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Review

# Smartphones as an integrated platform for monitoring driver behaviour: The role of sensor fusion and connectivity

Stratis Kanarachos[a,*], Stavros-Richard G. Christopoulos[a,b], Alexander Chroneos[a]

[a] Faculty of Engineering, Environment and Computing, Coventry University, Priory Street, Coventry CV1 5FB, United Kingdom
[b] Solid Earth Physics Institute, Faculty of Physics, National and Kapodistrian University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

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ABSTRACT

Nowadays, more than half of the world's web traffic comes from mobile phones, and by 2020 approximately 70 percent of the world's population will be using smartphones. The unprecedented market penetration of smartphones combined with the connectivity and embedded sensing capability of smartphones is an enabler for the large-scale deployment of Intelligent Transportation Systems (ITS). On the downside, smartphones have inherent limitations such as relatively limited energy capacity, processing power, and accuracy. These shortcomings may potentially limit their role as an integrated platform for monitoring driver behaviour in the context of ITS. This study examines this hypothesis by reviewing recent scientific contributions. The Cybernetics theoretical framework was employed to allow a systematic comparison. First, only a few studies consider the smartphone as an integrated platform. Second, a lack of consistency between the approaches and metrics used in the literature is noted. Last but not least, areas such as fusion of heterogeneous information sources, Deep Learning and sparse crowd-sensing are identified as relatively unexplored, and future research in these directions is suggested.

## 1. Introduction

Nowadays, the use of smartphones is, indisputably, a part of our lives. The fact that everything is becoming more portable is among others a result of this interaction (Shuib et al., 2015). In the late 1990s and within a few years the use of mobile phones completely changed the way of communication both in social and professional level (Comer and Wikle, 2008). A few years later, mobile Internet technology enabled us to exchange data, emails and mobile browsing giving us access to more information in our everyday life. Fast mobile Internet in combination with more advanced smartphone operating systems (i.e. Android, iOS) generated further opportunities for applications in multimedia, cloud-based services and mobility (Khan et al., 2013). At the end of the 2010s, the embedment of sensors facilitated the use of smartphones as flexible mobile measurement devices, see Table 1 (Ganti et al., 2011). Furthermore, from 2014 onwards, the operating system of smartphones improved significantly bringing energy savings and enhanced connectivity, see Table 2. Different fields of research investigated the new sensing and communication capabilities, including health monitoring (Ben-Zeev et al., 2015), commerce (Shaikh and Karjaluoto, 2015), education (Merchant, 2012), and well-being (Morillo et al., 2015).

This survey focuses on the use of smartphones as integrated platforms for monitoring driver behaviour, specifically the strategic and manoeuvring levels (Michon, 1985). The strategic and manoeuvring levels are interrelated and useful for the evaluation of

* Corresponding author.
*E-mail address:* stratis.kanarachos@coventry.ac.uk (S. Kanarachos).

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**Table 1**
Embedded sensors in a modern smartphone per Android version. In brackets the release date of the Android platform.

| Sensor | Android 1.5 [04/2009] | Android 2.3 [12/2010] | Android 4.0 [10/2011] | Android 4.3 [7/2012] | Android 5.0 [11/2014] | Android 6.0 [10/2015] | Android 7.0 [08/2016] |
|---|---|---|---|---|---|---|---|
| Temperature | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Camera | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| GPS | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Microphone | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Accelerometer | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Ambient temperature | – | – | ☺ | ☺ | ☺ | ☺ | ☺ |
| Gravity | – | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Gyroscope | – | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Light | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Linear acceleration | – | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Orientation | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Pressure | – | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Proximity | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Relative humidity | – | – | ☺ | ☺ | ☺ | ☺ | ☺ |
| Rotation vector | – | ☺ | ☺ | ☺ | ☺ | ☺ | ☺ |
| Game rotation vector | – | – | – | ☺ | ☺ | ☺ | ☺ |
| Tilt detector | – | – | – | – | ☺ | ☺ | ☺ |
| Gesture sensor | – | – | – | – | ☺ | ☺ | ☺ |

**Table 2**
Operating system changes per Android version. In brackets the release date of the Android platform.

| | Communication | Battery management |
|---|---|---|
| Android 5.0 [11/2014] | • New multi-networking features allow apps to query available networks such as Wi-Fi and cellular | • Allows apps to perform concurrent operations with Bluetooth Low Energy (BLE), allowing both scanning and advertising |
| Android 6.0 [10/2015] | • Allows association of an app with a web domain<br>• Allows users to directly share content<br>• Allows voice interaction | |
| Android 7.0 [08/2016] | | • Improved battery life by deferring CPU and network activities when device is unplugged, stationary, and with the screen turned off<br>• Removal of implicit broadcasts and therefore unnecessary apps operation |

Intelligent Transportation Systems (Chong et al., 2013). The driver behaviour at the reactive level was omitted, as it refers to actions with a span of only a few milliseconds. Modern cars have much more powerful computing capacity on board compared to smartphones for real-time and safety–critical applications.[1] The theoretical framework of this review is the Cybernetics model, (Simpkins and Simpkins, 2012), see Fig. 1. According to Cybernetics, driver behaviour depends on the iterative execution of a loop comprising five elements: sensing, information processing, decision-making, feedback and action.

The survey mainly considered scientific contributions that were comprehensive and self-contained, to allow theoretical comparison. We used the Scopus online database for this purpose. The survey did not cover non-smartphone-based publications. Driver behaviour was considered in a multi-modal context; for example, it is of interest to know the transportation mean used by the driver for the last mile coverage (park and ride schemes). Fig. 2 depicts a schematic of the review.

Smartphones have several shortcomings that may pose limitations to their use as integrated platforms. First, the low accuracy of smartphone signals, as smartphone sensors are usually from the lowest commercial grade. Second, the need to drain as little battery energy as possible. Although it is possible to charge the smartphone inside the vehicle, the drivers may use different transportation means in their journey. Third, the limited processing power compared to the one available on board of a vehicle. The latter was one of the main reasons why reactive driver behaviour was not covered. On-board vehicle systems are more suitable for this. On the other hand, smartphones facilitate crowd sensing, not possible for the majority of the current vehicle fleet. Hence, the research questions that drove this survey are: (a) How was information fused and what was the role of connectivity? (b) Which are the best practices that overcome smartphone shortcomings?

The paper is organised into five sections: Section 2 discusses sensor fusion methods for improving smartphone positioning accuracy and reducing battery drain. Smartphone-based driver behaviour monitoring at the strategic and manoeuvring levels is the focus of Section 3. In Section 4, a critical analysis of the publications reviewed is given. The conclusions and future research directions are given in Section 5.

[1] https://www.engadget.com/2018/01/07/nvidia-xavier-soc-self-driving-cars/, accessed on 10/03/2018.