American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-10, Issue-01, pp-237-244
www.ajer.org
Research Paper Open Access

Mechatronic Suspension Systems: A Survey and Directions for Future Work

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ABSTRACT: *The suspension system has always been essential in almost every robotic mechanism, not to mention motor vehicles. Since the early "Ford's Model-T car" days in 1908, the suspension system was a crucial component in vehicles. This paper presents a survey on the different types of the mechatronic suspension systems. Then it explores the Mercedes' active suspension systems the "Active Body Control (ABC)" and its successor the "Magic Body Control (MBC)". The ABC depends on the "Pre-Scan" function which uses lidar sensors that scan the road ahead and anticipate the obstacle before hitting it, while the MBC - which is basically an ABC with a camera - depends on the "Road Surface Scan" function that uses a stereo camera instead of the lidar sensors. The Road Surface Scan function calculates obstacles' heights and creates a precise road height profile. While the MBC is already a state-of-the-art system, its benefits can be doubled by reusing the road height profile. Then it follows by the outlines of the proposed approach for the reuse of the road height profile and its potential applications. This can be achieved by synchronizing the road height profile with the car's GPS system which will be linked to the internet and an "Over the Air" firmware to create a platform. This platform can be used by the ministry of transport so that it will be informed on roads condition and the priority of their maintenance. It can also be used by mobile applications developers in developing apps that guide users on choosing the most comfortable road. It can also minimize the uncertainties in the reaction of the suspension system in self-driving cars. Finally, if the proposed approach is implemented, it will be a novel use of the Mercedes' MBC system.*

KEYWORDS: *Mechatronic Suspension, Active Body Control (ABC), Magic Body Control (MBC), Road Height profile, Road Maintenance.*

Date of Submission: 04-01-2021 Date of acceptance: 19-01-2021

I. INTRODUCTION

One of the most essential requirements when purchasing a luxury car is its suspension system and the level of comfort it provides. But whether it is a luxury car or an ordinary one, the safety that the suspension system provides is vital. It absorbs shocks and vibrations that otherwise affect the passengers and may cause accidents. The "suspension system", the "Brakes" and the "Tires" are the three sides of the "safety triangle" which is a common expression used in automobile magazines. All of the three must be in good shape for a safe ride. The suspension system functions also include maximizing the passengers' comfort, reducing the effects of vertical vibrations, supporting the weight of the car and maintaining proper alignment of the wheels (Sharp and Crolla 1987). The leaf springs or the semi elliptical springs were popularized after the mid-18th century by vehicle and carriage makers in Europe (LANDAU 1912). Today after nearly 300 years, the leaf springs are still widely used but mainly in heavy trucks, sport utility vehicles (SUVs)and railroad carriages. Currently, most suspension systems available in commercial cars are passive systems including the ones that use the leaf springs. But since the 1950s, the need for more sophisticated and compacted suspension systems led car manufacturers to prefer modern designs that use coil springs instead of leaf springs. As the leaf spring system depends on a dry friction scissor damper which is less efficient than the hydraulic damper that is used in modern designs that use coil springs (Dixon 2008).

Then there was the age of the mechatronic suspension systems that could be generally categorized into four groups. The mechatronic suspension systems could either control the basic elements of the passive suspension system like the spring stiffness or the energy dissipated at the damper, or apply an actuator - either electric or hydraulic - that controls the vertical movement of the wheels relative to the vehicle chassis (Savaresi, Poussot-Vassal et al. 2010). First, there is the adaptive suspension system that provides slow adjustments for the characteristics of the spring and damping settings. Secondly, the semi-active suspension that could quickly adjust the spring stiffness and/or the energy dissipated at the damper. Thirdly, the slow active suspension system uses a low bandwidth actuator (normally up to 5 HZ), the actuator is linked in a series arrangement with the main spring. Fourthly, the fast or fully active suspension uses a high bandwidth actuator (normally 20 HZ or more), the actuator can replace or supplement the passive damper and then it will be connected in a parallel arrangement with the main spring (Fijalkowski 2011).

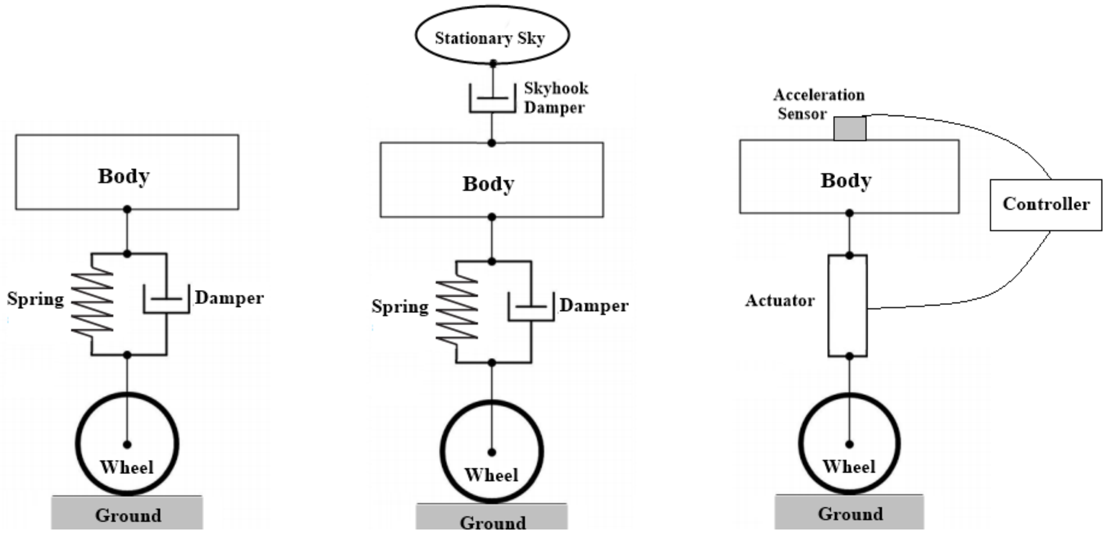
In 1999, Mercedes introduced the Mercedes-Benz CL-Class (C215) which is the first car ever to be equipped with the “Active Body Control” or (ABC). It is a hydraulic fully active suspension which uses sensors that detect the body movement to maintain the car level in fast corners and braking (Woitysak 2006). After that the Mercedes-Benz F700 was revealed in 2007. It is a concept car that uses the Pre-Scan function which is the first system to scan the road ahead and anticipate the obstacles rather than just reacting to them (Woitysak 2007). Then in 2013, the Mercedes-Benz S-Class (W222) was the first car to be equipped with the Magic Body Control (MBC) which uses an Active Body Control system as its core and the Road Surface Scan function that uses a stereo camera instead of the lidar sensors (Weist, Missel et al. 2013).

Since the Magic Body Control is still relatively new, there are few research papers discussing it. And there are few to no researches that propose adding modifications to it or propose applications to use it beyond the suspension system. So, the objective of this research is to discuss the types of mechatronic suspension systems, to examine the recent trends and to present a novel approach for reusing the road height profile created by Road Surface Scan function in different applications.

II. MECHATRONIC SUSPENSION SYSTEM

Since 1980s, the development of mechatronic suspension systems has remained an active area for research and development to this day. The active suspension system controls the wheels’ vertical movement in relation with the vehicle body according to the skyhook theory (Dean Karnopp 1974). This is opposite to what happens in passive suspensions where the vehicle only reacts to the obstacles using passive springs and dampers (Fijalkowski 2011).

Skyhook theory is the optimal concept that active systems are targeting so the vehicle will keep a leveled posture as if it is hung by a fictitious hook in the sky, unaffected by road obstacles (Song 2009). As shown in Figure 1.



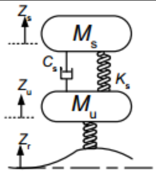
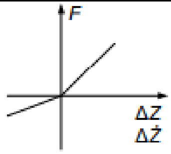
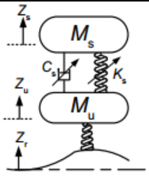
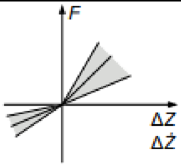
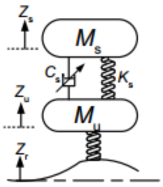
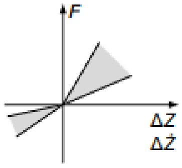
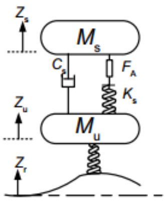
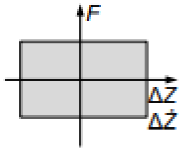
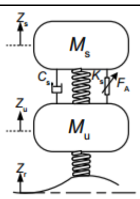
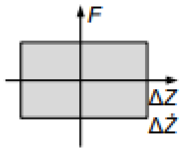
(a) Normal passive system, (b)Ideal skyhook system (c) Active suspension system

Figure 1 Skyhook theory, Adopted from (Song 2009) (Chen, Wang et al. 2012)

To keep the vehicle as leveled as possible, an acceleration sensor will be installed to detect any vertical acceleration above the skyhook theoretical line where the vertical acceleration equals zero, as shown in Figure 1 (c). when any value of vertical acceleration is detected by the sensor, the controller will get the actuator to exert force to oppose it (Chen, Wang et al. 2012).

Mechatronic suspensions can be generally classified into four classes: Adaptive Suspension, Semi-active Suspension, Slow Active Suspension and Fully or Fast Active Suspension. Table 1 shows the categorization of Mechatronic suspension systems against the passive system, according to (Fischer and Isermann 2004) and (Koch 2011).

Table 1 Categorization of suspension systems (Adopted from (Fischer and Isermann 2004) (Koch 2011)**)**

System Type	Model	Force Range	Operating Range (Hz)	Energy Demand (W)
Passive			No Actuator	0 W
Adaptive			< 1	Low
Semi-active			0 - 40	Low
Slow Active			0 - 5	Medium
Fully Active			0 - 30	High

According to table 1, the mechatronic suspension systems can be grouped into four categories. They will be discussed in the following sections.

2.1 Adaptive suspension systems

They are composed mainly of springs and/or dampers but with the ability to control them by making slow variations to the characteristics of the spring and the damper. They change them according to the car speed to lower its center of gravity to ensure its steadiness on the road and to provide good sports car performance (Koch 2011). The required power for its operation is low and relies mainly on the power demand to change the spring stiffness (Aboud, Haris et al. 2014).

2.2 Semi-Active Suspension Systems

They have the ability to make fast adjustments of the damper characteristics and/or spring characteristics. Semi-active dampers are able to adjust the dissipation amount of the energy but it does not provide the system with energy. The most economic types of semi-active system use the Solenoids/valves which are responsible for changing the flow of the hydraulic fluid inside the damper, therefore that changes the damping characteristics of the system. The solenoids are connected to the control unit which gives them commands according to the road surface. The semi-active system has a low power demand which ranges between 20 W to 40 W (in Watt) for each damper. The semi-active damper has a bandwidth that ranges up to approximately 40 Hz (Savaresi, Poussot-Vassal et al. 2010).

2.3 Slow Active Suspension Systems

They use low bandwidth actuators so they are normally known as the low bandwidth active systems. The actuator used is either a hydraulic cylinder or an electrical linear actuator that is linked in series configuration with the main spring. The bandwidth of slow active systems ranges up to approximately 5 Hz. The power required for their operation ranges from 1 kW to 5 kW (Fijalkowski 2011). Recent researches and advances in the semi active system shows that the semi-active suspension may be able to achieve the more superior performance of the fully active suspension system in the near future (Ghasemalizadeh, Taheri et al. 2017).

2.4 Fully or Fast Active Suspension Systems

They are called the high bandwidth active systems because they use high bandwidth actuators. The actuator replaces or supplements the passive damper. In case of a hydraulic cylinder actuator, it has a bandwidth that ranges up to 30 Hz. While in case of the electrical linear actuator, the bandwidth ranges up to 100 Hz (Villegas and Shorten 2006). The biggest disadvantage of the fully active suspensions is the high-power demand which lies in the range of 4 – 20 kW.

III. ACTIVE SUSPENSION SYSTEM

The types that will be discussed here are the Active Suspension system produced by Mercedes in 1999 the Active Body Control and its successor the Magic Body Control produced in 2013.

3.1 Active Body Control

Active Body Control (ABC) is the trade mane of the system developed by Mercedes-Benz and it used to describe its brand suspension. It is a low bandwidth (slow) active suspension which uses sensors that detect the body movement to compensate for the body roll and the pitch motions and to maintain the car level in fast corners and braking. In 1999, Mercedes introduced the Mercedes-Benz CL-Class (C215) which is the first car ever to be equipped with the Active Body Control (Woitysak 2006). The ABC system is composed of hydraulic struts, dampers, steel springs, a hydraulic pump, an accumulator, sensors, and an Electronic Control Unit (ECU). Figure 2 represents a Mercedes CL-Class fitted with the ABC system.

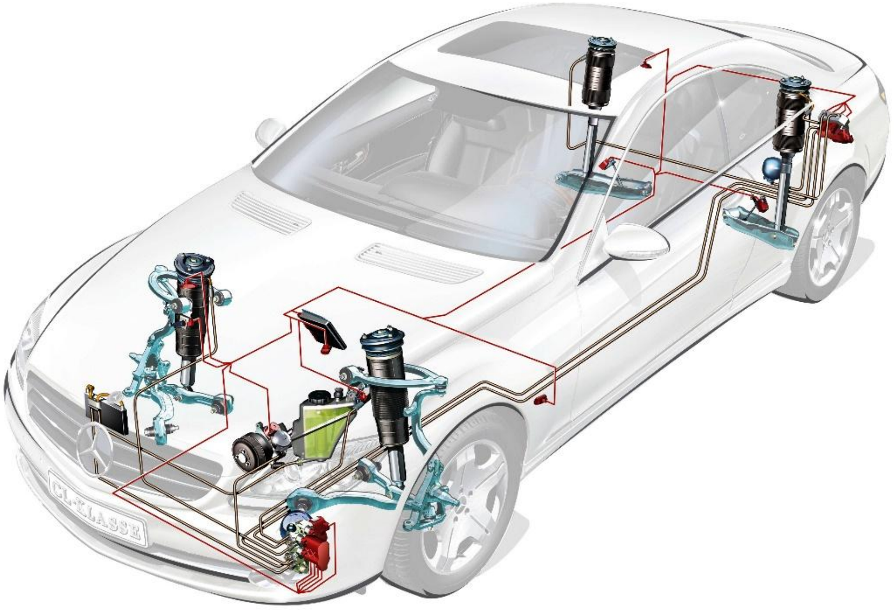


Figure 2 The hydraulic ABC of the Mercedes CL-Class (Adopted from (Woitysak 2006))

3.2 Magic Body Control

Mercedes-Benz F700 was revealed at the Frankfurt Motor Show in 2007. It is a concept car that uses "Pre-Scan" function which is the first system to scan the road ahead and anticipate the obstacles rather than just reacting to them. This was done by using two lidar sensors in the headlamps of the car to create a processed image of the road's condition (Woitysak 2007).

Then six years later in 2013, the Mercedes-Benz S-Class (W222) was the first car to use the new Magic Body Control (MBC), as shown in figure 3, which depends on the concepts of the Active Body Control and the Pre-Scan function but uses a stereo camera - mounted at the windshield adjacent to the rear-view mirror - instead of the lidar sensors. Thus, Mercedes introduced a new system called "Road Surface Scan". This system was presented by Udo Weist and the engineering team of Mercedes in their research paper (Weist, Missel et al. 2013).

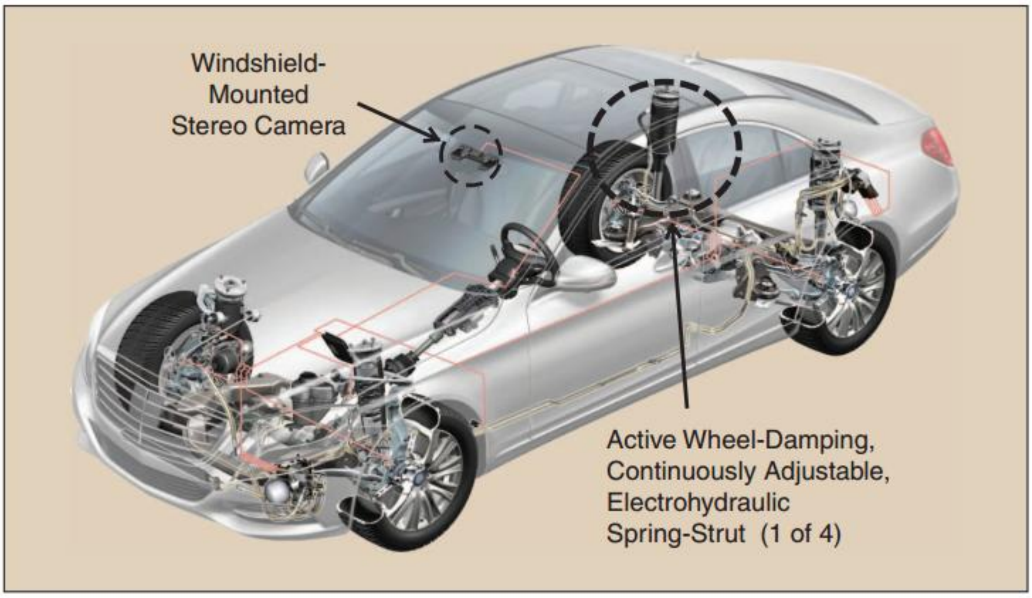


Figure 3 The anticipatory Magic Body Control system in the Mercedes S-class of 2014 (Adopted from (Fleming 2014))

Road Surface Scan system creates a three-dimensional (3D) road profile of the road surface. The camera allows the system to scan about 15 meters of the road surface ahead at velocities that amount to 130 km/h, as shown in figure 4. The system scans only those areas of the road that are rolled over by the wheels in order to reduce the calculation time. Every 60.3 milli seconds (ms), a new camera measurement is calculated, which creates a new road profile every 60.3 ms. So, as the car moves ahead, each section of the road is measured multiple times and from several view angles. Then a statistical operation is done to combine this big number of measurements to a precise estimate of the road height profile (Weist, Missel et al. 2013).

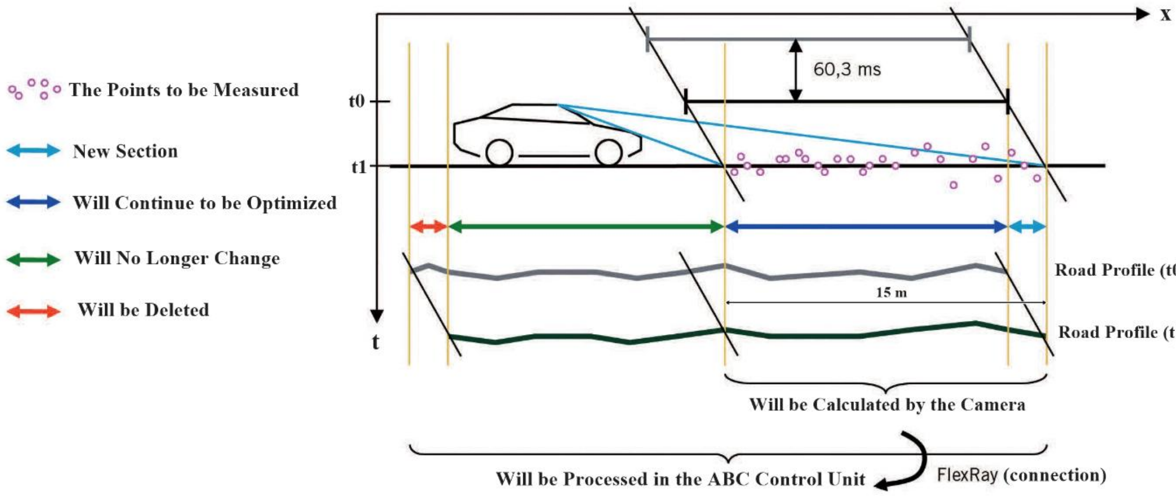


Fig.4 Structural system of the Road Surface Scan (adopted from (Weist, Missel et al. 2013))

The ABC system has been structurally modified to be used in the new MBC system. The adjustable damper makes the wheel damping continuously adaptable. The suspension struts' responses were upgraded and the pump efficiency is increased. The Control unit and sensors are connected by a digital interface while vehicle electronics and the control unit are connected by the faster FlexRay protocol. Compared to the predecessor ABC, the new computing power has been doubled.

The ABC system used in the MBC has an operating range of 0.5 Hz to 5 Hz. This means that the detected body motions in the range of the system natural frequency can almost be eliminated. Short obstacles such as manhole covers will not be overcome actively, but still will continue to be damped by the adjustable damper. The Road Surface Scan will always be active in "comfort" mode at speeds of up to 130 km/h. The adequate structure and the lighting of the road are essential for a good measurement of the road surface. When driving through a reflective surface such as shiny puddles or smooth concrete surfaces, The Road Surface Scan is temporarily turned-off and the vehicle continues with the ABC system only (Weist, Missel et al. 2013).

In 2014, Mercedes presented the C217 S-Class Coupe which is equipped with an upgraded model of the Magic Body Control, which is dubbed "Curve Tilting" function (Woitysak 2014). This system enables the vehicle to incline automatically in less than a second which is similar to a motorcyclist that leans into a corner. Their aim is not to achieve higher speeds at corners, but rather to provide a new driving experience.

Bill Fleming of IEEE wrote about the significant importance that Mercedes sees in the MBC as an element of great expectations that will eventually lead to the development of autonomous self-driving cars (Fleming 2014).

IV. THE PROPOSED APPROACH FOR THE PLATFORM To REUSE THE ROAD HEIGHT PROFILE

In addition to the use of the road height profile created by the Road Surface Scan function, the approach will also integrate the application of two technologies, the first is the GPS system and the second is "over the air" firmware. This can be achieved by synchronizing the road height profile with the car's GPS system which will be linked to the internet and the "Over the Air" firmware to create the platform.

4.1 The use of GPS as a reference to the road height profile

GPS satellites transmit their signals with a definite accuracy, but the accuracy of the signals you receive depends on other factors that include the geometry of the satellite, signal interception, atmospheric conditions, and the features and quality of the receiver design (U.S. Air Force).

Marko Modsching and R. Kramer presented a research that studied commercially available GPS receivers that targets the consumer. They found that the average position error is in the range of 2 meters on an exposed arena to 15 meters in wide roads with tall buildings (around four flours) on either side. The complex structures overshadow the satellites that are compatible for positioning (Modsching and Kramer 2006).

Civilian users with professional applications can increase the GPS accuracy by using dual-frequency receivers which are used by the United States of America military. By using additional GPS "augmentation systems" - which are systems that aid GPS by providing accuracy, improvement to positioning, and timing that were never a part of GPS itself -, this combination can provide real-time positioning with measurements around a few centimeters, and long-term measurements of millimeters (Federal Aviation Administration).

So, by assigning the positions of the obstacles on the GPS map such as if they were restaurants or hospitals, it will facilitate the realization of the proposed approach.

4.2 "Over the Air" firmware

When a new car model hits the roads, and then the company finds a hardware defect that needs to be fixed or else accidents may happen, it must call-back all the cars of that model to the factory. The call-back may weaken the reputation of the brand but no company will risk the safety of its users, as it also will be found liable for compensations. Well, if this was only a small hardware modification, the company will not risk recalling the cars and will add the modification in the next generation.

But if this was only a software modification, then thanks to "Over the Air" platform, car owners will not have to go to repair shops to physically connect their cars with the computer to update their systems. This firmware updates over the air, and that provides fast updates, remove bugs and enhances security (Nilsson and Larson 2008).

Since modern cars can have up to 80 Electronic control unit (ECU), the need for this firmware increases in order to always be updated and to save car owners' time. Also, Tesla, Inc upgrades its Full Self-Driving (FSD) Computer by adding self-driving features via an over the air firmware updates (Tesla press team).

The software must ensure that data is transferred only when it is safe to do so (preferably overnight). This helps keeping the driver's safety by evading the computer problem of requiring an automatic "shutdown and update" while driving.

4.3 The applications of this platform

Now, there are two types of applications from this platform and they are: real-time applications and non-real time applications.

4.3.1 Real-time applications

A real-time system is designed to be used in real-time applications which require processing data without any delay. The processing time is found to be at tenths of a second and even smaller. The processing time must be within the defined constraints or the system would be unsuccessful.

The application which requires real-time computing will benefit the self-driving cars. As the proposed platform can minimize the uncertainties of the suspension system which is related to the system reaction to the obstacles.

4.3.2 Non-real time applications

Non-real time system is a system that does not have the ability to ensure providing responses within any timeframe, as the deadline for its tasks ranges from minutes to hours, and even days.

These two applications below do not require real-time computing, as they can overcome the accuracy error of the GPS signals by assigning the potholes and obstacles to the GPS map. Then the platform will divide the road profile into sections where each section (a street for example) will have a score that represents the number of obstacles and their heights which will be called the "unevenness score".

If a section was to be long (about 500 meters long), an average error of 10 meters in the GPS accuracy will represent only 2% of the section's length which can be neglected. Hence, the applications are:

a. Road Maintenance: as the car rolls over bumps or holes, these reactions will be saved on the car computer. Organizations like the ministry of transport can benefit from these data, as they will be informed on the roads' conditions and the priority of their maintenance. They can also use the unevenness score as an indication to the damage that has been done to the road with adequate positions according to the GPS.

b. Selecting the most comfortable route: when you are using your GPS, there are different routes, one is longer and the other is shorter. Likewise, the platform will provide the opportunity to select the most comfortable route depending on the lowest value of the sum of the unevenness scores of the route's sections. Mobile applications developers can use this platform to develop applications that serve this purpose.

V. DISCUSSION

In order to understand the main difference between the Adaptive or the Semi-active system, Active suspension - either Slow or Fully -, and the Magic Body Control, let us suppose that the vehicle will face an obstacle such as a pothole, and then examine how each system will overcome it:

- The Adaptive or the Semi-active system will control its adjustable damper to be softer when starting to hit the pothole and stiff after it.
- The Active system - slow and fully - could direct its actuator to literally lift the wheel over the pothole immediately when starting to contact it which improves the ride comfort.
- The Magic Body Control will be anticipating the pothole, and so, it will calculate its height and the amount of force to be exerted by the actuator to lift the wheel over it

The proactive (semi-active) suspension used in Bose suspension – which was developed in the 1990s - depends on the quality and the real-time response of its own linear electromagnetic motors to react immediately when hitting an obstacle (Jones 2005). While in the fully active suspension, the system uses an actuator to literally lift the wheel when hitting an obstacle. Currently, the performance difference between the semi-active system and the fully active system is narrowing with the development of active dampers that significantly match the performance of actuators (Ghasemalizadeh, Taheri et al. 2017). In 2017, the American company Clearmotion, a company founded out of MIT, bought the control software developed by Bose Corp. in the 1990s (Clearmotion). So, these days, we might be seeing the Bose suspension on the roads after all.

If one might argue that the increased level of comfort that the MBC system provides is superfluous - compared to a slightly inferior performance by a state-of-the-art semi-active or an ABC system -, then does Mercedes collect data by the MBC system to only benefit the suspension system? In figure 4, it is shown that after the car passes the scanned area then the Road Surface Scan function deletes the road processed data collected. It does not say specifically that the system also deletes the road height profile or not.

So, either the system deletes the road height profile or keep it archived for analyzing, the Mercedes system does not utilize the road profile beyond overcoming obstacles in the suspension system. Hence comes the importance and the novelty of the proposed platform to reuse these data and utilize it in various applications.

VI. CONCLUSION

This paper presents an insight on the history of the suspension system in vehicles and its benefits. It discusses the mechatronic suspension family and the differences between their design structures and between their overall performances. It also studies the active suspension systems ABC and MBC, and follows the engineering team of Mercedes in their quest to invent the best active suspension in the market. The Active Body Control (ABC) by Mercedes improved the ride comfort and gained first class reviews from car users and reviewers alike.

But with introducing the Pre-Scan and the Road Surface Scan functions, Mercedes marked the beginning of a new era for the suspension system, an era that for the first time integrated the suspension system with the information technology (IT) in one operational application. And this application does not only benefit the suspension system but also creates a mine of data that can be very productive in the development of autonomous self-driving cars.

The proposed approach is to create a platform that reuses the road height profile and synchronize it with the GPS of the car which will also be linked to the internet and an “Over the Air” firmware. This platform can be used by the ministry of transport to be informed on road conditions. It can also be used by mobile applications developers to develop apps that determine the most comfortable ride between a number of roads. Finally, it can minimize the uncertainties associated with the reactions of the suspension system in the self-driving cars.

ACKNOWLEDGMENT

I would like to thank Dr. Hussein Fouad Ali of Benha faculty of engineering for teaching me the principles of academic research.

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