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A Survey on State of the art and future developments of measurement applications on smartphones

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Abstract — The modern smartphones contain different sensor technologies, so they were used as stand-alone measurement instruments on a wide range of application domains. The survey of measurement applications based on smartphones. In the begining part, the evolution of mobile phone technologies, including the mobile networks and sensors developments. Then, in order to highlight the sensors and the communication capabilities, the architectural overview of the hardware and software technologies, are available on latest series of smartphones. In the ending part, the integration of augmented reality to the measurement applications and new type of measurement systems, having a smartphone as processing support, is presented.

Index Terms — Smartphone, Measurement application, Smart sensor, Augmented reality.

1 INTRODUCTION

In the everyday experience, it is necessary to make measurements. Anytime one interacts with the environment around, he/she is making measurements of physical quantities. For this reason, it is important that measurements are available as friendly as possible for specialized and non-specialized people. A measurement is available if the measurement system is accessible and easy to use. For the everyday experience, a us ble measurement system has the following features: (i) non-invasive, (ii) user friendly, and (iii) portable. A modern smartphone allows measuring of different physical quantities directly from its embedded sensors, e.g. three-axis accelerometer, three-axis magnetometer, barometer, light sensor, and so on. Moreover, the smartphone can communicate with other apparatuses (e.g. wireless sensor nodes, data acquisition boards, etc.) through wireless interfaces, such as Bluetooth, Wi-Fi and Near Field Communication (NFC). Thanks to these technologies, the smartphone is candidate to be considered as a measurement system, too.

The statistical data available on [1] present the United States (US) smartphone users and penetration on the market. In 2010, the US smartphone users were 60.2 millions, the 26.0% of mobile phone users and the 19.4% of population. Last year, the number of smartphone users was 106.7 millions, the 44.0% of mobile phone users and the 33.8% of population. In 2015 the number of smartphone users is expected to be around 148.6 millions, the 58.0% compared to mobile phone users and the 45.6% of US population. The smartphones are becoming even more popular and their market is expanding continuously.

In this paper, applications, where the smartphone is described from the point of view of measurements, are presented. Furthermore, a new class fication of smartphone applications, which looks the smartphone as a handheld measurement instrument, is presented. In order to highlight the hardware and the software capabilities for using the smartphone in mea urement applications, the smartphone technology is described. A new user interface for measurement application, based on mobile augmented reality, is described, too.

2. The evolution of mobile phones

In the last 20 years, mobile technologies had an exponential growth due to the development of new network capabilities, the integration of sensors on mobile phones and the introduction of more communication interfaces, as it is shown in Fig. 1.

The second generation networks (2G) are the first digital mobile networks at the global level. The Global System Mobile (GSM) network was released in 1991 and it is the first 2G network [9–11]. The Nokia 1011 is the first GSM Nokia mobile phone and the microphone is the main embedded sensor, which is used for vocal communication [12].

The High Speed Circuit Switched Data (HSCSD) was developed in the 1998 [11]. This allows a communication with different data rates using the same physical layer of the GSM technology and it uses multiple channels per single connection [13]. In the same period, the Nokia 8810 was the first phone without an external antenna and with the infrared communication interface [14].

In 1999 appeared the 2.5G networks, such as General Packet Radio Service (GPRS), which are an extension of 2G networks [11]. In this year, different technologies for mobile phones were developed. A phone called Benefon Esc! was the first GPS integrated mobile phone [15]. The first mobile phone with MP3 music capabilities was the Samsung SPH-M100, and the first mobile phone to offer a WAP browser supporting Internet and Web applications such as email was the Nokia 7110 [16]

In 2000, the 2.75G, known as Enhanced Data rates for GSM Evolution (EDGE), has been developed [11, 17]. In the same period of time the first mobile phone having on a 110 kpixel CMOS camera, called Sharp J-SH04, was developed [18]. In 2001, the first Bluetooth v1.0b capable phone, Ericsson T39 was born [19]. In the same year, the third generation (3G) network have been developed [11]. 3G permits video calls and wireless broadband data transmission

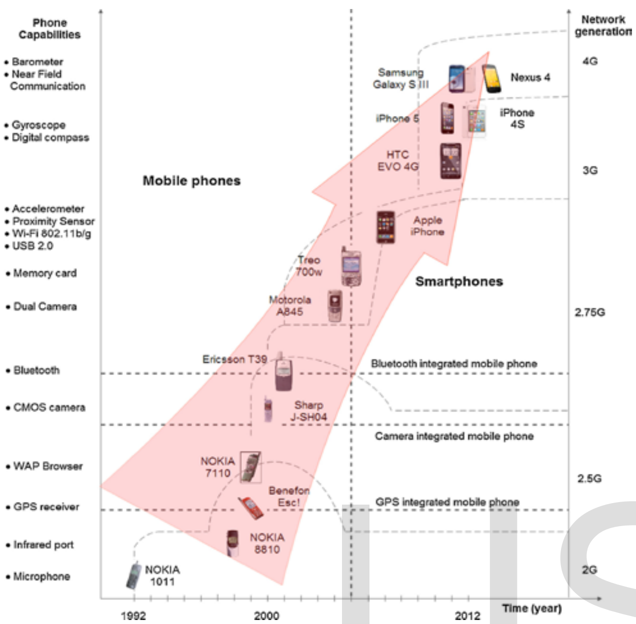

Fig. 1. The evolution of mobile phone vs the number of integrated sensors and the mobile network standard since 1992 to 2012.

[20]. The most used 3G protocol is the Universal Mobile Tel communication System (UMTS) [21]. In 2004, the first mobile phone for video conversation with two 300 kpixel cameras, Motorola A845 was born [22].

The first Palm smartphone, called Treo 700w having the Windows Mobile CE was developed in 2005. The phone had a Bluetooth v1.2 interface, a 1 Mpixel camera, a GPS receiver and a Secure Digital (SD) memory card slot [23].

The 3.5G networks were developed in 2006. The High- Speed Downlink Packet Access (HSDPA) [24] has a bit rate up to 8–10 Mbps. The complementary technology of HSDPA is the High-Speed Uplink Packet Access (HSUPA), an UMTS uplink evolution technology [20]. In 2007, the Apple iPhone was launched on the market. It includes different sensors: a 2 Mpixel camera, a three-axis accelerometer, a proximity sensor, an ambient light sensor, a Global Positioning System (GPS) and a microphone and it has different data interfaces: GPRS, EDGE, Wi-Fi 802.11b/g, Bluetooth v2.0 and USB v2.0 [25].

The fourth generation network 4G was developed on 2009 [26]. In 2011, the first 4G mobile phone HTC EVO 4G was launched on market. The phone specifications are: dual camera including an 8 Mpixel backside camera and a 1.3 Mpixel frontside camera, a GPS receiver, a proximity sensor a three-axis accelerometer, a three-axis gyroscope, a digital compass, an ambient light sensor and a 1 GHz Snapdragon processor [27].

The iPhone 4S appeared on market on October 2011. It is a 3G smartphone with embedded sensors: a three-axis gyroscope, a three-axis accelerometer, a proximity sensor, an ambient light sensor, a microphone, a digital compass, a GPS receiver and two cameras. It has the Bluetooth 4.0, Wi-Fi 802.11/b/g/n and USB 2.0 interfaces [28].

The Samsung Galaxy SIII is a smartphone designed on 2012 by Samsung Electronics [29]. It has 4G communication capability and presents different integrated sensors: a three-axis accelerometer, a RGB light sensor, a digital compass, GPS receiver, a proximity sensor, a three-axis gyroscope sensor, a barometer, a microphone, a 8 Mpixel backside camera and a 1.9 Mpixel frontside camera. The Galaxy SIII has different data exchange interfaces: Bluetooth 4.0, Wi-Fi 802.11 a/b/g/n, Near Field Communication (NFC) and Universal Serial Bus On-The-Go (USB OTG). Two main important competitors of Galaxy smartphone are the iPhone 5 and the Google Nexus 4. The iPhone 5 has all the type of sensors of the Samsung Galaxy S III without the barometer and it does not provide the NFC. iPhone 5 is a 4G smartphone produced by Apple on September 2012 [28]. The Nexus 4 was available on market by Google on October 2012. It has the same type of sensors family of the Samsung Galaxy SIII and it permits the wireless charging [30].

The 5G network will integrate different wireless technologies. The 5G phone will have software for an adaptive wireless communication and new error control schemes that can be downloaded from the Internet. The phone will communicate with different wireless technologies at the same time [31].

3. Smartphone architecture

The definition of smartphone has changed in the time. The simplest mobile device on the market today has been considered a smartphone 10 years ago [32]. Nowadays, a smart phone, in according to [32] has a multitasking operating sy tem, a full desktop browser, Wi-Fi capability, 3G connection, a music player, a GPS or an Assisted GPS, a digital compass, video camera, TV out, Bluetooth, touch display, 3D video a celeration and Inertial Magnetic Sensors (IMS). The develop ment of the smartphone technology has been accelerated t gether with the technology advances and miniaturization [33].

A general architecture of a modern smartphone is shown in Fig. 2 and it is composed of: (i) Application Procesor (AP), (ii) GPS module, (iii) network interface, (iv) data transfer interface, (v) sensors, (vi) Power Management (PM), (vii) External Memory, (viii) Subscriber Identity Module (SIM), (ix) touch display, (x) Internal Memory, and (xi) speaker module.

The AP is a System-on-Chip (SoC) which contains different multimedia components [34]: (i) Processor Core, (ii) group of Multimedia Standard Modules (MSMs), (iii) Wireless Interface Modules (WIMs), and (iv) Device Interface Modules (DIMs). The Processor Core is the most important part of the AP. It has the same capabilities as the processors in personal computers or la tops; and it is optimized for minimal power consumption. The MSMs are the hardware implementation of one or more multimedia standards (e.g. JPEG, MPEG and Audio). The WIMs are used for the wireless communication, for example Bluetooth, GSM and Wi-Fi. The DIMs allow commun cating with different peripheral devices, such as touch display and video camera [34]. The ARM Cortex-A chips series introduced processors d signed for smartphone applications. The Cortex-A15 MPCore processor is the latest of the Cortex-A series and it is based on ARMv7-A Cortex architecture with processor speed up to 2.5 GHz [35]. Exynos 5 Dual core is the Samsung Galaxy SIII AP, based on the ARM Cortex-A15 processor with clock speed up to 1.7 GHz [36].

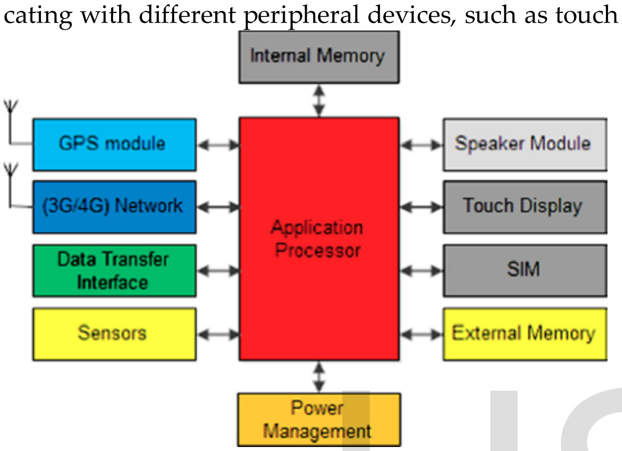

Fig. 2. General architecture of a modern smartphone.

The ARM Cortex-A chips series introduced processors designed for smartphone applications. The Cortex-A15 MPCore processor is the latest of the Cortex-A series and it is based on ARMv7-A Cortex architecture with processor speed up to 2.5 GHz [35]. Exynos 5 Dual core is the Samsung Galaxy SIII AP, based on the ARM Cortex-A15 processor with clock speed up to 1.7 GHz [36].

Another AP is the A6 from Apple, which is based on the ARM Cortex-A15 Dual core processor with clock speed up to 1.3 GHz and it is used in iPhone 5 [28]. The Nexus 4 AP is the Qualcomm Snapdragon S4 Pro, a Quad ARM Cortex 5 with clock speed up to 1.2 GHz [30]. There are measurements instruments, which elaborate the measured value from differ - ent sensors in order to evaluate indirect measures. To this aim, the APs on smartphones can be used for the data processing. Another important aspect of the AP is the possibility to communicate with external measurement equipment, in order to have specific measurements not available from the smartphone sensors.

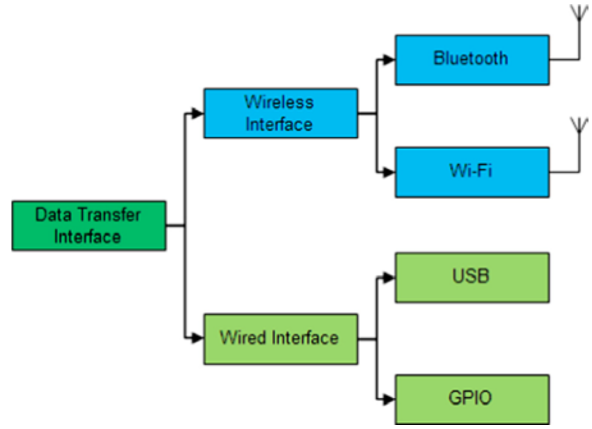

Fig. 3. Data transfer interfaces.

The Data Transfer Interfaces (DTIs) can be divided in two categories, as shown in Fig. 3: (i) Wireless Interfaces (e.g. Bluetooth and Wi-Fi), and (ii) Wired Interface (e.g. USB or General Purpose Input Output-GPIO). These DTIs are used to co municate with other devices such as smartphone, PC, tablet, PDA, etc.

A smartphone may be considered as ''a computer linked to sensors'' [33]. The possible sensors, which are embedded on a smartphone, are shown in Fig. 4. Each sensor communicates to the AP through different interfaces (e.g. Inter- Integrated Circuit-I2C, Serial Peripheral Interface-SPI and System Management Bus-SMBus). The Audio Compressor and DECompressor (CODEC) converts the microphone audio signal to a digital signal through an Analog to Digital Converter (ADC) and digital signal to audio signal for the speaker module through a Digital to Audio Converter (DAC). The video camera communicates with the AP through a Camera Interface protocol, which was standardized by the Mobile Industry Processor Interface (MIPI). The interface can be parallel (Ca era Parallel Interface-CPI), or serial (Camera Serial Interface-CSI) [37].

The user interface plays an important role in a measurement instrument, because it allows interacting between the user and the instrument equipment. The smartphone user interface is the touch display. The position of touch on the screen is detected through a matrix of capacitive sensors on the smartphone display [38].

For stand-alone measurement application, it is important the storage of measured value. Usually, the smartphone has an internal and an external memory slot to store the data. The external memory is the Secure Digital (SD) card type, which is an integrated flash memory [39]. As it has been previously described, the smartphone has the hardware features of a measurement instrument: (i) the AP is used for the implementation of data processing and user interfaces, (ii) the embedded sensors, (iii) the wireless and wired interfaces, (iv) the touch display and (v) the SD card slot.

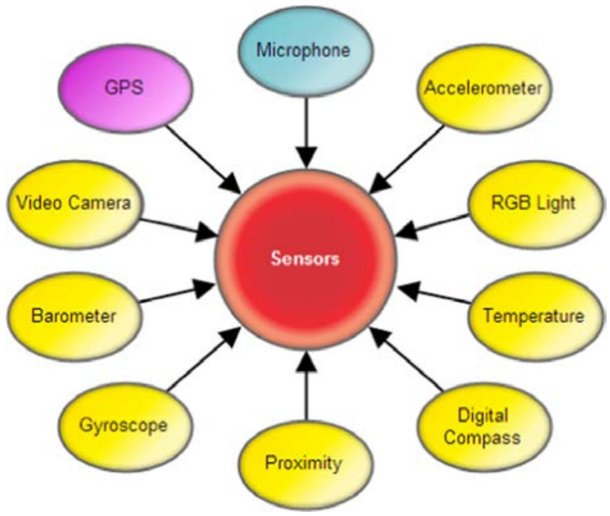

Fig. 4. Sensors integrate on a modern smartphone

4. Operating systems for smartphone

The operating system (OS) represents the software core on smartphone. The smartphone OS can be classified on the basis of [55]: (i) supported mobile phone, (ii) development environment, (iii) software features, (iv) hardware support, (v) power management, and (vi) multimedia capabilities. The market shares of smartphone OSs are shown in Fig. 8. Today, Android is the most popular OS for mobile platforms. It has 56.1% of market share as it is presented in [56]. Android OS was announced by Open Handset Alliance (OHA) in 2007 [55] and it is based on five layers: (i) applications, (ii) application framework, (iii) libraries, (iv) android runtime, and (v) Linux kernel [57].

The core of Android OS is the Linux kernel. This layer contains the drivers to control the hardware. The Libraries Layer contains all the main libraries to manage graphics, data and Web pages (e.g. OpenGL, SQLite and WebKit). The Android Runtime layer contains the Java core libraries and the Dalvik virtual machine, used to execute Android applications. The code is compiled from Java byte code to Dalvik byte code and afterwards the Dalvik virtual machine interprets this code in the native one. The Application Framework provides abstractions for native and Dalvik libraries. The Applications layer contains the applications, which interface directly with the user (e.g. Browser, Phone, Contacts) [57,58].

The iOS is the operating system that is shipped with iPhone, which is based on Darwin open source operating system developed by Apple Inc. [55]. The iOS architecture can be divided in four layers: (i) Cocoa Touch, (ii) Media, (iii) Core Services, and (iv) Core OS [28]. The Cocoa Touch layer permits to build iOS applications and defines the basic application infrastructure. In order to program graphics, audio and video technologies, iOS has the Media layer. The Core Services layer contains the fundamental system services that are used by all the applications (e.g. iCloud storage, SQLite library and XML support). The Core OS layer contains the low level functionalities that the other levels use to make applications [28]. Higher level frameworks are an object-oriented abstractions of lower level functionalities.

Two types of applications can be developed for iOS: (i) native applications, and (ii) web applications [28]. The market share of iOS is equal to 22.9%, as shown in Fig. 8. Another OS is the Symbian which appeared first time on the market in 2000, with the Ericsson R380 mobile phone [59]. Today, Symbian OS has 8.6% of market share as shown in Fig. 8. It is optimized to minimize the power consumption and the used memory. The Symbian core can be divided in three layers: (i) UI Framework, (ii) Application Services, and (iii) Kernel Services and Hardware Interface [59]. The UI Framework layer contains the libraries to create user interfaces. The Application Services layer provides different services as application frameworks, services for messaging and multimedia protocols. The Kernel Services and Hardware Interface layer contains the OS kernel and drivers for specific hardware of the mobile phone [59]. The Microsoft OS for mobile phone was the Windows MobileCE. It was focused providing a friendly user interface for applications on different hardware platforms using the Win32 Application Programming Interfaces (APIs) [55]. It had 1.9% market share as shown in Fig. 8. In 2008, Microsoft started to develop the Windows Phone family OSs, successors of the Windows Mobile platform. Windows Phone 8 has been developed in order to share the same file system, graphics engine, device driver framework and hardware abstraction layer intented to run on PC-class devices [60].

BlackBerry OS was released in 2002 by Research In Motion (RIM) company. The most important capabilities of BlackBerry OS was to integrate existing e-mail services on mobile phones [55]. At the time of this writing, Black- Berry OS has 6.9% market share as shown in Fig. 8. For measurement applications, it is important to have each measured value in a deterministic time. For this reason, it is necessary a Real Time Operating System (RTOS) on smartphone, which guarantees the measurement within a specified time constraint. Different works have focused on the development of RTOSs for smartphones [61]. Furthermore, as previously mentioned, each OS provides the libraries and the APIs for using the sensors and the communication modules. In this way, the development of measurement applications on smartphone is facilitated and lately the number of available applications has grown exponentially.

5. Future developments and conclusions

The increasing number of measurement applications on smartphones is due to their capabilities of (i) sensing more and more physical quantities, so that new measurements can be carried out as a fusion of different measured values from new embedded sensors on the smartphone, and (ii) offering wider wireless and wired connection possibilities and smart visual interfaces in order to receive measurements from different systems external to the smartphone. The development of these capabilities depend on different technologies, such as microelectronics, communications, software, and so on. The top ten trends that will shape the future of mobile smart devices over the next 5 years are widely described in [88]. According to this study the future trends are on: (i) the display technology for more power efficient and flexible displays, (ii) the AP technology in order to increase the power processing and to reduce the power consumption at the same time, (iii) the sensor technology, the smart devices will integrate new sensor types, such as biometric, pressure, and environmental sensors, (iv) the battery technology for wireless battery charging, faster battery charging, and adaptive battery management, (v) the material technology that will enable a new generation of lighter, more flexible, durable, and transparent devices, (vi) the OSs in order to present users an unified experience on different devices, (vii) the Web technology which will move the computing power from the devices to cloud services, (viii) the User Interface (UI) will use the gesture and retina tracking, the infrared keyboard and context- aware UIs, (ix) the cloud service will permit the storing of data online and the data synchronization between different devices, and (x) the mobile network capabilities.

In the measurement field, in order to implement measurement systems based on smartphone, different future developments are necessary: (i) RTOSs for smartphone oriented to measurements, (ii) methods for the calibration of mea urements on smartphone, (iii) hardware integration and miniaturization, in order to embed more sensors on the smartphone, and (iv) user friendly interfaces, which use the MAR capabilities. This trend will increase the use of smartphones in measurement field both as embedded smartphone measurement instrument (ESPMI) and as smartphone measurement instrument interface (SPMII). For each application field, there are different future developments. In the medical field, the trend is to combine biomedical-sensing equipments in a smartphone for health enhancing services. In order to give a feedback of the performance to the user, sport applications will incorporate the recognition of different physical activities and the interaction with physical devices such as training equipment.

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