron, P. Pisu

Abstract—Connected vehicles are one of the promising technologies for future Intelligent Transportation Systems (ITS). A connected vehicle system is essentially a set of vehicles communicating through a network to exchange their information with each other and the infrastructure. Although this interconnection of the vehicles can be potentially beneficial in creating an efficient, sustainable, and green transportation system, a set of safety and reliability challenges come out with this technology. The first challenge arises from the information loss due to unreliable communication network which affects the control/management system of the individual vehicles and the overall system. Such scenario may lead to degraded or even unsafe operation which could be potentially catastrophic. Secondly, faulty sensors and actuators can affect the individual vehicle's safe operation and in turn will create a potentially unsafe node in the vehicular network. Further, sending that faulty sensor information to other vehicles and failure in actuators may significantly affect the safe operation of the overall vehicular network. Therefore, it is of utmost importance to take these issues into consideration while designing the control/management algorithms of the individual vehicles as a part of connected vehicle system. In this paper, we consider a connected vehicle system under Co-operative Adaptive Cruise Control (CACC) and propose a fault diagnosis scheme that deals with these aforementioned challenges. Specifically, the conventional CACC algorithm is modified by adding a Kalman filter-based estimation algorithm to suppress the effect of lost information under unreliable network. Further, a sliding mode observer-based algorithm is used to improve the sensor reliability under faults. The effectiveness of the overall diagnostic scheme is verified via simulation studies.

Keywords—Fault diagnostics, communication network, connected vehicles, packet drop out, platoon.

I. INTRODUCTION

IN recent years, wireless technologies are becoming ubiquitous in several engineering applications and transportation system is not an exception to this. Vehicular electronics systems are continuing to become more complex every day. Nowadays, modern vehicles contain more than 70 Electronic Control Units (ECUs) to manipulate and control the vehicle in real time. All these controller units communicate with sensors and actuators via Controller Area Network (CAN) bus. In addition to in-vehicle network, smart vehicles have wireless gateways to connect and communicate with external world [1]. The opportunity of vehicle to vehicle and vehicle to infrastructure communication develops the concept of connectivity in ITS which can potentially improve the safety, efficiency, and effectiveness of the overall system [2].

Z. B. and P.P are with the Clemson University International Center of Automotive Research, Greenville, SC 29607 USA (e-mail: zabdoll@clemson.edu, pisup@clemson.edu).

Although vehicle control systems are becoming information-rich, physical failures in sensors and actuators introduce challenges in control strategy as well as wireless networks to transmit/receive. Similar to any Networked Controller System (NCS), the controller algorithm relies on two categories of information: I) physical system information depends on, on-board sensors and actuators. II) External data received from other systems through communication network. Hence, first challenge arises from failures in sensors and actuators, whereas the second one emerges due to data loss in the communication. Therefore, there is a crucial need to design these control/management systems taking such faulty sensors and unreliable network communication into consideration and maintain the safety and performance of the system. In this paper, we explore a physical sensor/actuator fault diagnosis problem along with unreliable wireless network in connected vehicles.

Several studies exist on analyzing data over unreliable network. In [3], the problem of channel modeling of packet drops out for unmanned aerial vehicle (UAV) communication is discussed and a two-state Markov model is proposed. In [4], authors consider problem of Kalman filtering with intermitted observations when sensor data travel along unreliable communication channels in a large wireless network. To explore this, the packet drops out as a typical failure in networks is modeled with binary random variables and the statistical convergence properties of the estimation error is analyzed under network with packet drop out. There are some studies on modeling the packet drop out in vehicular network and stability analyzes of a vehicle platoon over faulty network communication [5], [6]. In [7], a platoon of vehicles equipped to CACC is studied under unreliable communication network. The preceding vehicle's information is estimated using the onboard sensors measurement in order to improve the performance of the platoon. However, the proposed estimation approach is based on derivative of velocity of the vehicle to find the acceleration which may not be reliable under noisy sensor measurement.

Although there are some investigations on modeling, system stability and parameter estimation under lossy communication network, fault diagnostics of connected vehicles over unreliable network is an underexplored topic. In one of the existing studies, Meskin and Khosravani studied the problem of fault detection and isolation in a network of UAVs when imperfect communication channels exist among the vehicles [8]. The diagnostic scheme is a centralized scheme to detect which vehicle has faulty actuator in the network. In [9], a network of unmanned vehicles is considered, and the

cooperative fault accommodation in formation flight of unmanned vehicles is investigated through a hierarchical framework. Among few studies on fault diagnostics in networked control systems under unreliable communication, the robustness of the controller in presence of both physical failure and unreliability of the network. The connected vehicles are not exception for this research gap. The issue of insecure communication in connected vehicles control can be more critical comparing to other networked control systems.

In this paper, we extend current researches by exploring the problem of network failure as well as on-board sensor fault for a specific connected vehicle system, namely a homogeneous platoon of vehicles under CACC. The aim of this paper is to modify the existing CACC strategy to be more robust to packet drop out in the network communication and capable to diagnose the faults in sensors and actuators.

The rest of paper is organized as follows: platoon modeling and problem statement are described in Section II. Section III contains modifying strategy of CACC. Diagnostics scheme to detect and isolate the physical faults and failures in connected vehicles is explained in Section IV. The simulation results and discussions are described in Section V. Finally, in Section VI, we state our conclusion.

II. MODELING AND PROBLEM STATEMENT

CACC is essentially a vehicle- following control system that automatically accelerates and decelerates the vehicle to keep a desired distance to the preceding vehicle [10]. The use of CACC control strategy, especially in heavy duty vehicles, can cause lower traffic flow in roads. To achieve this task, onboard sensors such as radar are employed that measures relative distance and velocity between vehicles. Further, additional information of preceding vehicle(s), such as the desired acceleration is received through the wireless communication network.

In the current existing Adaptive Cruise Control (ACC) system, the range (i.e., relative distance) and range rate to the preceding vehicle are measured with a radar or LIDAR sensor [11]. Moreover, CACC is essentially a vehicle-following control methodology that automatically accelerates and decelerates so as to keep a desired distance to the preceding vehicle [12]. To do this, in addition to onboard sensors like radars, vehicles should be equipped with wireless communication devices, such as Dedicated Short-Range Communication (DSRC), to receive extra information of the preceding vehicle(s). For example, the desired acceleration is received through a wireless communication link. A platoon of vehicles equipped with CACC is considered in this paper, see Fig. 1. Unlike most of the existing literature in vehicle platooning that consider constant velocity profiles, here the leader follows driving cycle velocity profile which is a time-varying velocity reference. Each vehicle in the platoon measures range and range rate regarding to its preceding vehicle using on board radar and receives preceding vehicle's desired acceleration through the DSRC network.



Fig. 1 A platoon of vehicles

A. Vehicle Dynamics

Following similar notation of [7], a nonlinear model has been considered for each vehicle in the platoon as shown in (1):

$$\begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} = \begin{bmatrix} v_{i-1} - v_i \\ a_i \\ -\frac{1}{\tau} a_i + \frac{1}{\tau} u_i \end{bmatrix}, i = S_m \setminus \{1\} \quad (1)$$

where S_m stands for set of all vehicles in the platoon of length of m . $d_i = q_{i-1} - q_i - L_i$ is the distance between vehicle i and $i-1$, where q_i and q_{i-1} are the rear bumper position of vehicle i and $i-1$, respectively, and L_i is the length of vehicle i , v_i is the velocity, and a_i is the acceleration of vehicle i . Moreover, u_i is the vehicle input, to be interpreted as desired acceleration, and τ is the time constant representing the driveline dynamics. Also, the following control policy for the inter-vehicle spacing is adopted:

$$d_{r,i}(t) = h v_i(t), \quad i \in S_m \setminus \{1\} \quad (2)$$

where $d_{r,i}$ is the desired distance between vehicle i and $i-1$, h is the time headway. The main objective is to regulate the d_i to $d_{r,i(t)}$, i.e.,

$$e_i(t) = d_i(t) - d_{r,i}(t) \rightarrow 0 \text{ as } t \rightarrow \infty \quad (3)$$

without losing the generality, we consider $L_i = 0$ for simplicity. Substituting the equation $d_i = q_{i-1} - q_i - L_i$ in (3), the regulating error can be re-written as:

$$e_i(t) = q_{i-1}(t) - q_i(t) - h v_i(t) \quad (4)$$

The following dynamic controller is considered to achieve the zero regulation error:

$$\dot{u}_i = -\frac{1}{h} u_i + \frac{1}{h} (k_p e_i + k_d \dot{e}_i) + \frac{1}{h} u_{i-1} \quad (5)$$

where u_{i-1} is the desired acceleration for the preceding vehicle. This information is communicated through the DSRC

network, hence, it is subject to packet drop failure in the network. k_p and k_d are the controller coefficients. Furthermore, it is shown that for a bounded u_{i-1} and subject to following constraints on the controller gains: $k_p, k_p > 0$, the inter-vehicle distance d_i is regulated to $d_{i,r}$ as defined by spacing policy (2) [8].

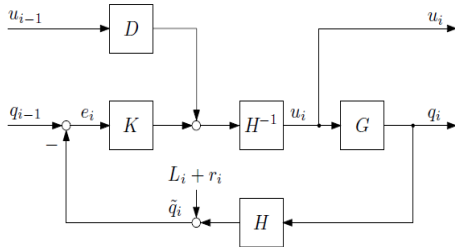


Fig. 2 Block scheme of the CACC system

The block diagram of the closed-loop system for vehicle i , subject to the controller is shown in Fig. 2 with

$$\begin{aligned} G(s) &= \frac{q_i(s)}{u_i(s)} = \frac{1}{s^2(\tau s + 1)} \\ H(s) &= hs + 1 \\ K(s) &= k_p + k_d s \\ D(s) &= e^{-\theta s} \end{aligned} \quad (6)$$

B. Packet Drop

In presence of packet drop out in the network, the model presented in (1) can be rewritten as:

$$\begin{aligned} \dot{u}_i &= -\frac{1}{h}u_i + \frac{1}{h}(k_p e_i + k_d \dot{e}_i) + \frac{1}{h} \times \chi(k) \times u_{i-1} \\ \chi(k) &\in \{0, 1\} \\ \begin{cases} p(\chi(k) = 0) = \lambda \\ p(\chi(k) = 1) = 1 - \lambda \end{cases} \\ k \times T_s &\leq t < (k+1) \times T_s \end{aligned} \quad (7)$$

where $\chi(k)$ shows the packet drop out modeling in the network. T_s is sampling time for the network. During each sample time interval, the value of received data will be hold. We define the arrival of the observation as a binary random variable with probability distribution λ . With probability of λ , the transmitting packet through the network will be lost and the vehicle receives zero as the preceding vehicle's desired acceleration. Consequently, with probability of $1 - \lambda$, the vehicle will be received correct transmitted data through the network.

C. Sensor and Actuator Fault

In this study, two faults on velocity sensor and acceleration pedal actuator are considered for each vehicle in the platoon.

Therefore, the dynamics of each vehicle in presence of faults will be:

$$\begin{aligned} \begin{bmatrix} \dot{d}_i \\ \dot{v}_i \\ \dot{a}_i \end{bmatrix} &= \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} d_{im} \\ v_{im} \\ a_{i-act} \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix} u_i \quad (8) \\ &, i = S_n \setminus \{1, 2\} \end{aligned}$$

where d_{im} and v_{im} are the measured relative distance and velocity respectively. a_{i-act} is actual acceleration acted in vehicle i .

III. MODIFIED CACC

In order to make the control strategy to packet loss, a Kalman filter is used to estimate the correct control input even in presence of packet drop out in communication network.

In this part, we modify the existing CACC strategy in [7], by adding the extra information received from two preceding vehicles instead of just one preceding vehicle. This is a common assumption in platooning system to refrain from collision avoidance or sending warning messages through the platoon [7]. However, this extra information is not helpful since it may subject to packet drop. Therefore, a Kalman filter is designed to filter the receiving data needed for CACC strategy.

To modify the existing CACC strategy in [7], the assumption of receiving information from two preceding vehicles has been considered. This is a common assumption in platooning system to prevent collision avoidance or sending warning messages through the platoon [7]. Therefore, in addition to receiving u_{i-1} from vehicle $i-1$, vehicle i receives q_{i-2} as the position of the vehicle $i-2$ and u_{i-2} as the desired acceleration of the vehicle $i-2$. Since both q_{i-2} and u_{i-2} are transmitted with the same DSRC network, this information also is subjected to packet drop out. Therefore, the dynamic of desired acceleration of the vehicle $i-1$ can be written as:

$$\dot{u}_{i-1} = -\frac{1}{h}u_{i-1} + \frac{1}{h}(k_p e_{i-1} + k_d \dot{e}_{i-1}) + \frac{1}{h} \chi(k) u_{i-2} \quad (9)$$

where,

$$e_{i-1}(t) = q_{i-2}(t) - q_{i-1}(t) - hv_{i-1}(t) \quad (10)$$

Note that, vehicle i has measurement of $q_{i-1}(t)$ and $v_{i-1}(t)$ using its own information and the on-board range and range sensors data.

To improve the performance of each vehicle under unreliable network communication, a Kalman filter observer is

designed in vehicle i to estimate the correct value of u_{i-1} . Since the receiving value of u_{i-2} and q_{i-2} in vehicle i can be zero at some instants due to packet drop out, a sample holding strategy is considered where the previous data can be used and hold for another sample time interval. Therefore, q_{i-2} which is used in Kalman filter observer designed in vehicle i to estimate the u_{i-1} will be as:

$$\hat{q}_{i-2}(t) = \begin{cases} q_{i-2}((k-1)T_s) & \text{if } \chi(k) = 0 \\ q_{i-2}(kT_s) & \text{if } \chi(k) = 1 \end{cases} \quad (11)$$

for $kT_s \leq t < (k+1)T_s$,

where \hat{q}_{i-2} is the modified receiving q_{i-2} data in vehicle i after transmission through the unreliable network. Similarly, \hat{u}_{i-2} is the modified receiving u_{i-2} data in vehicle i after transmission through the unreliable network.

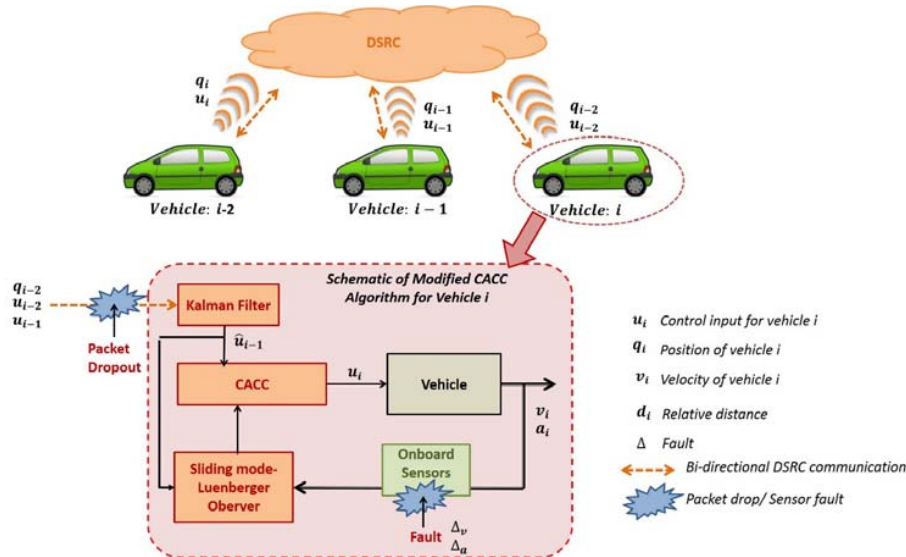


Fig. 3 Modified CACC scheme for each vehicle in the platoon

Using these assumptions, the estimation of the preceding vehicle's desired acceleration in vehicle i can be achieved with the following Kalman filter:

$$\begin{aligned} \dot{\hat{u}}_{i-1} = & -\frac{1}{h}\hat{u}_{i-1} + \frac{1}{h}(k_p\hat{e}_{i-1} + k_d\dot{\hat{e}}_{i-1}) \\ & + \frac{1}{h}\hat{u}_{i-2} + L_K(u_{i-1} - \hat{u}_{i-1}) \end{aligned} \quad (12)$$

where L_K is the Kalman gain. Therefore, the estimation error dynamic will be:

$$\begin{aligned} \dot{\tilde{u}}_{i-1} = & -\frac{1}{h}\tilde{u}_{i-1} - L_K\tilde{u}_{i-1} + \Delta u_{i-1,PD} \\ \tilde{u}_{i-1} = & u_{i-1} - \hat{u}_{i-1} \end{aligned} \quad (13)$$

where $\Delta u_{i-1,PD}$ represents lumped effect of packet drop out in using the holding previous value strategy. In the Kalman filter design, $\Delta u_{i-1,PD}$ can be considered as process noise which can potentially be suppressed by tuning the error covariance matrices. Therefore, the control input u_i , can be modified during packet drop out in communication network and the performance of vehicle in a platoon will be improved using modified CACC strategy comparing to CACC.

IV. DIAGNOSTICS SCHEME

Physical part of any Cyber Physical System (CPS) such connected vehicles, is vulnerable to physical failures containing sensor and actuator faults. Since, these failures as transmitted data to cyber part of connected vehicles affect the performance of controller, it is crucial to diagnose these faults in their occurrence time.

In this section, the output of the modified CACC, u_i , is considered as the control signal to the plant. Therefore, two observers using Luenberger and sliding mode approaches are designed and implemented in controller of each car, to detect and isolate actuator and sensor faults in each car. In this investigation, according to CACC platooning configuration as discussed in system modeling section, two on-board sensors are relative distance and velocity sensors and the actuator is accelerator pedal in the car.

The detail of this scheme is discussed in the following.

According to (1)-(3) and modified CACC control input with similar dynamic in (5), dynamic model of each car in the platoon in equipped with the modified CACC strategy can be rewritten as:

$$\begin{bmatrix} \dot{\hat{d}}_i \\ \dot{\hat{v}}_i \\ \dot{\hat{a}}_i \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} d_i \\ v_i \\ a_i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix} \hat{u}_i \quad (14)$$

$, i = S_m \setminus \{1, 2\}$

where \hat{u}_i is the estimated desired acceleration for vehicle i by using the estimated desired acceleration for preceding vehicle \hat{u}_{i-1} in the proposed modified CACC.

In presence of fault in velocity sensor measurement,

$$v_{im} = v_i + \Delta v_i \quad (15)$$

Similarly, actuator real value would be,

$$a_{i-act} = a_i + \Delta a_i \quad (16)$$

where v_{im} is the measured velocity, and Δv_i represents the sensor faults. Also, a_{i-act} is actual acceleration acted in vehicle and Δa_i is the actuator fault. The observer structure is chosen as:

$$\begin{bmatrix} \dot{\hat{d}}_i \\ \dot{\hat{v}}_i \\ \dot{\hat{a}}_i \end{bmatrix} = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix} \begin{bmatrix} d_i \\ v_i \\ a_i \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} v_{i-1} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{\tau} \end{bmatrix} \hat{u}_i \quad (17)$$

$, i = S_m \setminus \{1, 2\}$

$$+ \begin{bmatrix} L_{11} & L_{12} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} (d_{im} - \hat{d}_i) \\ (v_{im} - \hat{v}_i) \end{bmatrix} + \begin{bmatrix} 0 \\ \eta_{22} \text{sgn}(v_{im} - \hat{v}_i) \\ 0 \end{bmatrix}$$

Defining the

$$\tilde{d}_i = d_i - \hat{d}_i, \tilde{v}_i = v_i - \hat{v}_i, \tilde{a}_i = a_i - \hat{a}_i \quad (18)$$

Choosing $L_{11} < 0, L_{12} = -1$, the error dynamics can be written as:

$$\begin{bmatrix} \dot{\tilde{d}}_i \\ \dot{\tilde{v}}_i \\ \dot{\tilde{a}}_i \end{bmatrix} = \begin{bmatrix} -L_{11} \tilde{d}_i + \Delta v_i \\ \Delta a_i - \eta_{22} \text{sgn}(v_{im} - \hat{v}_i) \\ -\frac{1}{\tau} (\tilde{a}_i + \Delta a_i) \end{bmatrix} \quad (19)$$

under condition of no fault in the system, $\tilde{d}_i \rightarrow 0$ and $\tilde{a}_i \rightarrow 0$ as $t \rightarrow \infty$, due to their first order stable dynamics.

The sliding surface (which is defined by the terms inside 'sign') is $S_v = v_{im} - \hat{v}_i$. The convergence to the first sliding surface can be analyzed by using the Lyapunov function candidate. $V_v = 0.5S_v^2$. The derivative of the Lyapunov function candidate can be written as:

$$\dot{V}_v = S_v \dot{S}_v = S_v (\dot{v}_{im} - \dot{\hat{v}}_i)$$

In no fault condition,

$$v_{im} = v_i$$

$$v_{im} - \hat{v}_i = v_i - \hat{v}_i = \tilde{v}_i$$

$$\Rightarrow \dot{V}_v = S_v (-\eta_{22} \text{sgn}(S_v))$$

$$\Rightarrow \dot{V}_v \leq |S_v| (-\eta_{22}) \quad (20)$$

Since the derivative of Lyapunov candidate is negative definite, the stability condition of sliding surface and error convergence to zero is proved.

Two residuals R_{i1} and \dot{R}_{2i} are defined for each car, using estimated states and the measured variables as:

$$R_{i1} = d_{im} - \hat{d}_i \quad (21)$$

$$\dot{R}_{2i} = \theta_v$$

θ_v is the filtered version of the switching term $\eta_{22} \text{sgn}(S_v)$ [13]. Next, we analyze the error dynamics under separate fault conditions:

Case 1. ($\Delta a_i = 0, \Delta v_i \neq 0$):

Since there is no fault on range sensor measurement, d_{im} , from the error dynamic it can be inferred that, the fault in velocity sensor will show up in both residuals.

The sliding surface (which is defined by the terms inside 'sign') will be $S_v = \tilde{v}_i + \Delta v_i$. The convergence to the first sliding surface can be analyzed using the Lyapunov function candidate. $V_v = 0.5S_v^2$. The derivative of the Lyapunov function candidate can be written as:

$$\dot{V}_v = S_v \dot{S}_v = S_v (\dot{\tilde{v}}_i + \Delta \dot{v}_i)$$

$$\Rightarrow \dot{V}_v = S_v (\Delta a_i - \eta_{22} \text{sgn}(S_v) + \Delta \dot{v}_i) \quad (22)$$

$$\Rightarrow \dot{V}_v \leq |S_v| (|\Delta \dot{v}_i + \Delta a_i| - \eta_{22})$$

Therefore, under the assumption of bounded $\Delta \dot{v}_i$, Δa_i and a choice of sufficiently high positive gain η_{22} , the sliding surface $S_v = 0$ can be reached. Now, on the sliding surface, we have $S_v = \dot{S}_v = 0$ [12]. Therefore, based on the error dynamics equation and the aforementioned conditions, we can write that:

$$\Delta \dot{v}_i + \Delta a_i = \theta_v \quad (23)$$

where θ_v is the equivalent output error injection which is the filtered version of the switching term $\eta_{22} \text{sgn}(S_v)$ [12]. Note that, the input signal θ_v to the above filter care available by passing the term $\eta_{22} \text{sgn}(S_v)$ through a low pass filter.

Case 2. ($\Delta a_i \neq 0, \Delta v_i = 0$)

Fault in actuator which is failure in acceleration pedal, makes the estimation error nonzero in (19). As it can be, the fault will show up in second residual corresponding to velocity dynamic.

Based on the above analysis, the following fault signature table can be constructed. Note that, in case of Δv_i fault, we have $R_{1i} \neq 0, \theta_v \neq 0$ and hence $R_{1i} \neq 0, R_{2i} \neq 0$. In case of Δa_i fault, we have $R_{1i} = 0, \theta_v \neq 0$ and hence $R_{1i} = 0, R_{2i} \neq 0$.

TABLE I
FAULT SIGNATURE TABLE

Residual	Velocity sensor fault	Accelerator actuator fault
R_{1i}	1	0
R_{2i}	1	1

V. SIMULATION RESULTS

To evaluate the analysis done in previous section, a platoon of four vehicles equipped with CACC is considered. The relative distance between two vehicles is considered as criteria of the performance of the platoon, Fig. 4, shows the performance of vehicle 3 in the platoon regarding of different packet drop out probabilities in the communication network. As it can be inferred from Fig. 4, higher probability in packet loss, causes to more accident, zero relative distance, between two vehicles. It is worth mentioning that, unlike several researches done on cooperating vehicles, the leader does not have constant velocity. Indeed, in this study, the leader of the platoon follows US06 driving cycle.

For this case study, we consider the probability of packet drop out $\lambda = 0.2$, hence, the probability of receiving correct data from the preceding vehicle in each vehicle is 80%, and with 20% the sending data will be lost. To discuss about the effect of network failure in each vehicle's performance, d_3 relative distance between vehicle 3 and its preceding vehicle (vehicle 2) has been selected as an example. Fig. 5 shows the performance of vehicle 3 in presence of drop out $\lambda = 0.2$. Solid blue line is the relative distance between vehicle 2 and vehicle 3 when the conventional CACC is implemented in vehicle 3. As it can be inferred in this case, at least 3 accidents are happening during the whole US06 driving cycle time. On the other hand, solid red line shows the same relative distance when the modified CACC is considered in vehicle 3. In this case, no accident happens for the same driving cycle.

Under assumption of using modified CACC which shows better performance in presence of packet drop out, the fault diagnostic procedure can be run in each vehicle in the platoon.

To evaluate the fault diagnostics, in vehicle 3, an average 10% velocity sensor fault occurs at $t=450$ sec and remains in the system. Also, an acceleration pedal failure as actuator fault, happens at $t= 200$ sec and remains for 50 seconds with amplitude of 5%. To make the simulation results close to real case scenarios, a white Gaussian noise is added as measurement noise to on-board sensor data. Using the fault diagnostic scheme implemented in vehicle 3, both faults can

be detected and isolated regarding to their signatures in residuals. Fig. 6 shows two residuals driven from the designed observers in the system. As it can be inferred, fault in velocity sensor makes both residuals non-zero. Consequently, both thresholds corresponding to these residuals are triggered while fault occurs in velocity sensor. Similarly, when fault happens in actuator due to the analysis mentioned in previous section, it will not show up in first residual, while it triggers the second residual's threshold.

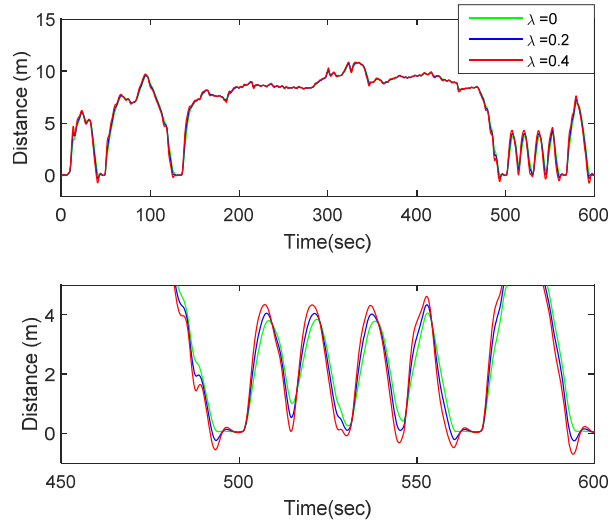


Fig. 4 Relative distance between vehicle 3 and vehicle 2, d_3 in different probability of packet drop out in communication network

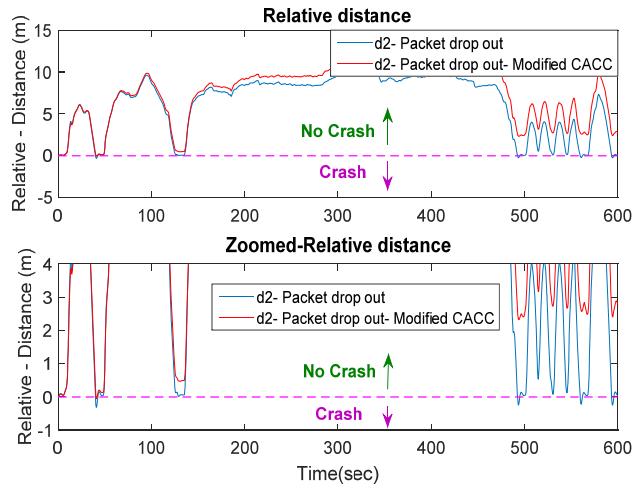


Fig. 5 Relative distance between vehicle 2 and vehicle 3, in faulty network with probability of packet drop $\lambda = 0.2$

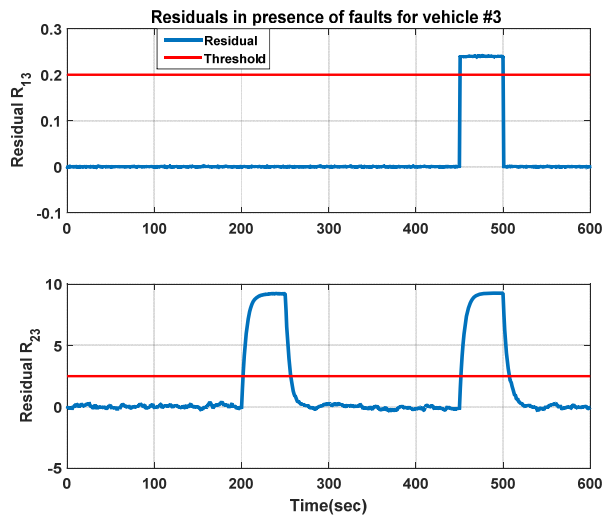


Fig. 6 Residuals in vehicle 3 in presence of velocity sensor fault and acceleration fault

VI. CONCLUSION

In this paper, a sensor/actuator fault diagnosis problem along with packet drop out phenomenon in communication network is explored for a connected vehicle system under CACC. The diagnostic scheme is designed by taking the unreliable communication network in connected vehicles into consideration. To suppress the effect of information loss in the network, a Kalman filter-based estimation scheme is used. The filter provides an improved estimate of the information received via network which is in turn used by the CACC controller to construct the control signal. Further, a sliding mode observer-based diagnostic scheme is used to detect, isolate, and estimate different sensor and actuator faults in the individual vehicles. The CACC controller uses this estimated fault information to reconstruct the control signal. Therefore, inclusion of the filter and the observer essentially supplies the controller with more accurate information which improves the overall safety of the connected vehicles. Simulation studies are presented which confirms the effectiveness of the overall scheme.

ACKNOWLEDGMENT

This research is based upon work supported by the National Science Foundation (NSF) under grant No. 1544910. Any opinions, findings and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

- [1] U. E. Larson, and D. K. Nilsson, "Securing Vehicles against Cyber Attacks", CSIIRW'08 Proceedings of the 4th annual workshop on Cyber security and information intelligence research, pp.1-3, 2008.
- [2] T. L. Willke, P. Tientrakool, and N. F. Maxemchuk, "A Survey of Inter-Vehicle Communication Protocols and Their Applications", IEEE Communications Surveys and Tutorials, vol. 11, no. 2, Second Quarter 2009, pp:3-20.

- [3] Y. Zhou, J. Li, L. Lamont and C.A. Rabbath " Modeling of Packet Dropout for UAV Wireless Communications", International Conference on Computing, Networking and Communications Invited Position Paper Track, 2012, pp. 667-682.
- [4] B. Sinopoli, L. Schenato, M. Franceschetti, K. Poolla, M. I. Jodan and S. Sastry, " Kalman Filtering with Intermittent Observations", IEEE Transactions on Automatic Control, Vol. 49, No. 9, Sep 2004. Pp. 1453-1464.
- [5] J. Ploeg, N. Wouw, and H. Nijmeijer, "Lp string stability of cascaded systems: Application to vehicle platooning," IEEE Trans. Control Syst. Technol., 2013, accepted.
- [6] J. Ploeg, B. T. M. Scheepers, E. Nunen, N. Wouw, and H. Nijmeijer, "Design and experimental evaluation of cooperative adaptive cruise control," in Proc. 14th Int. IEEE Conf. Intell. Transp. Syst., Washington D.C., USA, Oct. 5-7 2011, pp. 260-265.
- [7] J. Ploeg, E. Semsar-Kazerouni, G. Lijster, N. Wouw, and H. Nijmeijer, "Graceful Degradation of CACC Performance Subject to Unreliable Wireless Communication", Proceedings of the 16th International IEEE Annual Conference on Intelligent Transportation Systems (ITSC 2013), The Hague, The Netherlands, October 6-9, 2013.
- [8] N. Meskin, K. Khosravani, and C. A. Rabbath, "Fault Diagnosis in a Network of Unmanned Aerial Vehicles with Imperfect Communication Channels", AIAA Guidance, Navigation, and Control Conference, August 2009, pp: 1-18.
- [9] S.M. Azizi, and K. Khorasani, "Cooperative actuator fault accommodation in formation flight of unmanned vehicles using relative measurements", International Journal of Control, Vol. 84, No. 5, 2011, pp: 876-894.
- [10] D. Cody, F. Bu, S. Dickey, D. Nelson, J. Spring, C. Nowakowski, and S. Shladover, " Effects of Cooperative Adaptive Cruise Control on Traffic Flow: Testing Drivers' Choices of Following Distances", California Path Program Institute of Transportation Studies University of California, Berkeley, 2008.
- [11] F. Bu, H. Tan, and J. Huang, "Design and field testing of a cooperative adaptive cruise control system", 2010 American Control Conference, pp: 4416-4421, 2010.
- [12] R. Rajamani, and C. Zhu " Semi-autonomous adaptive cruise control systems", IEEE Transaction Vehicle Technology, vol. 51, no. 5, pp: 186-1192. Sep. 2002.
- [13] V. Utkin, J. Guldner, and J. Shi, Sliding mode control in electromechanical systems. CRC press, 1999.