Automotive Electronic Control Unit Ground Line Health Monitoring Method

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ABSTRACT

Electronic Control Units (ECUs) have been used in the automotive industry for decades to control one or more of the vehicle subsystems. The ECUs communicate primarily using the in-vehicle Controller Area Network (CAN) communication protocol. The recent rapid development of connected, electric, and autonomous vehicles expands the number of ECUs and complexity of the CAN network required to integrate vehicle systems and deliver the desired functionalities. This demands increased reliability of the ECUs to ensure robust vehicle performance. One of the most common ECU failure modes is an ECU ground fault. A ground fault occurs when the ground path from the ECU circuit to the vehicle chassis is corroded, which usually develops slowly over time. Such a failure usually results in various symptoms including ECUs incapable of functioning and further impacts the vehicle functionalities negatively. This type of fault is difficult to detect prior to vehicle functionality loss. Common methods include routinely testing the resistance of the ground circuit, visually inspecting the connectors and wirings, and checking the voltage drop across the ground circuit. Therefore, it is highly desirable to continuously monitor the ECU ground line health status to predict any degradation and thus prevent vehicle functionality losses.

This paper presents a novel method to monitor the health status of the ECU ground line. The method leverages measured CAN voltage data to estimate the ECU ground state of health. The CAN voltage measurements are preprocessed and fed into a real-time data buffer of predefined size. Statistical moments are calculated from the buffered data to generate health indicators, which are then combined to form a fused health indicator. The fused health indicator is used to determine the health stage of ECU ground line. The health stage is classified based on the relationship between ground line degradation level and the ECU communication loss status. The method was developed and validated using actual vehicle data.

1. INTRODUCTION

In an Electronic Control Unit (ECU), the ground line is an essential component to ensure proper operation and reliable communication. The ground line serves as a reference point for electrical signals within an ECU; so, that all components share a common voltage reference, i.e., the same electrical potential. This is crucial for maintaining accurate and reliable communication between various components within the system.

In the context of CAN communication, which is widely used in automotive applications, the ground line plays a critical role. In a CAN bus network, multiple ECUs and other devices are interconnected, and they rely on a shared ground line to establish a common reference point for signal voltages. This ensures that the transmitted signals are interpreted correctly by all devices on the network (ISO11898-2, 2016). The increasing demands from customers for new features have resulted in a significant rise in the number of ECUs present in vehicles.

The ECU ground failure is one of the most common failure types as the ground line of ECUs is commonly exposed to harsh environmental conditions. The ECU ground failure can be represented, for example, as corrosion of the ECU ground line. Ground line corrosion may develop over time and is difficult to detect prior to the loss of functionality. This requires robust diagnostics and prognostics for ECU failures (Du, Jiang, Nagose, Zhang, & Wienckowski, 2016) (Robertson, 2014) (Du, Jiang, Zhou, Bani Milhim, & Sadjadi, 2023). As a result, it is desirable to detect ground line degradation of ECUs prior to communication loss in addition to estimate remaining useful life of the ECU ground line.

Ground faults continue to be a prevalent subject across all electrical and electronic systems (Guerrero, Mahtani, Serrano-Jimenez, & Platero, 2021) (Pardo, Mahtani, Platero, & Sanchez-Fernandez, 2023) (Kumar, Vaijayanthi, Deshmukh, Vedik, & Shiva, 2022) (Bani Milhim, et al., 2022). Various approaches for ground fault health monitoring have been proposed by other researchers.

Tornare *et al.* developed a device capable of detecting loss of ECU ground connection. However, an integration of a secondary diagnostic circuit is required for each ECU, which is an expensive solution for the automotive application (US Patent No. 20160240022, 2014). Gaona *et al.* proposed a novel technique to detect the ground failure for synchronous machines. The method relies on analyzing the frequency of voltages or currents at a grounding impedance located at the neutral terminal of the excitation transformer (Gaona, Blazquez, Frías, & Redondo, 2010). However, the method is strictly for synchronous generators. Muth developed a circuit for detecting ECU offset ground. ECU offset ground is detected by analyzing the recessive voltage level for a predefined time window (US Patent No. 7257740B2, 2007). The method requires a designed circuit for this application.

This paper presents a novel method to monitor the health status of ECU ground line for automotive application. Based on our previous work (Du, Jiang, Zhou, Bani Milhim, & Sadjadi, 2023)., the novel CAN voltage-based health indicators are proposed. The rest of the paper is organized as follows. The ECU ground line section presents the ground line modeling and architecture in an ECU. Then, a general prognostic framework is utilized to develop prognostics for the ECU ground line; the main prognostics framework components are discussed thoroughly. The results using actual vehicle data are presented followed by the conclusion.

2. ECU Ground Line

The physical layer characteristics for the CAN bus are specified in ISO-11898-2. In the case of a high-speed CAN bus, the physical layer comprises paired wires, terminators on both ends, and ECUs equipped with CAN transceivers for message reception and transmission, as shown in Figure 1. Typically, parallel wires with a nominal impedance of 120 Ω (95 Ω minimum and 140 Ω maximum) are utilized. For a data rate of 1 Mbps, the maximum allowed length for the CAN bus is specified as 40 meters (ISO, 1993).

For the split termination, each terminator consists of two resistors of approximately 60 Ω each, R_L1 and R_L2 or R_R1 and R_R2, along with a coupling capacitor (such as 100 nF) C_L or C_R. The coupling capacitor serves the purpose of connecting high-frequency noise to the ground, effectively filtering it out. According to ISO 11898-2, ECU internal resistance is 10K to 100K Ω, which is much higher than the terminator resistance. The two signal lines of the bus are called CAN Hi and CAN Lo, respectively.

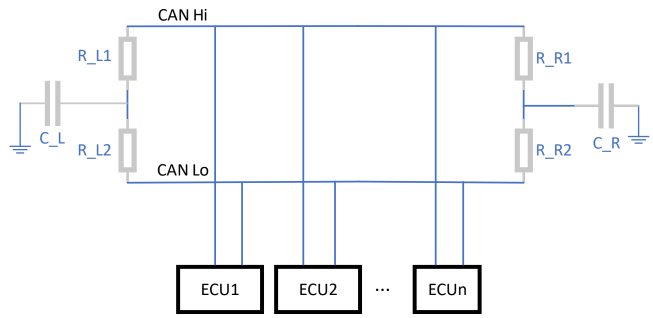

Figure 1. The schematics for a typical high-speed CAN bus.

Communication via CAN protocol is achieved by creating dominant and recessive states on the bus. In the recessive state, the bus voltages are equal to 2.5 V. The dominant state on the bus typically drives the CAN Hi up to 3.5 V, and CAN Lo down to 1.5 V, creating a 2 V differential signal. Figure 2 depicts a typical voltage profile of a CAN bus, where the voltage levels are sampled at a rate of 10 msec.

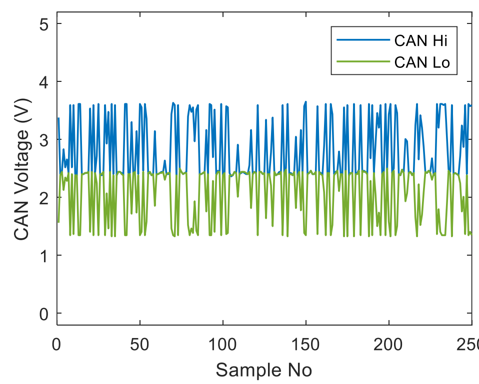

Figure 2. CAN bus voltage under normal conditions.

The ground line plays a significant role in ECUs, particularly in relation to CAN communication. In CAN transceiver, the focus is solely on the differential voltage between CAN Hi and CAN Lo to distinguish between dominant and recessive bits. These transceivers are designed to accommodate various input voltage ranges (*i.e.* -3 V and +32 V according to ISO11898-2) and handle different noise conditions. This

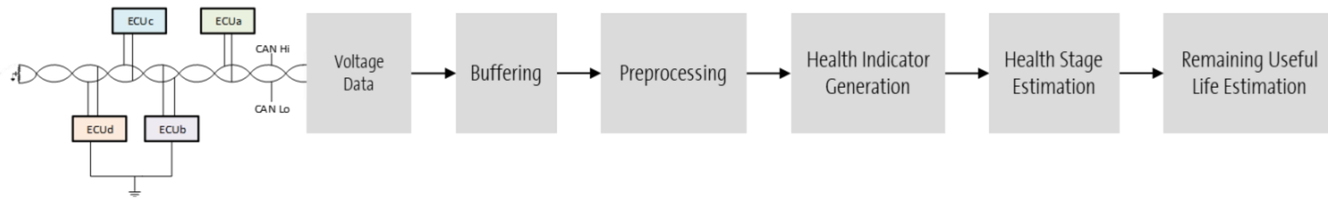

Figure 3. Prognostics development framework for ECU ground line.

implies that the CAN bus can continue to operate effectively without encountering failures, even with a restricted offset ground.

In the event of incipient degradation on the ECU ground line, the asymmetrical voltage variation in CAN Hi and CAN Lo leads to the generation of an electromagnetic signal. These voltage variations do not effectively cancel each other out, resulting in the emission of electromagnetic signals. Furthermore, incipient degradation may evolve into severe degradation and eventually a floating ground, which disables the ECU operation. It is worth mentioning that when an ECU is not operating due to the floating ground line, it ceases communicating and become disconnected from the CAN bus. Nevertheless, the other unaffected ECUs can continue to communicate with each other through the same CAN bus.

An ECU offset ground case can be modelled as shown in Figure 4, where an offset is represented by a resistor between the ECU module and ground (see the red rectangular shape in the figure). When an ECU with an offset ground transmits messages, the electrical current travels from the power source through the offset ground resistor to the ground. This causes a voltage drop across the resistor, resulting in an elevated voltage between the power source and the offset ground resistor.

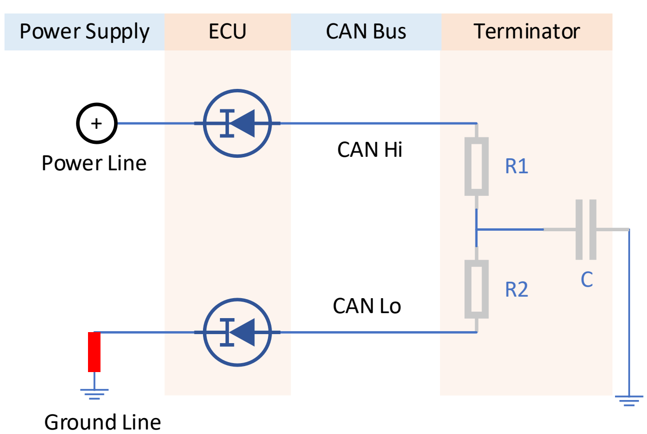

Figure 4. Equivalent circuit of ECU with ground offset.

Such behavior is totally different from an ECU software fault or a power fault. The level of inter-frame voltages depends on the internal circuit of each ECU. The floating ground failure potentially damages the ECU itself if the application is using an inductive load (Infineon, 2007).

3. ECU Ground Prognostics Framework

As discussed in the previous section, the monitoring of ECU ground line health status can be achieved by analyzing the raw CAN voltage profile. The proposed method for monitoring the health status of the ECU ground line is illustrated in Figure 4. Initially, the raw CAN voltage data is collected and subjected to preprocessing. Subsequently, health indicators are generated from the voltage data and fused. The estimation of the ECU ground line health stage is then based on the fused health indicator. The health stage data is buffered for the purpose of predicting the most suitable Remaining Useful Life (RUL) model. The subsequent subsections will provide a detailed discussion of each of these steps.

3.1. Data Collection

Real-time CAN bus voltages are continuously measured. The data will be considered when there is no communication fault present on the CAN bus. CAN communication faults include physical CAN wiring fault and abnormal power supply level.

The voltage range of the measurements is between 0 V (lower limit) and 5 V (upper limit). If the measured CAN bus voltage is greater than the upper limit, a ceiling value of 5 V is applied. The measurements are taken at a sampling rate of 10 Hz.

3.2. Preprocessing

Within the collected raw CAN voltage data, the recessive common mode voltage data points are identified and then stored in a buffer. The following condition should be met for a data point to be classified as being in a recessive state:

$$|CAN\ Hi(t) - CAN\ Lo\ (t)| < K_{REC\_TH} \qquad (1)$$

where K_{REC_TH} is utilized to determine whether a data point is in a recessive state.

The common mode for the buffered CAN voltage in recessive state (CM_{REC}) is then computed as follows:

$$CM_{REC} = \frac{[CAN\ Hi_{Buffer} + CAN\ Lo_{Buffer}]}{2} \qquad (2)$$

where $CAN\ Hi_{Buffer}$ and $CAN\ Lo_{Buffer}$ are the buffered raw CAN voltage data points in recessive state.

After that, an adaptive outlier removal is employed to eliminate outlier data points. The adaptive outlier removal can be applied based on the threshold of the statistical mean ± two times the standard deviation.

To characterize the ground fault, the data was collected using one of the ECUs in a vehicle. A wide range of electrical resistance values were installed on the ground line to simulate different ECU ground line degradation levels. Figure 5 shows the different level of the ECU ground line degradation and the computed common mode.

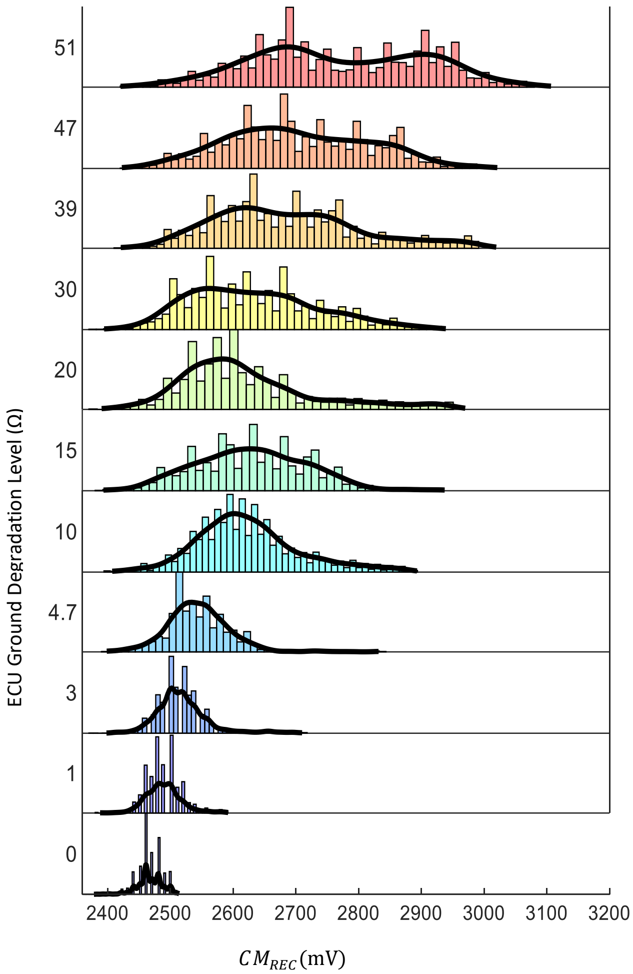

Figure 5. ECU ground line degradation level behavior.

3.3. HI Generation

ECU ground line health indicators are calculated based on statistical moments using the preprocessed data. Various statistical moments were examined, including the analysis of the moving mean, and moving kurtosis. Moving mean can be defined as a statistical calculation that involves averaging of a specific number of data points within a sliding window. On the other hand, the moving kurtosis can be defined as a statistical metric that quantifies the shape or "peakedness" of a distribution within a moving window. The proposed health indicators derived from vehicle data encompassing various resistors are illustrated in Figure 6.

Due to the distinct insights offered by the two proposed health indicators regarding the ECU ground line, a fusion of these indicators is suggested to enhance the estimation of the health stage.

$$HI_{fused} = \alpha \times Mean(CM_{REC}) + \beta \times Kurtosis(CM_{REC})$$

where α and β are the fused coefficient. CM_{REC} was defined in equation (2).

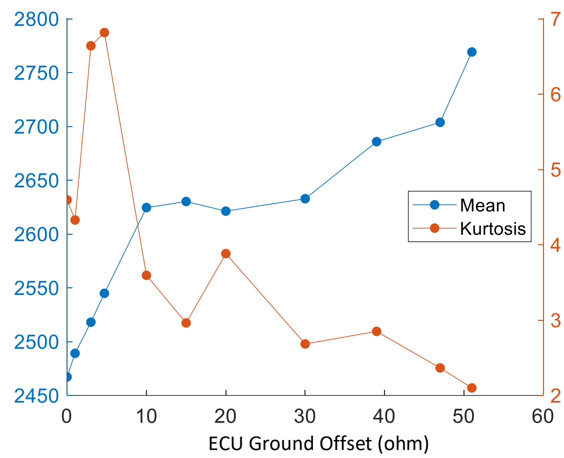

Figure 6. The proposed health indicators for ECU ground line using vehicle data.

The next step is to estimate the health stage of the ECU ground line.

3.4. HS Estimation

The health stage is estimated by classifying the relationship between the ECU ground line and communication status. ECU ground health stage is modeled based on the fused health indicator as shown in Figure 7.

In addition to the ECU communication status, the levels of the fused health indictor are used to categorize the health stage of the ECU ground line. Five different health stage levels are considered here. 100% ECU ground line health status indicates the ground line degradation doesn't result in any communication loss with equivalent electrical resistance is less than 10 Ω. Minor communication loss for the ECU ground offset of between 8 Ω and 22 Ω. Moderate communication loss (50% healthy) for the ECU ground offset of between 22 Ω and 38 Ω. Severe communication loss (25% healthy) for the ECU ground offset of between 38 Ω and 56 Ω. When the equivalent ECU ground offset exceeds 56 Ω, the ECU completely ceases communication. The estimated levels of the ECU ground health stage can be shared with customers, including vehicle owner, dealership, and vehicle fleet management. This allows them to conveniently perform the necessary repairs or maintenance based on the provided information.

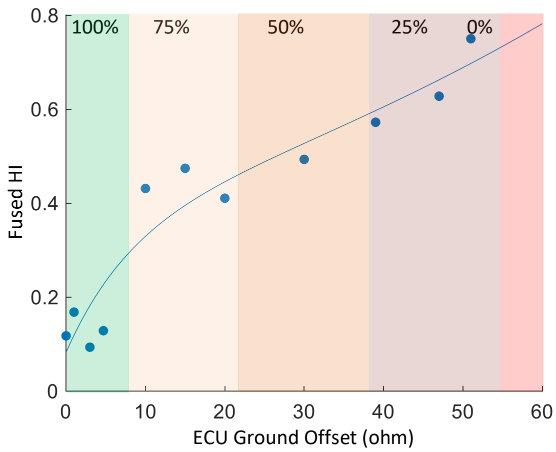

Figure 7. Health stage estimation for ECU ground line.

3.5. Remaining Useful Life (RUL)

Health stage data is buffered to predict the most suited RUL model. RUL represents the estimated remaining time until the ECU ground line undergoes complete failure. The degradation levels and confidence intervals are adjusted accordingly as new data is obtained. The accuracy of the RUL model is continuously enhanced by leveraging the collected vehicle data. The selection of RUL models depends on factors such as the ECU software and hardware, as well as the specific characteristics of the CAN bus topology. As more data is gathered, the RUL model will improve the accuracy. Figure 8 depicts multiple candidates for the ECU ground line. Please note that the specific RUL models may vary based on the system and data available.

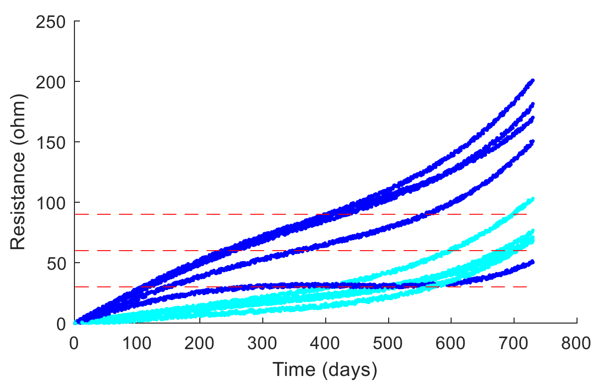

Figure 8. ECU ground line RUL models.

4. Results and Discussions

At this point, the ECU ground line prognostic components have been developed, including the fused health indicator, health stage modeling, and initial RUL models. This signifies the completion of the development stage in the prognostics process. Once the development stage is complete and implemented, the running stage begins as illustrated in Figure 9.

During the running stage, when the vehicle is operational, and the ECU is active, raw CAN voltage data is collected and subjected to preprocessing techniques as described in section 3.1 and 3.2. Subsequently, the fused health indicator is computed based on the preprocessed data. The fused health indicator serves as a comprehensive measure of the ECU ground line's health status. To predict the health status of the ECU ground line, the calculated health indicator is input into the health stage modeling. Depending on the projected health stage level, the appropriate outcomes will be communicated to the customers, enabling them to perform the necessary repairs or maintenance actions.

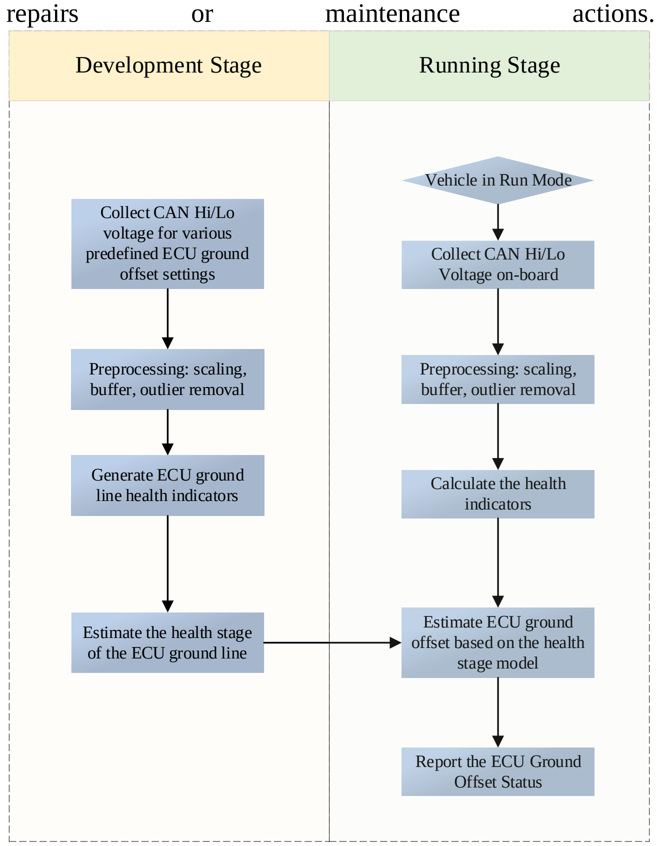

Figure 9. Development and running stages of the ECU ground line prognostics.

5. Conclusion

The proper functioning of each ECU is vital for the overall performance of a vehicle. When the ECU ground line degrades, it has a detrimental effect on the operation of the ECU, particularly in terms of communication with other ECUs. Furthermore, a degraded ECU ground line often leads to a complete failure over time. Therefore, having the capability to estimate the health status of the ECU ground line is crucial to prevent sudden ECU failures that can result in the disabling of critical vehicle functionalities.

This paper introduces a methodology for predicting the health status of the ECU ground line using raw CAN voltage data. The collected data is first preprocessed to ensure quality and reliability. Subsequently, a fused health indicator is developed based on the processed data. By incorporating the fused health indicator and the ECU communication status, the health stage of the ECU ground line is estimated. Additionally, the collected data is utilized to adjust the RUL model, allowing for the estimation of the remaining time until the ECU ground line experience complete failure. The proposed method can be enhanced by collecting data from diverse ECUs situated at various locations on the CAN network.

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BIOGRAPHIES

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