IoT-Based Onboard Prognostic Health Evaluation System for Automotive Suspensions

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***Abstract*—We consider the problem of developing functionally safe suspension components and sub-assemblies for automotive systems. Safety is prominent in all modes of transportation. Failure of suspension components represents a significant reason for car accidents. We develop an IoT-based continuous monitoring solution to predict the impending degradation of suspension through real-time detection and analysis of abnormal vibrations in these parts in real-time. Our system includes onboard sensors and computation modules for real-time detection, together with an offline analyzer in the cloud for the refinement of prediction accuracy through the lifetime of the part. We present a prototype of the system and discuss the architecture and implementation concerns involved in its design.**

I. INTRODUCTION

The goal of safety in an automotive system is to ensure that failure in an electrical or mechanical component does not result in harm to the occupants of the vehicle or its environment. Obviously, safety is a foremost concern for modern vehicles, given the potential for a failed component to cause catastrophic accidents resulting in loss of human life and significant damage to infrastructure. Over the last decade, safety challenges have been exacerbated by the trend of increasing infusion of autonomous features augmenting and replacing the actions of a human operator. As the complexity of both electro-mechanical and electronic systems increases in automotive systems, it is crucial to design each component with safety concerns from the ground up. Most vehicular failures, particularly those involving mechanical components, start with the quality degradation of a single component, possibly due to fatigue. If not detected early, the degradation can result in drastically reduced service life of other downstream components, eventually resulting in a system failure. Early detection of a degrading part (and corresponding mitigation) can obviously prevent a routine problem with a part from turning into a system-level safety concern. However, it is non-trivial to perform such early detection. In particular, as systems are getting integrated with sophisticated infotainment components as well as autonomous and semi-autonomous features, it is getting harder for the occupant of the operator to pay significant attention to minor inconsistencies that could divulge the (*e.g.*, subtle acoustic patterns resulting from increased friction with an aging component, or slight loss of smoothness in driving functionality). On the other hand, estimating impending fatigue in a part statically, through analysis of material properties of the part and its dependencies during vehicular operation is also non-trivial.

In this paper, we consider the problem of designing functionally safe vehicular suspension systems. According to National Highway Traffic Safety Administration, failure in suspension represents a significant reason for car accidents [1]. Our approach is based on the observation that degradation in suspension can be estimated by monitoring the amplitude of stresses in the sub-assembly affected by the suspension system. Based on this observation, we introduce an IoT solution that monitors motion and vibration data. The data is logged into the cloud, where it can be used for prediction of suspension quality, as well as subsequently by technicians for analysis of root causes of failures. We are not aware of any other safety system for suspension systems that enables real-time detection of quality degradation through continuous monitoring. In addition to addressing safety concerns resulting from suspension failures, the system can facilitate the design of weight-optimized suspension mechanisms that impact the environment positively.

II. RELATED WORK

There have been several studies that estimate the fatigue life of a variety of critical infrastructures, including bridges [2], buildings [3], rolling stock [4], aircraft [5], and automotive components [6]. Transportation applications such as aerospace [7] and automotive requires estimating the life of components, considering that they could involve life-threatening risks. Ling *et al.* [8] and Kulkarni *et al.* [9] discussed two critical aspects of a typical Structural Health Monitoring System (SHM) system used for monitoring a fatigue crack: (1) a procedure to predict macrocrack initiation and (2) a technique to quantify the effect of imperfect inspections. In transportation systems, especially terrestrial systems, there have been many studies [4], [10] where fatigue life was evaluated for rolling stock components such as railway bogies and axles. Samad *et al.* [11] and Moon *et al.* [6] discussed the methods to estimate fatigue life calculation for hyperelastic materials like rubber used in highly loaded components in automobiles.

There is less work on an onboard system that evaluates the life of safety-critical assemblies like that of suspension and steering components. One exception is from Hu *et al.* [12]; however, it does not employ onboard evaluation and instead uses IoT for verification and better accuracy to notify the driver of the remaining life of these components. Both Hu *et al.*and Luo *et al.* [13] used a long short-term memory (LSTM) neural network to predict partial damage levels pertaining to

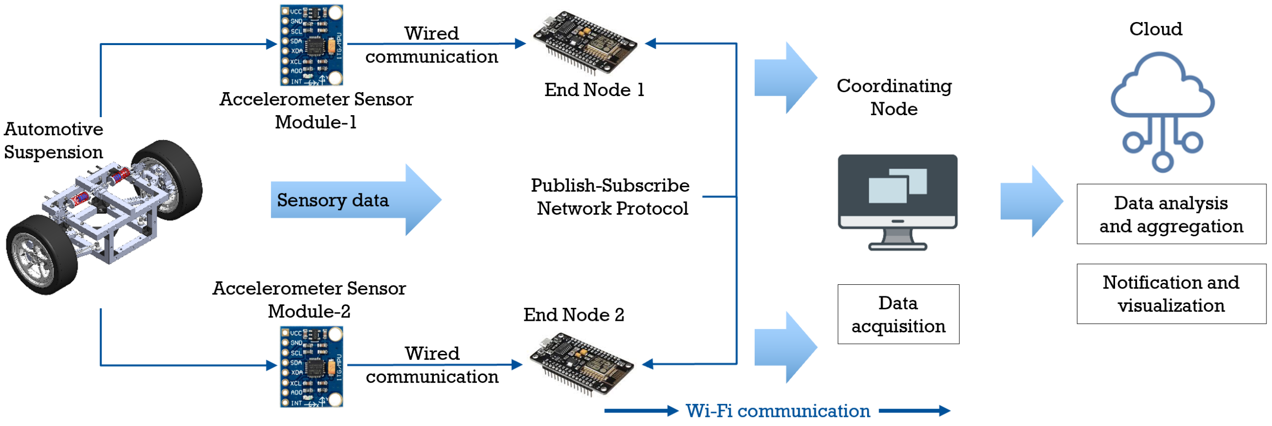

Figure 1. High level architecture

automotive suspension durability. Their work is driven by the need for structural health monitoring to have high prediction accuracy and quick computation. Ijagbemi *et al.* [14] designed and optimized a suspension system to reduce weight by simulating the assembly for fatigue life using Finite Element Analysis (FEA). Internet of Things (IoT) has the potential to be crucial for automotive health monitoring by connecting users, processes, data, and things through networks. Shafi *et al.* [15] presented an IoT-based architecture for remote vehicle health monitoring and prognostic maintenance that is based on real-time data collected while the vehicle is moving.

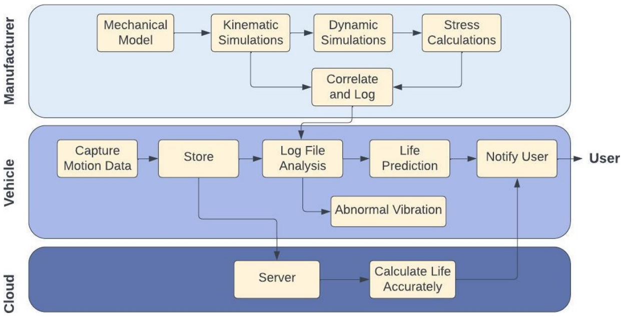

Figure 2. Workflow process model

III. ARCHITECTURE

A. System Design

The system includes a collection of accelerometer sensor modules that communicate through a hierarchy of nodes with a cloud-based infrastructure for ML-based data analysis. We divide the overall prototype into three primary sections: 1) sensory activity, 2) network protocol, and 3) cloud analysis. Fig. 1 shows the high-level architecture of our proposed system. Since the goal is to detect suspension motion for preventive measures, the right and left suspensions will be integrated with accelerometer sensor modules in the vehicle. The sensory data is acquired through multiple end nodes (*i.e.*, WiFi modules) and transmitted via a publish-subscribe network protocol. Note that low power consumption is typically a crucial requirement when connecting locally networked sensors to a coordinator node; to achieve that, the system can be configured to employ a portable computer, an ECU, or a small single-board computer (*e.g.*, Raspberry Pi) that can act as the bridge between the sensor network and the cloud with respect to the vehicular environment.

B. Workflow

Fig. 2 depicts the workflow process of our system. The system is designed to smoothly integrate with the automotive suspension design and deployment process. In particular, one crucial step in suspension design involves the static and dynamic analysis of loads on the components affected by the suspension. The manufacturer analyzes the loads on each component for different loading conditions. These are logged into a file that correlates the motion data directly to the fatigue life for that particular load. The onboard component of the safety system exploits this data log to translate motion and displacement data to cycle life. The suspension motion upon usage is compared with the log and fatigue life for each displacement and fed to the Rainflow-Counting algorithm [16]. The algorithm analyzes the load profiles and lets the user know the remaining life of the system. On the other hand, packets of data are uploaded to the cloud at regular intervals and based on the availability of the network to provide better feedback and prognosis. Additionally, the same spectral data is used to analyze vibrations, and any abnormal vibrations that are detected would be notified to the driver immediately.

IV. PROTOTYPE IMPLEMENTATION AND ANALYSIS

To enable exploration of the actual functioning of an automotive suspension, we used a double wishbone configuration as part of an independent rear suspension. We chose a quarter-car model, hence one of the four axles is simulated. The model is not optimized for any specific stress values since this model only requires the kinematics involved for a particular suspension geometry. To capture the motion data, we used an MPU6050 accelerometer, gyroscope, and temperature module. The MPU6050 is mounted on the outer side of the upright

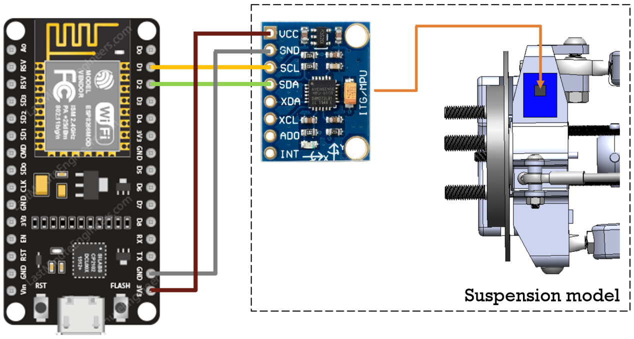

Figure 3. Connection diagram of our prototype data acquisition

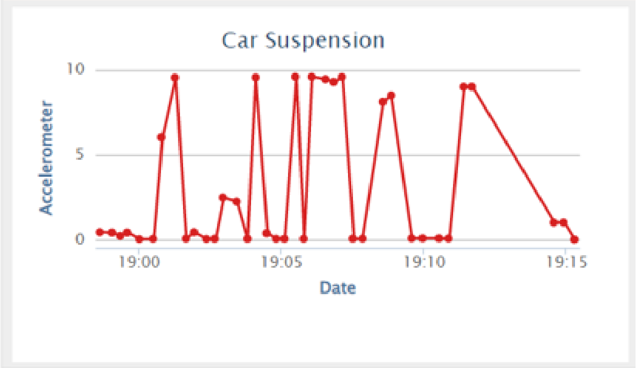

Figure 4. Stored Sensor Data on Cloud

for easy access and inspection. We employ a NodeMCU (ESP8266) microcontroller for processing accelerometer sensor data (connection diagram shown in Fig. 3). It is also programmed to send data to the Raspberry Pi, which acts as a coordinator node in our case. The second node is also introduced to show the effects of another axle. A crucial part of communication is sending the acquired data wirelessly to the coordinator node and beyond. We use a standard MQTT connection using two components: (1) ESP8266 (publisher) and (2) Raspberry Pi (broker and subscriber).

Data generated from the accelerometer can be interpreted as both acceleration and vibration of the vehicle. Fig. 4 shows how the sensory data are stored in the sensor field of the server's private channel. Data is stored in a 2-axis graph in the channel. Each of the input instances is logged with the timestamp of the record. Data storage in the cloud allows for easy access to live-stream data. Users can observe the trend of their car's data from the ThingView app. We integrate this setup with a front-end interface for monitoring the sensor data coming in from the end devices on every insertion to the cloud server. When the inserted data crosses the threshold value, the cloud server executes the react analysis of the sensor data.

V. CONCLUSION AND FUTURE WORK

We presented a functionally safe automotive suspension design through an IoT-based monitoring system with integrated sensor, compute, and communication elements. The system can capture (and differentiate between) normal and abnormal values and predict the degradation of the suspension system. We discuss the architectural elements of the system and a prototype implementation. Furthermore, since the analytics infrastructure is cloud-based, it enables the flexibility of integrating sophisticated ML algorithms based on domain-specific insights.

In future work, we plan to use our system with suspension components made of tested isotropic materials. We would like to extract stress data based on displacements and compare the simulations using finite element analysis. Additionally, we plan to use the same setup for other auto parts, including steering and transmission systems.

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