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VEHIOT: Evaluation of Smartphones as Data Acquisition Systems to Reduce Risk Situations in Commercial Vehicles

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***Abstract*—Vehicle dynamics studies are an indispensable characteristic to improve the vehicle stability and handling. To fulfil this requirement, control systems are included in commercial vehicles nowadays. These control systems consider variables such as lateral acceleration, roll rate and sideslip angle, that can be directly obtained from sensors or estimated from the collected data. With the objective of incorporating control systems without increasing the price of these vehicles, it is necessary to develop low-cost embedded systems, capable of acquiring data from a diversity of sensors to execute estimations and to perform control actions under real-time constraints. The increase of capabilities and features provided by smartphones enable them as data acquisition and processing devices. In this paper, an analysis in terms of reliability, accuracy and acquisition have been performed for two different smartphones in order to study the possibility to use this kind of devices as a low-cost sensing platform for vehicle dynamic applications. Each smartphone used in this study is classified into a different category (low-end or high-end device) depending on not only its price but also its specifications. Both yaw rate and lateral acceleration have been analyzed in order to quantify the performance of each smartphone. These variables have a direct influence on the vehicle lateral dynamics. Experimiental tests have been carried out in a real scenario and the VBOX IMU connected with the VBOX 3i data logger of Racelogic has been used as the ground truth.**

I. Introduction

Many of the recent research works focus on control systems for commercial vehicles in order to reduce the number of vehicle-crashes [1], [2], [3]. These systems can be used to improve the vehicle stability, comfort and handling. To fulfill these objectives, it is necessary to known the vehicle dynamics (angular rates, angular positions, accelerations) in order to actuate in the vehicular systems and improve its behavior. Angular rates (roll, pitch and yaw) and accelerations (vertical, lateral and longitudinal) can be measured by Inertial Measurement Unit (IMU) sensors.

Vehicle angles (roll, pitch and yaw) can be obtained from a Global Positioning System (GPS) dual-antenna but cannot be directly measured from sensors. The GPS dual-antenna method is very expensive and would increase the price of commercial vehicles. These variables can be estimated using the data provided by low-cost devices in order to solve this problem. Many studies estimate sideslip using data fusion from low-cost GPS and Inertial Navigation System (INS) [4] or by combining the data fusion from yaw rate and the lateral acceleration [5], [6].

Concerning the estimation of vehicle roll angle. In [7] the roll angle is estimated through the fusion of a wheel speed sensor, yaw rate, steering angle and the data from low-cost GPS. In [8] a sensor fusion of yaw rate, roll rate, lateral acceleration and longitudinal acceleration parameters is carried out. In [9] roll angle is estimated fusing the data provided from a six-dimensional IMU. According to these works, IMU sensors comprise the most common solution used to estimate vehicle dynamics.

Bayesian filters, including Kalman filters, artificial intelligence based approaches and robust observers [3], [5], [6], [7], [8], [10] are some of the main techniques used to estimate vehicles angles.

Vehicle on-board systems require small response times, high accuracy and easy mounting. It is also desirable that the inclusion of these systems do not increase the overall price of vehicles' production. Nowadays, smartphones are widespread devices with increased and improved capabilities every year. These improvements give smartphones the ability to perform very complex processes as traffic state detection [11] and ion detector based on the smartphone camera [12]. The usage of smartphones with high computing capabilities allows to delegate in them estimators and controllers execution for vehicles to increase their safety. There are many studies that use smartphones to acquire data. In [13] smartphones are used to monitor the heart activity. In [14] a smartphone based sensor-fusion is used to detect and recognize the driving style.

In [15] the smartphone inertial sensor is used to detect driving events in electrical vehicles. Road traffic is measured using data from smartphones in [16]. In [17] the information provided from smartphones is used to analyze the transportation data.

The novelty reflected in this work is the study of smartphone sensors accuracy under high dynamic conditions. As previously stated, IMUs, which are integrated in commercial smartphones, are the most common sensor used to estimate vehicle dynamics. That is why this type of sensors are considered in this work. Two different smartphones have been analyzed in this research work in terms of accuracy and acquisition time. The VBOX IMU connected with the VBOX 3i data logger of Racelogic was used as the ground truth to compare the results of both smartphones, and to analyze the measurements accuracy.

This article is structured as follows. Methodology is presented in Section II, including experiments definitions. Experimental results are shown in Section III. Finally, the discussion and conclusions of the results are presented in Section IV.

II. Methodology

In this section, experimental testbed and experiments defined to achieve the objectives pursued for this research work are presented.

A. Experimental Testbed Design

In order to carry out the experimental tests, a Mercedes Sprinter van was used which was equiped with three kits of sensors:

- Kit 1: A Xiaomi Redmi 3 smartphone which is categorized as a low-end device due to its low price and features. In table I, its technical specifications are shown.
- Kit 2: A Samsung Galaxy S8 which is categorized as ahigh-end device due to its high price and features. In table II, its technical specifications are shown.
- Kit 3: VBOX IMU connected with the VBOX 3i data logger [18] of Racelogics. The measurements obtained from this device are used as a ground truth to properly perform a comparative analysis of both smartphones. In table III, its technical specifications are shown.

TABLE I
Technical specifications of hardware elements included in Xiaomi Redmi 3

Xiaomi Redmi 3			
RAM	2GB	**CPU**	4 x 1.5 GHz 4 x 1.2 GHz
Weight	144g	**Dimensions**	139x69x8mm
Angular rate range	±1000 deg/s	**Angular rate resolution**	0.06 deg/s
Acceleration range	±7.8 g	**Acceleration resolution**	0.006 g
Price		120 €	

The smartphones and the VBOX IMU of Racelogic were located close to the gravity center of the vehicle as is depicted in figure 1. The position of the devices is essential to improve the accuracy of the collected measurements [19].

TABLE II
Technical specifications of hardware elements included in Samsung Galaxy S8

Samsung Galaxy S8			
RAM	4GB	**CPU**	4 x 2.3 GHz 4 x 1.7 GHz
Weight	155g	**Dimensions**	149x68x8mm
Angular rate range	± 1000 deg/s	**Angular rate resolution**	0.04 deg/s
Acceleration range	± 7.8g	**Acceleration resolution**	0.02 g
Price		600 €	

TABLE III
Technical specifications of the VBOX IMU connected with the VBOX 3i data logger of Racelogic

VBOX 3i Data Logger Plus GPS Dual Antenna			
Latency	8.5 ± 1.5 ms	**Memory**	Compact Flash: Type I
Sampling rate	100 Hz	**Velocity accuracy**	0.1 km/h
Velocity range	from 1000 mph to 0.1 Km/h	**Power consumption**	Max. 5.5 Watts
Weight	900g	**Size**	170×121×41mm
IMU (RLVBIMU03)			
Angular rate range	±150 deg/s	**Angular rate resolution**	0.01 deg/s
Acceleration range	±1.7 g	**Acceleration resolution**	0.001 g
Price		13,000 €	

Fig. 1. Vehicle used in tests equipped with two smartphones: Samsung Galaxy S8 and Xiaomi Redmi 3; and the VBOX IMU connected with the VBOX 3i data logger of Racelogic

The SensorLab app for android was used to acquire the data from the smartphone sensors. This app checks all sensors of a smartphone (accelerometer, gyroscope, light sensor, etc.) and it allows to recorded the data received for each of them into a CSV file. However, the variables considered for this study were just the lateral acceleration and the yaw rate, the measurements were gathered without a specific sampling rate.

The root mean square (RMS), maximum error between each point and normalized error were computed in order to determine the accuracy of the devices. The comparison was done using Racelogic VBOX as the ground truth. This comparison was done off line after the tests. In Section III, results are presented.

B. Experiments Definition

The hypothesis evaluated in this work is that the precision provided by the smartphones is similar than the one provided by costly devices, such as VBOX IMU connected with the VBOX 3i data logger of Racelogic.

To evaluate this hypothesis, both lateral acceleration and yaw rate are measured meanwhile two typical maneuvers such as J-Turn and Lane Change (LC) are conducted. These variables have been decided to be used because they have direct influence on the vehicle lateral dynamics and they suffer higher variation in these maneuvers. Three different tests were carried out for each maneuver in order to verify the validity of the results.

TABLE IV
EXPERIMENTS PROPOSED

Maneuver	Evaluation	Variables to measure
J-turn in a roundabout with a radius of 20 m at around 40 km/h	Measurement accuracy and sampling rate	Yaw rate and lateral acceleration
Lane change at around 40 km/h	Measurement accuracy and sampling rate	Yaw rate and lateral acceleration

As it can be seen in Figure 2, tests have been carried out in Legans (Madrid, Spain) using a commercial vehicle, a Mercedes Sprinter van.

Fig. 2. Experiments' context (Map scale 1:7800 cm)

III. Experimental Results

For experimental testing, two of the most common maneuvers were performed: J-Turn and Lane Change.

A. Test1: J-Turn maneuver

A J-Turn maneuver, in a roundabout with a radius of 22 m, is carried out at a constant speed of 40 km/h on dry pavement as shown in Figure 3. Figures 4 and 5 show the lateral acceleration and yaw rate, respectively, obtained from the sensors inside of the Xiaomi Redmi 3 (Blue) and Samsung Galaxy S8 (Red). These two sets of data are compared with the one obtained from the VBOX IMU (Green). It can be seen that the behavior of the three sensors are very similar, and the norm, RMS (root mean square) and maximum errors have also been computed in order to quantify the accuracy of the different devices. The norm error as a function of time is calculated as follows [5]:

$$E_t = \frac{\varepsilon_t}{\sigma_t} \cdot 100, \qquad (1)$$

where:

$$\begin{aligned} \varepsilon_t^2 &= \int_0^T \left(\phi_{GT} - \phi_{lc}\right)^2 dt \\ \sigma_t^2 &= \int_0^T \left(\phi_{GT} - \mu_{GT}\right)^2 dt \end{aligned} \qquad (2)$$

ϕ_{GT} is the measurement obtained from the VBOX IMU (ground truth) , ϕ_{lc} is the measurement from the smartphone's sensors and μ_{GT} is the mean value of the ground truth data obtained during the period T.

Fig. 3. Trajectory followed by the vehicle in Test 1 (Map scale 1:2100 cm). Start point (green) and end point (red)

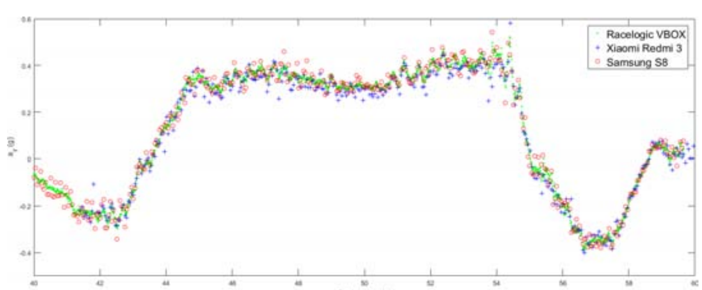

Fig. 4. Lateral acceleration measured by the VBOX IMU (green points), by the Xiaomi Redmi 3 accelerometer (blue points) and by the Samsung Galaxy S8 accelerometer (red points) in Test 1

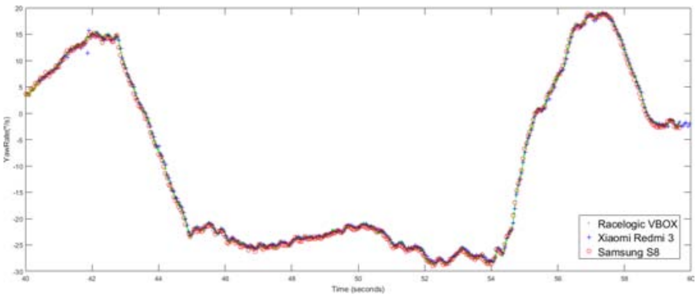

Fig. 5. Yaw rate measured by the VBOX IMU (green points), by the Xiaomi Redmi 3 accelerometer (blue points) and by the Samsung Galaxy S8 accelerometer (red points) in Test 1

To validate the results for J-turn maneuver, three similar tests have been carried out in the same roundabout. For RMS error, the standard deviation has been included to quantify the data dispersion. The results in Table V show that the errors are very similar for both smartphones. Regarding lateral acceleration errors, these are higher for Xiaomi Redmi 3 than Samsung Galaxy S8 with a difference of 2%, 0.01 g's and t 0.3 g's for norm, RMS and maximum errors, respectively. Nevertheless, the yaw rate errors are higher in Samsung Galaxy S8 (with a difference of 0.4% for norm error and 0.06 °/s for RMS error) except for the maximum errors which have a difference of 0.5 °/s). These data indicate that the smartphones have low sensitivity to noise cause the dispersion is very small compared with the mean error. In Figures 4 and 5, a low scattering for both smartphones can be observed.

TABLE V
OBTAINED ERRORS FOR TEST 1

	Lateral Acceleration		
	Norm Error	**RMS Error**	**Maximum Error**
	(%)	**(g's)**	**(g's)**
Xiaomi Redmi 3	11.29	0.034±0.004	0.3612
Samsung Galaxy S8	9.44	0.028±0.008	0.0871
	Yaw Rate		
	Norm Error	**RMS Error**	**Maximum Error**
	(%)	**(°/s)**	**(°/s)**
Xiaomi Redmi 3	2.16	0.36±0.02	2.0983
Samsung Galaxy S8	2.53	0.42±0.07	1.5181

B. Test 2: Lane Change maneuver

A slalom maneuver on dry pavement is carried out as shown in Figure 6. This kind of test is very useful to check if the sampling frequency is sufficient, because lateral acceleration and the yaw rate parameters vary very fast in a lane change. Figures 7 and 8 show the lateral acceleration and yaw rate data, respectively, obtained from Xiaomi Redmi 3 (Blue) and Samsung Galaxy S8 (Red) sensors. These two sets of data are compared with the one from VBOX IMU (Green). It can be seen that the sampling frequency for both devices is enough to properly sample the signal. Again, the behavior of the smartphones is close to the VBOX devices.

Three similar test have been carried out in order to validate the results for LC maneuver. For RMS error, the standard deviation has been included to quantify the data dispersion. The results in Table VI show that the errors are very likely for both smartphones. Concerning the norm and RMS errors between Samsung Galaxy S8 and Xiaomi Redmi 3, the difference is about 1.5%, 0.12 g's and 3%, 0.15 °/s for lateral acceleration and yaw rate, respectively. For maximum errors, the difference between them is about 0.6 g's and 2.2 °/s, for lateral acceleration and yaw rate, respectively.

TABLE VI
OBTAINED ERRORS FOR TEST 2

	Lateral Acceleration		
	Norm Error	**RMS Error**	**Maximum Error**
	(%)	**(g's)**	**(g's)**
Xiaomi Redmi 3	26.58	0.03±0.008	0.1418
Samsung Galaxy S8	25.16	0.028±0.006	0.0878
	Yaw Rate		
	Norm Error	**RMS Error**	**Maximum Error**
	(%)	**(°/s)**	**(°/s)**
Xiaomi Redmi 3	9.18	0.25±0.05	0.9943
Samsung Galaxy S8	12.35	0.40±0.09	3.1024

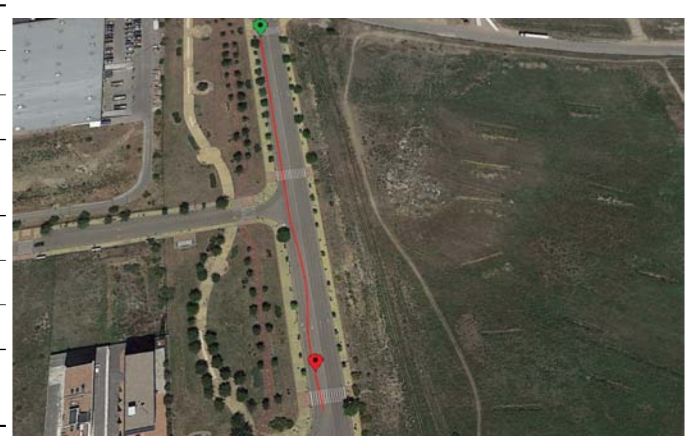

Fig. 6. Trajectory followed by the vehicle in Test 2 (Map scale 1:2100 cm) - Start point (green) and end point (red)

IV. DISCUSSION AND CONCLUSION

The results can be used as first approach to design an efficient and versatile low-cost system, able to be integrated on vehicles, and based on commercial smartphones. A sensor fusion based system can be implemented in order to perform real-time

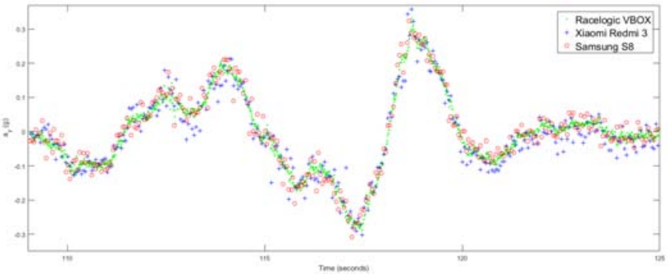

Fig. 7. Lateral acceleration measured by the VBOX IMU (green points), by the accelerometer of Xiaomi Redmi 3 (blue points) and by the accelerometer of Samsung Galaxy S8 (red points) in Test 2

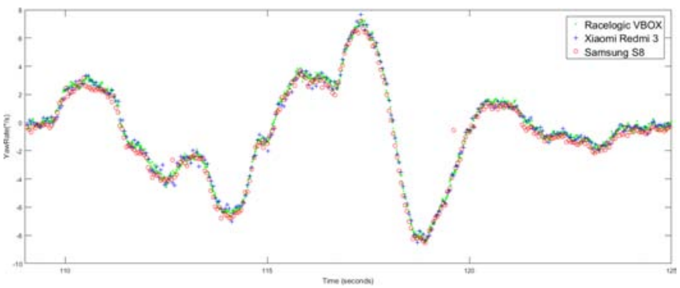

Fig. 8. Yaw rate measured by the VBOX IMU (green points), by the accelerometer of Xiaomi Redmi 3 (blue points) and by the accelerometer of Samsung Galaxy S8 (red points) in Test 2

estimation and control tasks, resulting in the improvement of vehicular safety.

The data shows that under used testing conditions the accelerometers and gyroscopes from both smartphones produce similar results as Racelogic VBOX IMU. The results are very similar for both smartphones, so their price is not related to the performance of the sensors.The noise impact is despicable. The average RMS error in the sensors from Xiaomi Redmi 3 is 0.033 g's for lateral acceleration and 0.35 for yaw rate and the average RMS error in the sensors from Samsung Galaxy S8 is 0.028 g's for lateral acceleration and 0.4 for yaw rate.

Finally, Racelogic VBOX IMU provides all the data at a constant sampling rate of 100 Hz, but for the smartphones there is not a constant sample rate, being always higher than 50 Hz. The sample rate is directly related to the capture software, and there are some applications that allow to fix a constant sample rate. Anyhow, experiments determined that for the considered case, 50 Hz is a sampling rate high enough to perform reliable experiments [20].

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