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Abstract—Smartphone-based medical diagnosis and biomedical health monitoring have rapidly shifted classical invasive methods to bedside non-invasive approaches. The turning point for Mobile Health (mHealth) is close, awaiting the Food and Drug Administration (FDA) approval for unattended deployment of smartphone-based medical devices. From various medical applications, biomedical imaging is one of the most prominent practices, which promote non-invasive treatments and this paper covers this application from a futuristic perspective, which tries to contribute to the notion of the power that lies within current and future smartphone in performing medical diagnosis and prognosis.

Keywords—biomedical imaging, Mobile Health (mHealth), visual diagnosis, visual prognosis.

I. INTRODUCTION

Image technologies have been used in medical applications for many years with two turning points dating back to 1895 and 1898 when Wilhelm Roentgen discovered X-ray and Marie Curie discovered two radioactive elements (radium and polonium) establishing nuclear medicine [1, 29]. In X-ray applications, patient are subjected to the radiations, generated by the radiation tube, which penetrate the skin and soft tissues. On the other hand, in nuclear medicine, patients receive injections or oral dosages of radioactive drugs. While traces of radioactive drugs pass through the patient’s bodies, sensors sensitive to radioactive materials sense the accumulations of radioactivity around arteries, soft, and hard tissues, which map the signatures, showing cancerous regions and blockages in the tissues and other internal organs (outward radiation).

This paper is centered around visual imaging (visible light) as the source of biomedical imaging and the power of smartphone and the growing processing power to capture, analyze and identify possible health issues based on the visual images.

The organization of this paper is based on the following: Section II provides a brief introduction to Mobile Health (mHealth). Section III introduces a number of biomedical image technologies. Section IV covers the mHealth technology for diagnosis and prognosis using visible light. Section V is dedicated to the smartphone feasibility study from the hardware perspectives, followed by mHealth medical imaging future directions, which is then followed by references.

II. INTRODUCTION TO MOBILE HEALTH (MHEALTH)

The term mHealth is associated with the intersection of smartphone technologies and healthcare services, which have paved the way towards medical provisioning through smartphone systems a reality. Figure 1 (adapted from [2, 3]) displays the mHealth medical imaging framework, consisting of the Handheld Medical Image Device (HMID) transmitters, smartphone (data collector), medical subject (e.g., patient’s body), and communication protocols.

A. Handheld Medical Image Devices (HMIDs)

The functionality of HMIDs normally revolves around the transmission of ultrasonic (sound) waves or Radio Frequency (RF) electromagnetic onto the medical subject (patient’s body). The HMIDs may also act as a wave receptor, sensing the reflections of the waves, visual, and temperature-based applications. The HMID is typically connected to a smartphone via a link technology (e.g., Bluetooth, ZigBee).

![Fig. 1. Mobile-Health (mHealth) Medical Imaging Framework (adapted from [29])](image)

B. Medical Subjects

In medical imaging, the patient is subjected to the radiation to or from the HMID, centered on one of the two main applications, first of which the radiation waves are reflected back to the HMID and in the second application type, the radiation passes through the body tissues in which an auxiliary patch of sensor may be required to collect the reflected
signatures. The sensor patch communicates with the HMID or smartphone through one of link technology protocols.

C. Link Technologies

Link technology protocols are associated with short-path communications often used to connect RF transmitters within 0.1 to 100 meters from one another [4]. Figure 1 displays the communication path of a typical mHealth-based imaging system, where the smartphone and the HMID (as well as possible on-body sensor) communicate with one another via a link technology.

There are various protocols used for link technologies, normally based on open standards and sometimes based on proprietary protocols. Open source protocols are normally preferred for variety of reasons (e.g., interoperability, scalability, and security). The most widely used open standard link technology protocols are based on IEEE 802.15 family suits, including; IEEE 802.15.1, 802.15.4, and 802.15.6 [4].

III. BIOMEDICAL IMAGING TECHNOLOGIES

In this section, biomedical imaging technologies are discussed, which are categorized by the types of physical interactions between the medical subjects and the HMIDs as well as the targeted medical conditions.

A. Medical Imaging Physical Properties

There are various physical properties associated with medical imaging, pertaining to:

Electromagnetic Radiations (EMRs) – this includes a large family of members, such as: X-ray, MRI (Magnetic Resonance Imaging), NM (Nuclear Medicine), and visible light. Based on the radiation energy levels, there are two varieties of EMRs; ionizing and non-ionizing. Ionizing EMRs carry high energy levels altering the structure of the atoms by liberating electronics, such as in X-ray. Non-ionizing radiations may not cause such structural changes, therefore they are safer to use. Figure 2 shows EMR’s frequency spectrum used for imaging, such as microwave (MW) and millimeter Wave (mmW).

A.1 X-Ray

X-ray belongs to the ionizing electromagnetic radiation image technologies and with a wavelength between 10⁻¹¹ and 10⁻⁸ meters, corresponding to the frequency range of 3×10¹⁸ to 3×10¹⁹ Hz [10, 11]. X-ray is widely used for general radiology since it passes through thick tissues with limited absorption, thus due to its ionizing properties, excessive usage may cause tissue damage, therefore needs to be limited.

A.2 MRI (Magnetic Resonance Imaging)

MRI (2-85 MHz) is based on the NMR (Nuclear Magnetic Resonance) property, which maps the atoms nuclei image inside the body. MRI scanners align atoms nuclei magnetization, which results in the creation of two and three dimensional (2D and 3D) images with high resolutions. MRI is used extensively for medical image purposes and is well documented in the literature [8-10].

<table>
<thead>
<tr>
<th>X-ray</th>
<th>Ultra-</th>
<th>Visible Light</th>
<th>Infrared (IR)</th>
<th>Terahertz (TH) Gap</th>
<th>mmW</th>
<th>MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>10⁻¹⁰ Hz</td>
<td>10⁻³⁰ Hz</td>
<td>10⁻⁶ Hz</td>
<td>10⁻⁸ Hz</td>
<td>10⁻¹⁰ Hz</td>
<td>10⁻³⁰ Hz</td>
<td>10⁻⁶ Hz</td>
</tr>
</tbody>
</table>

CT Imaging → TH Pulse Imaging (TPi) → MRI Ultrasonic 2-85 MHz

Fig. 2. EMR Imaging Technologies Frequency Spectrum (adapted from [8, 29])

A.3 NM (Nuclear Medicine)

NM was introduced earlier in this paper. There are a few diagnostic techniques related to NM, including [8, 12, 13]: 2D scintigraphy based on internal radio nuclides and 3D using Single Photon Emission Computed Tomography (SPECT).

A.4 Visible Light

There is no mystery in face-to-face contact between the patients and medical practitioners during medical consultations and diagnoses. This uses visible light and its reflection from the patient’s body. The extended version of this is used for remote patient examinations using web camera, and other visual-based diagnostics and treatments, such as: Structured Light Plethysmography (SLP). In SLP, the image of the patient is captured, which helps tracking and measuring the movement in the motion images and producing real-time and accurate data on respiratory changes [14]. Pulse oximeter (SpO2) is another light-based application, which is used to calculate the amount of oxygen level in the patient’s blood.

A.5 Millimeter-Wave (mmW) and Terahertz Technologies

Based on Figure 3, the frequency spectrum between 10¹⁰ Hz and 10¹³ Hz is associated with the millimeter-wave and terahertz technologies. Systems based on these technologies rely on the transmission of mm-Wave and terahertz radiations and analyzing the changes in the reflections (signatures) [15].

A.6 Ultrasonic Medical Diagnosis (UMD)

Ultrasound relies on sound waves between 20 kHz up to several gigahertz, which is used to monitor the growth of the fetus, locate tumors, and other medical anomalies [16]. This is done by transmitting sound signals and analyzing the reflected sound waves (signatures). There are a number of ultrasound techniques, such as [16]: Doppler-based, bone sonography, echocardiography, and other 3D-4D ultrasound-based imaging techniques.

IV. MHEALTH VISUAL DIAGNOSIS AND PROGNOSIS

In this section we focus our attention to the utilization of visible light in performing medical diagnosis of the patient who is exhibiting a number of visual symptoms as well as for medical prognosis of the patients with already diagnosed health condition and on appropriate treatment regimes. In both cases, the smartphone and the relevant hardware and software systems are used to identify possible health issues or keep track of the status of the existing illnesses.
A. Application Characterizations

The application considered in this article requires visual monitoring of the subject for the signs of health issues, therefore the smartphone is expected to make the best use of the camera system and accommodate the following key aspects in the application:

A.1 Intuition

There needs to be a high degree of intuition built into the application in terms of medical subject identification and the physical condition of the person. This may cooperate with other input systems for more accuracy, including: microphone, accelerometer, GPS, radio system, calendar, and biometric identification system.

A.2 Visual Setting Variation Compensation

This application is deployed in highly dynamic scenarios where most of the visual parameters are variable, such as the subject who may be moving, the backlight, the exact distance between the smartphone and the subject, and many other parameters may be dynamic in nature. Therefore the application should be capable of compensating the variability of the parameters and offering intelligent adjustments making the visual effects of the subject appear as constant as possible.

B. Fast Signal Processing

Once visual details of the subject is collected a fast signal processing capability (hardware and software based) is required to carry out extensive computing algorithms to categorize the visual findings. These findings will have to be normalized and compensated (as discussed in subsection A.2) and then compared with the database (for diagnosis) or compared with the history of the subject (for prognosis).

C. Rapid Access to Online Diagnostic/Prognostic Information

Following the fast signal processing, the findings need to be compared with the online database, which will help the system decide on the diagnosis/prognosis. The visual information exchange and comparison may require a rapid online access with a high bandwidth.

D. Hardware Requirements

The most important component in the structure of a smartphone that will be used extensively for this mHealth diagnosis/prognosis application is the camera.

A.1 High Definition (HD) Camera System

The smartphone’s camera is the most important hardware used for our application therefore top of the range quality and features are required to be built into the camera system, including:

Resolution – The current smartphones are equipped with front and rear camera with Samsung Galaxy S5 featuring a 16 megapixel rear and 2.1 megapixel front camera and iPhone 6 is expected to feature a 13 megapixel rear and a 3.2 megapixel front camera. For this application the front camera is of much higher importance since the front camera is used much more. Therefore a higher resolution front camera will be needed.

Low-Light Operation – Since the subject may be indoor while using this application, the application must be useable in low-light situations. Therefore highly sensitive CMOS sensors may be used.

HD Video Recording – 1080 recording is the standard for the video recording and it should be maintained for this application with added features such as: video editing, zooming, snapshot, and variable contrast.

E. Diagnosis of Health Condition

Many health conditions, which feature visual presentations, may be diagnosed using this application (Figure 5 shows a few visual-based medical conditions). These medical conditions feature the following visual effects:

E.1 Flushing

Flushing is the sudden or gradual onset of facial and upper chest redness of the skin, which may (wet flushing) or may not (dry flushing) be accompanied with sweating. Such sudden or gradual change in the skin color can easily be noticed by this the mentioned application. Flushing can occur for variety of causes, such as for anger, embarrassment, menopause, carcinoid syndrome, and thyroid/testosterone problems.

E.2 Skin Problems

There are a number of medical conditions that may present themselves as skin problems, such as: acnes (Figure 5), bumps, rashes, and discoloration. Flushing may also be related to skin, such as in cutaneous lesions and Rosacea.

E.3 Inflammation

Inflammation may be part of a complex biological response of vascular tissues due to irritants and cell damage. Inflammation (visible) shows itself in swelling of the tissue with mild to severe reddening of the skin. This medical condition can also be easily noticed by comparing the current and the history pictures of the affected tissues.
E.4 Mood identification

Identifying changes in the mood can be a complex process, however with a simple mechanism (smile detection, Figure 6), it can provide a good estimate on the subject’s mood. This can become more accurate when combined with other sensory inputs, such as voice (subject, ambient sounds, context identification), accelerometer (motion pattern of the subject), and so on.

E.5 Motion-based Diseases

A number of medical conditions affect the motion capability of the patient, such as Parkinson’s disease, epilepsy (seizure), and paralysis. The visual analysis of the subject may offer clue about the diagnosis and prognosis of such conditions.

The motion issues can be best detected when other sensor information (such as accelerometer) is also presented.

E.6 Pediatrics

Pediatrics is a branch of medicine that deals with infants covering a wide range of medical issues, including Sudden Infant Death Syndrome (SIDS). In 2010, SIDS has globally taken the lives of more than 22,000 infants and those the numbers are declining; SIDS is of a continuing concern. The mentioned application can provide a visual presentation of the infant, which can detect premature apnea that leads to SIDS.

E.7 Geriatrics

This solution may also provide practical solutions for aged-care, including location tracking and activity monitoring.

F. Diagnosis based on Multiple Parametric Inputs

Many health issues can be tracked more effectively by making use of multiple sensory inputs, such as [4]: microphone, calendar, and optional biomedical sensory inputs to monitor fever (temperature sensor), electric-based (Electrocardiography; ECG, Electromyography; EMG, Electroencephalography; EEG, and Electrooculography; EOG), oximeter (light), respiration and voice hoarseness (sound), blood pressure (pressure), motion-based diseases (epilepsy Parkinson's disease using gyroscope and accelerometer), and aged-care (GPS), and Alzheimer (gaming/calendar).

V. Feasibility Study

The current smartphone systems are based on strong hardware capabilities as well versatile operating systems, offering much more than simple telephone usage and basic internet connectivity.

In this section a brief comparison is given based on the current top-of-the-line smartphone systems (as of September 2014), such as: iPhone 6, Samsung Galaxy S5, HTC One M8, Nokia Lumia 930, and BlackBerry Z30. Table 1 summarizes the technical details of the mentioned smartphones. The most important part of this table is the performance of the camera system, especially the resolution of the front camera that would impact the performance of this application greatly.

A. Smartphone Limitations

The current nowadays smartphones come with the following capabilities:

Processing Power – According to Table I, Samsung S5 has one of the fastest CPU (Quad Core Cortex ARM A15, Krait 400) in the current smartphone market, which runs at 2.5 GHz and is capable of running 3.3 Dhrystone MIPS (Million Instructions Per Second, in the Dhrystone benchmarking scale) per MHz core, which is 6,270 MIPS per core [23]. This CPU processing power is more than sufficient to process one very high resolution, high definition medical image at a time.
### TABLE I. COMPARISONS CHART BETWEEN VARIOUS HIGH-END SMARTPHONES (ADAPTED FROM [20, 21, 22])

<table>
<thead>
<tr>
<th></th>
<th>iPhone 6</th>
<th>Samsung Galaxy S5</th>
<th>HTC One M8</th>
<th>Nokia Lumia 930</th>
<th>BlackBerry Z30</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operating System</strong></td>
<td>iOS 8</td>
<td>Android 4.4.2</td>
<td>Android 4.4.2</td>
<td>Windows Phone 8.1</td>
<td>Blackberry 10.2</td>
</tr>
<tr>
<td><strong>Screen Size</strong></td>
<td>4.7&quot; x 334 x 750, 326 ppi</td>
<td>5.5&quot;, 1920x1080x432 ppi</td>
<td>5.0&quot;, 1920x1080x441 ppi</td>
<td>5.0&quot;, 1920x1080x441 ppi</td>
<td>5.0&quot;, 1280x720 294 ppi</td>
</tr>
<tr>
<td><strong>CPU</strong></td>
<td>DC A8, M8 1.4 GHz</td>
<td>2.5 GHz QC A15, Krait 400</td>
<td>2.26 GHz QC Krait 400</td>
<td>2.2 GHz QC Krait 400</td>
<td>1.7 GHz QC Snapdragon</td>
</tr>
<tr>
<td><strong>GPU</strong></td>
<td>PowerVR GX6650</td>
<td>QM Adreno 330 Mali T628MP6 QM QC Adreno 330, 578 MHz</td>
<td>QM QC Adreno 330, 578 MHz</td>
<td>QM QC Adreno 330, 578 MHz</td>
<td>QM QC Adreno 320</td>
</tr>
<tr>
<td><strong>RAM</strong></td>
<td>1 GB, 2 GB</td>
<td>2 GB, 2 GB</td>
<td>2 GB, 2 GB</td>
<td>2 GB, 2 GB</td>
<td>2 GB, 2 GB</td>
</tr>
<tr>
<td><strong>MicroSD</strong></td>
<td>No</td>
<td>128 GB</td>
<td>128 GB</td>
<td>No</td>
<td>64 GB</td>
</tr>
<tr>
<td><strong>Data Protocol</strong></td>
<td>LTE/HSPA+</td>
<td>LTE/HSPA+</td>
<td>LTE/HSPA+</td>
<td>LTE/HSPA+</td>
<td>LTE/HSPA</td>
</tr>
<tr>
<td><strong>Max Data Rate</strong></td>
<td>150 Mbps</td>
<td>150 Mbps</td>
<td>150 Mbps</td>
<td>150 Mbps</td>
<td>150 Mbps</td>
</tr>
<tr>
<td><strong>Rear Camera</strong></td>
<td>8 MP, 1080p@60fps, 720p@240fps</td>
<td>16 MP, 2160p@30fps, 720p@120fps</td>
<td>8 MP, 1080p@60fps, 720p@120fps</td>
<td>20 MP, 1080p@30fps</td>
<td>8 MP, 1080p</td>
</tr>
<tr>
<td><strong>Front Camera</strong></td>
<td>1.2 MP, 720p</td>
<td>2 MP, 1080p@30fps</td>
<td>5 MP, 1080p@30fps</td>
<td>1.2 MP, 720p</td>
<td>2 MP, 720p</td>
</tr>
<tr>
<td><strong>Bluetooth</strong></td>
<td>4.0 + A2DP</td>
<td>4.0 + A2DP</td>
<td>4.0 + A2DP</td>
<td>3.1 + A2DP</td>
<td>4.0 + A2DP</td>
</tr>
<tr>
<td><strong>Wi-Fi</strong></td>
<td>802.11 abgn/ac</td>
<td>802.11 abgn/ac</td>
<td>802.11 abgn/ac</td>
<td>802.11 abgn/ac</td>
<td>802.11 abgn</td>
</tr>
<tr>
<td><strong>GPS</strong></td>
<td>A-GPS</td>
<td>A-GPS</td>
<td>A-GPS</td>
<td>A-GPS</td>
<td>A-GPS</td>
</tr>
<tr>
<td><strong>NFC</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Sensors</strong></td>
<td>AL, AM, CP, GC,</td>
<td>AL, AM, CP, GC, BM, PM</td>
<td>AL, AM, CP, GC, PM</td>
<td>AL, AM, MM, GC, PM</td>
<td>AL, AM, MM, GC, PM</td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>1810 mAh</td>
<td>2915 mAh</td>
<td>2800 mAh</td>
<td>2680 mAh</td>
<td>2420 mAh</td>
</tr>
</tbody>
</table>

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**Digital Medical Images (DMI)** – The specifications of DMIs vary between technologies and applications used in medical imaging. Nuclear medicine is considered as one of the least computationally intensive medical image technologies, typically requiring 128 pixels by 128 pixels with 12 bits resolution (per pixel) [24]. Digital mammography is one of the most computationally intensive medical image technologies, which requires 3000 pixels by 4000 pixels with 16 bits resolution (per pixel) [20]. Table II shows a comparison of a few medical imaging technologies and the minimum required pixel/bit resolutions.

**Communication Data Rate** – Data rate is governed by three sources, the sender, receiver, and the intermediate communication protocol. Based on the literature [25–27], the required data rates for medical imaging vary from 1 Mbps (e.g., for NM images) to 80 Mbps (e.g., for DM images), which also depends on the quality and the resolution. The link technology poses the most probable bottleneck between the transmitter (i.e., HMID) and the receiver (i.e., smartphone). The highest data rate offered by Bluetooth (Bluetooth v3.0 + HS) is 24 Mbps [4], therefore in order for the smartphone medical imaging paradigm to accommodate high resolution/definition imaging technologies, other communication protocols, such as low-power Wi-Fi (e.g., IEEE 802.11n/ac) may be required to offer data rates of up to 100 Mbps.

**On-Device Random Access Memory (RAM)** – The current offered RAM capacities for smartphone systems (Table I) are limited to 2 GB, which may not be sufficient, in particularly for Mobile Cloud applications requiring images to be sent to the cloud using online resources [28]. According to Table II a digital mammography file can be as high as 160 MB. Therefore higher RAM capacities (up to 128 GB) are required for the future smartphone offering imaging technologies.

**Quality of Service (QoS)** – In a local sense, QoS is limited by delay, offered bandwidth, processing power, and limitations within the end-to-end communication path. However in a global sense, in particular in the mobile cloud paradigm, QoS schemes become much more complex, which may include all the hops, nodes, and processing units all the way from the source to the destination. From the current smartphone imaging point of view, local QoS requirements are supported for relatively high quality image applications (up to 24 Mbps), however the global QoS requirements are out of the scope of this article.
TABLE II. COMPARISONS OF DMI RESOLUTIONS (ADAPTED FROM [23], [29])

<table>
<thead>
<tr>
<th>DMI Technology</th>
<th>Typical Resolution (pixels, bits/pixel, bpp)</th>
<th>Typical File Size (MB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Medicine (NM)</td>
<td>128 p x 128 p, 12 bpp</td>
<td>2</td>
</tr>
<tr>
<td>Terahertz Signature (TS)</td>
<td>256 p x 256 p, 8 bpp</td>
<td>6</td>
</tr>
<tr>
<td>MRI</td>
<td>256 p x 256 p, 12 bpp</td>
<td>8</td>
</tr>
<tr>
<td>DSA</td>
<td>512 p x 512 p, 8 bpp</td>
<td>7</td>
</tr>
<tr>
<td>CAT Scan</td>
<td>512 p x 512 p, 12 bpp</td>
<td>12</td>
</tr>
<tr>
<td>Ultrasonic Imaging (UI)</td>
<td>512 p x 512 p, 24 bpp</td>
<td>20</td>
</tr>
<tr>
<td>CDR</td>
<td>2048 p x 2048 p, 12 bpp</td>
<td>16</td>
</tr>
<tr>
<td>Digitized X-Ray</td>
<td>2048 p x 2048 p, 12 bpp</td>
<td>16</td>
</tr>
<tr>
<td>DM</td>
<td>3000 p x 4000 p, 16 bpp</td>
<td>160</td>
</tr>
</tbody>
</table>

Security – The same “local/global scenarios” applicable to QoS, also applies to the security requirements. In a local sense, the link between the HMID and the smartphone needs to be secured. The current security strength offered by Bluetooth [4] provides sufficient security power (e.g., Suite-B-based coverage [4]). However in the global sense, the analysis of the security of the mobile cloud is needed, which is also out of the scope of this article.

A few other limitations of the smartphone imaging technology paradigm are summarized below.

B. Dimension and Size

The actual size of a typical medical image system (e.g., MRI and CT Scan) is normally very huge (room size). This is due to the fact that high precision and power radiation systems are deployed with effective shielding. Such capabilities are not feasible for handheld imaging systems due to many physical and application limitations. Future handheld-based imaging systems need to compensate for these limitations.

C. Operational Power

Future handheld-based imaging systems are required to operate at very low powers due to the limitations in size and weight. Therefore low-power, low-noise amplification is required with ultra-fast signal processing techniques to acquire high precision imaging outputs using variety of digital filters.

D. Operational Safety

One again due to the size/weight limitations, offering high levels of operational safety may become challenging, due to not enough radiation shielding and exposure to excessive (and sometimes unwanted/second-hand) radiation, which may limit the deployment of handheld imaging systems. To tackle this challenge, high efficiency micro-shielding may be required.

E. Program Intuition

The applications running on smartphones will become increasingly more intuitive therefore a great deal of processing power will be dedicated to their operations. This requires major collaborative efforts across multidisciplinary domains, which will help link computer scientists with professionals in psychology, sociology, medicine, and health departments.

REFERENCES
