

TOPICAL REVIEW

A Review of Inductive Sensing and Imaging Technologies in Healthcare

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ABSTRACT The demand for biomedical devices that can collect high-fidelity data from patients in various environments, inside and outside medical clinics, and can provide high-precision diagnosis and long-term monitoring, is high in the healthcare industry. Among different sensing technologies, this study specifically focuses on providing a review of inductive sensing-based devices used in healthcare. Although the concept of inductive sensing has been used in other fields aside from healthcare, we believe that there is a high potential for a wide range of use of this sensing method across various biomedical devices due to the low cost, flexibility in the sensor design, mature fabrication technologies, and high sensitivity. This review first summarizes the mechanisms of inductive sensing-based devices and design considerations. Then, three main groups of applications that are used in healthcare and rely mainly on inductive sensing for their diagnosis and treatments are presented, including motion tracking and continuous monitoring systems, bio-signal detection systems, and imaging biological tissues. We conclude with a summary of the current status of inductive sensing devices used in healthcare, highlighting the promising capabilities and barriers to overcome.

INDEX TERMS Coils, imaging, inductive sensing, medical devices.

I. INTRODUCTION

In the last decades, we have witnessed a rapid growth in technological developments which has impacted many systems, including medical and healthcare systems. The advancement and development of biomedical sensing technologies is driven by the high demand for use of these technologies in healthcare [1], [2], [3], [4], [5]. This is due to the unbiased measurements that can be collected from the device in daily clinical practice, scientific research, and as wearable devices [6], [7], [8], [9]. To overcome several limitations for the medical diagnosis and treatments (such as in the data collection and processing, the complexity of the devices being used, or the environment where they are used), sensing-based devices can enable long-term monitoring and signal detection inside and/or outside the medical clinics, high-speed data collection, and processing.

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Several review articles have been presented in the past discussing bio-medical sensing devices and imaging. For instance, in [10], an overview of recent advances in sensing technologies, including sensors and smart devices, and their applications in healthcare, biomedical, and environmental research has been presented. Another article [11], focuses on the advancements made in the development of materials for the fabrication of biosensors.

Since recently wearable sensing technologies have attracted great attention due to their many advantages, there are multiple review articles on this topic. In [12], a review of wearable devices for healthcare applications has been provided. The paper summarizes all major components in wearable healthcare systems, such as materials, chemical analysis techniques, equipment design, and manufacturing methods. It also gives a discussion on the progress made in this field and future challenges. Another article [13] focuses on the latest research on various wearable devices used in physiological signal monitoring and data processing methods for cardiovascular, locomotive, and brain signals.

Other review articles on wearable devices used in healthcare are presented in [14], [15], [16], [17], and [18].

Different types of sensing mechanisms are used on wearable devices, including flexible sensors. In [19], an overview of flexible sensors is presented. Different from the previous articles, in [20], a review of silicon-based sensors for biomedical applications has been provided. A unique review, highlighting the potential applications of graphene as a biomedical sensing element has been presented in [21].

As optical sensors have gained prominence for biomedical applications, different concepts of optical sensing used in healthcare have been presented in review articles [22], [23], [24].

Microwave imaging for biomedical applications has been brought to the attention of researchers in the last few decades. In [25], a comprehensive review of different ultra-wideband antenna designs for near-field microwave imaging has been provided with attention to radiation mechanisms and the techniques to reduce the size and improve the bandwidth. In comparison to the previous review article, in [26], the recent progress in flexible imaging sensors for biomedical applications has been reviewed. In [27], an analysis of current developments in the field of terahertz antennas in terms of sensing and imaging in general applications has been provided while in [28], the current status and prospects of Terahertz imaging and sensing in healthcare have been discussed. Similarly, another article [29] reviews the current state of the art of Terahertz imaging for biomedical applications, by highlighting the current limitations and presenting the future potentials. Furthermore, the use of antennas for implantable sensors in biomedical applications has been presented in [29].

As spectral imaging integrates conventional imaging and spectroscopy to get both spatial and spectral information from an object, [31] introduces the basics of spectral imaging, imaging methods, current equipment, and recent advances in biomedical applications.

Although there are many review articles on biomedical sensing and imaging in healthcare as discussed above, yet to our knowledge, there has not been a review article on inductive sensing-based devices for biomedical applications and imaging. We aim to bring to attention important features of inductive sensing technologies along with their corresponding applications. The review provides the principles of inductive sensing and imaging, design considerations, utilized materials and costs, various application opportunities, and challenges.

We believe that inductive sensing is still a “new” sensing technique and in its early stage of development for the healthcare industry with a high potential to make a shift in this field, compared to other sensing techniques, such as resistive, capacitive, piezoelectrical, and optical techniques [32], [33], [34], [35]. Each one of these technologies offers certain advantages while suffering some limitations. The working principle of a stretchable resistive strain sensor [32] is based on mechanical strain, which leads to a

change in the electrical resistance. Despite the high sensitivity of this type of sensor, the main disadvantage is the mechanical deformation which directly affects the electrical resistance. In turn, mechanical deformation can be caused by the nominal operating heat which makes them difficult to use for a long period [33]. On the other hand, capacitive sensors have shown less hysteresis, more linear behavior, and faster response. However, these sensors may require a very complex manufacturing process [34], wearing them can be uncomfortable, and they are affected significantly by interfering objects. The optical strain sensor has demonstrated immunity to electromagnetic interference and electrical safety but has a limitation in stretchability [35]. Overall, the above-mentioned technologies suffer various limitations in sensing mechanism, long-term monitoring, interference, complexity, and most commonly, limitations in geometries and practical applications.

On the other hand, inductive sensing-based devices offer high resolution, long lifetime, high stability, simple structure, simple principle of work, and immunity to environmental fluctuations [36], [37], [38]. The sensing elements are simple coils that are made of conductive traces, threads, or wires shaped spirally in various geometrical forms (circular, rectangular, square, elliptical, etc.). This provides limitless possibilities for fitting the inductive sensor elements in practical conditions and within any confined form factor. Furthermore, the cost of making such sensor elements is very low. This makes them suitable for mass production for “home use” medical devices by non-experts as defined by the Center for Devices and Radiological Health, U.S. Food and Drug Administration (FDA) [39]. Using conductive threads to make wearable inductive sensors also allows for integrating these sensor elements seamlessly into the regular cloth which offers users comfort and avoids the use of bulky sensors that limit mobility as well as real-time and long-term monitoring. Aside from all the mentioned advantages, a very recent way of data processing seems to work well with such systems. As inductive sensors can be measured with high precision and high dynamic range using resonant circuits as discussed later, the data can be processed using Machine Learning Algorithms (MLAs), which opens a new path to those biomedical sensors for fast computing and autonomous decision-making, especially for on-site detection and diagnostics. Due to these significant advantages, medical devices using inductive sensors are growing fast for diverse applications in healthcare. Fig. 1 summarizes the advantages of using inductive sensing in healthcare and also the three main categories of applications that will be discussed in this article. Also, Table 1 provides a brief comparison of the common sensing methods used in healthcare.

In the following sections, we discuss, inductive sensing-based devices that are used for motion tracking systems, bio-signal detection systems, and imaging systems. More specifically, we present the principles of the sensing that are used in such applications, categorize recent advances in inductive sensing and imaging based on the applications,

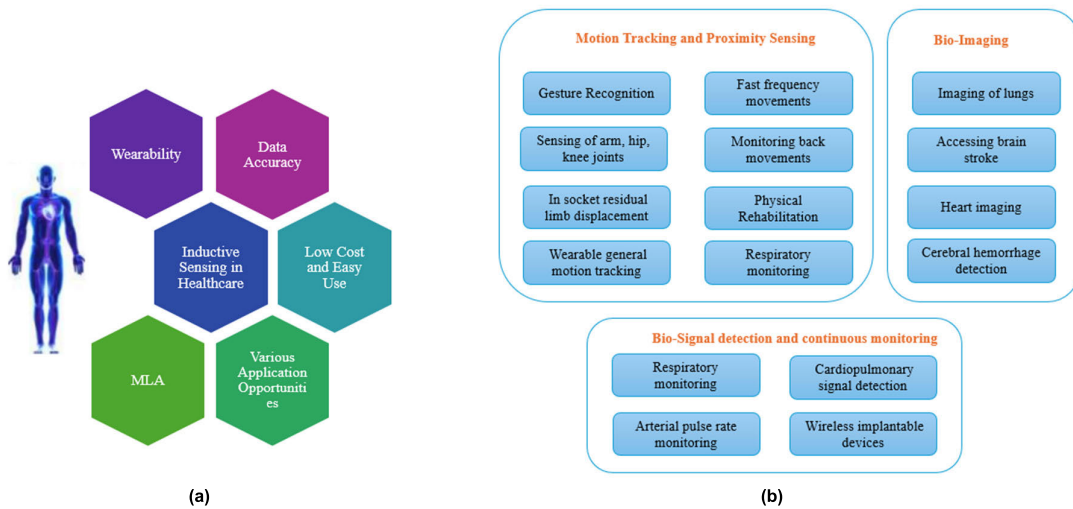


FIGURE 1. (a) Advantages of using inductive sensing in healthcare and (b) three main categories of applications.

TABLE 1. A Comparison Of the common sensing methods used in the Healthcare.

Comparing aspect	Inductive sensing	Capacitive sensing	Resistive sensing	Optical sensing
Sensing principle	Inductance change due to coil deformation or proximity of conductive objects	Capacitance change due to dielectric properties/distance	Change in resistance due to physical deformations	Changes due to light properties
Response	Fast, depending on the application	Fast	Fast	Very fast
Precision	High	High	High	Very high
Typical applications	Biosignal monitoring and detection, motion tracking and biomedical imaging	Biosignal monitoring and detection	Used as a pressure sensor for biosignal monitoring and detection	Biomedical imaging
Advantages	Various applications, flexibility in design, low cost, possible for "home use", wearable/non-wearable, easy implementation	Non-invasive Accuracy for proximity sensing	Easy implementation	High-accuracy
Disadvantages	Susceptible to magnetic and electric field interference	Susceptible to electromagnetic interference	Affected by temperature and mechanical stress	Affected by ambient light and physical conditions

provide the current status of those technologies and compare their features and associated sensors, and provide a discussion on the efficacy of each sensing technique and challenges on its applications.

II. PRINCIPLES OF INDUCTIVE SENSING AND IMAGING

As discussed earlier, for biomedical applications, sensing methods that use inductive coils as the main sensors, have attracted great attention due to their high sensitivity and low cost among other advantages. The sensing coil typically consists of copper wires wound in different ways such as in a spiral or serpentine pattern. This creates a winding that acts as an inductor, i.e., has inductive property. When the alternative current (AC) is applied to the coil, a magnetic flux is produced, which in turn, results in inductance property. Because of this, the inductance of the sensor depends on its

geometry such as shape, size, gap between turns, number of turns, and the ratio of the inner to outer diameter. To maximize the sensor sensitivity, these parameters can be optimized using simulations or experiments.

In general, there are two common types of coils for biomedical applications: 1) coils fabricated by printed circuit board (PCB) technology on flexible or rigid substrates and 2) coils made by conductive threads on regular fabric and cloth. Fig. 2 shows samples of these two types of coils.

The PCB coils refer to coils that are directly fabricated onto dielectric substrates using conductor (such as copper) traces. The trace dimensions and the layout pattern determine the total inductance. They can be fabricated in multi-layers to achieve higher inductance as fabricating multi-layered boards is a mature PCB technology. Various shapes and geometries of PCB coils can be used in healthcare sensing and

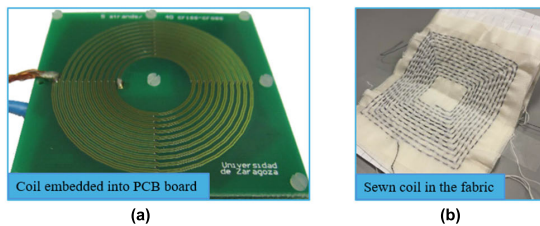


FIGURE 2. Sample coils for biomedical applications: (a) a PCB coil and (b) a coil made out of conductive threads sewn on a piece of fabric.

imaging applications. The most commonly used are spiral coils, circular coils, and square/rectangular coils. PCB coils offer a compact design and high inductance properties [40].

On the other hand, coils made of conductive threads offer more flexibility in the design and the application. For this reason, they are widely used for the design of wearable sensors as discussed in more detail later. Due to the high demand in the medical field, these sensors are made in a way such that they are practical for daily use by users under certain medical conditions. It is worth highlighting that the biggest advantage of building sensors with conductive threads is that, not only can the sensor be attached to a surface, but also, due to the similarity of these threads to regular threads, they can be sewn to the fabric in various shapes making them very adequate for wearable sensing applications.

In the following, we describe three basic inductive sensing principles used across multiple biomedical devices.

A. INDUCTANCE/FREQUENCY CHANGE DUE TO PHYSICAL DEFORMATIONS OF COILS

A group of inductive sensing systems consists of the sensing coil (single coil or multiple coils) connected in parallel to a capacitor to form an LC tank circuit. An example of that is in the commercial data acquisition board manufactured by Texas Instruments [41] for data acquisition from inductive sensors. Construction of this LC tank circuit allows for measuring the changes in the inductance of the coil with much higher sensitivity via the measurement of the resonant frequency of the tank circuit. Since the sensor consists of a single coil, any physical deformation that happens to the coil is translated into self-inductance change. Thus, the resonant frequency of the LC tank circuit changes. For systems built with more than one coil, typically the coils are connected in series. Then, the mutual inductance between the coils is considered as another parameter that affects the total inductance of the coils connected in series. Another factor that affects the overall performance of the system is the geometry of the sensor, including the shape of the coil, the number of turns, the gap between the turns, and the number of layers.

B. SENSING BASED ON ELECTROMAGNETIC INDUCTION

Electromagnetic induction-based devices are usually contactless, i.e., they measure without the need for physical contact. However, the measured object needs to be in the close range of the sensor (coil). As their name implies, the sensing principle is based on magnetic induction and Eddy

currents [42]. Typically these systems are built by placing the coil in proximity to the sensing target, in most cases, biomedical tissues. In principle, an alternating magnetic field is generated by an excitation coil carrying AC current. This field induces Eddy currents into the conductive tissue. The currents, in turn, produce secondary magnetic fields which can be measured and processed with the same coil or a pickup (receiver) coil. Any changes in the shape or position of the conductive tissue can then be reflected in the characteristics of the secondary magnetic fields such as its amplitude and phase that are measured by the pickup coil.

C. IMAGING BASED ON THE ELECTROMAGNETIC INDUCTION

Electromagnetic induction imaging aims at mapping the electromagnetic properties (conductivity, permittivity, and permeability) distribution of a target medium [43], [44] or reconstructing a qualitative image of the subsurface conductive objects [45], [46]. Usually, the system consists of an array of transceiver coils (where each coil works as a transmitter and receiver). The imaged object (tissue or tissue phantom) is surrounded by the coils and is illuminated by the magnetic field produced by the transmitter coils. Similar to the previous discussion for sensing based on electromagnetic induction, the illuminating fields produce Eddy currents in the conductive object (normally tissue) which, in turn, generate secondary fields picked by the receiver coils. Various algorithms have been developed for the reconstruction of images of the conductive objects. For instance, please refer to the fast image reconstruction techniques proposed in [45] and [46].

III. APPLICATIONS OF INDUCTIVE SENSING-BASED DEVICES IN HEALTHCARE

In this section, we categorize biomedical devices that are based on inductive sensing or magnetic induction into three groups based on their applications.

A. MOTION TRACKING SYSTEMS

Inductive sensing-based devices have been widely used for motion tracking and continuous monitoring systems due to their durability, high sensitivity, and flexibility in building the sensor. In [47], a detailed study of the design and fabrication of small-scale planar coils with a high number of turns has been provided. There, the self-inductance is used as a parameter to measure the sensor performance. On the other hand, some recent articles have shown that inductive sensors made of conductive threads offer more flexibility in the design due to the easy fabrication process, different attachment methods, and elasticity. In [48], a contact-based inductive sensing technique has been presented for contextual interactions on interactive fabrics. The sensor is used for target sensing, such as recognizing conductive objects within the given sensing area. Similar sensing topology is used also in healthcare, to build more advanced sensing systems. A very unique system, which has many possibilities for use

in healthcare by children with autism spectrum disorder and more, has been introduced in [49]. This system consists of an array of inductive sensors used for hand gesture recognition. The sensing is based on the proximity between the fingers and the elements of the array of planar coils (sensors). The utilized coils are long rectangular coils that are commercially available (made by Texas Instruments [40]). In [50], a wearable multi-axis motion tracking has been developed using four size-adjustable sensors which are attached to a pair of shorts for motion capturing. There, a random forest MLA is used for hip joint angle prediction. In [51], a hand gesture recognition system called GloveSense has been proposed. There, conductive threads have been utilized to sew coils (sensors) into a glove. The coils are sewn in rectangular shapes along each finger (on the front side and back side) in the glove. The sensing technique is based on physical deformation due to the bending of the fingers. GloveSense has been tested across 10 participants who made gestures corresponding to numbers 1 to 10 in the American sign language (ASL). An MLA has been used for data prediction. In [52], a comparison performance of three inductive sensors has been made for tracking the human arm joints. There, the sensors are made of conductive threads in different shapes and configurations such as helical coil, rectangular folding coil, and two rectangular coils connected in series. For ambulatory monitoring, a highly sensitive wearable angular joint position sensing has been presented in [53]. This system uses a three-dimensional (3D) helical coil knitted in the sleeve of a garment. The sensing mechanism is based on the variation of the mutual inductance between the windings. Another study which also can be used for motion capturing as well as for respiratory monitoring [54], investigates the use of conductive fibers. More on wearable inductive sensing, in [55] and [56], a wearable system based on inductive sensing is used for monitoring back movements. There, textile inductive sensors have been employed for detecting the forward bending of a user while neglecting lateral bending or trunk rotations. It was shown that the fabricated inductive sensor has stable responses, can be fabricated readily, and offers low power usage.

Different from what we have discussed so far, in [57], an inductive sensing system has been presented for measuring in-socket residual limb displacement for people using lower-limb prostheses. More specifically, this work proposed a sensing system to measure limb distances at various locations in the prosthetic socket while the limb-socket interface is not disturbed. The sensors were used to evaluate the limb-socket positions for the stance phase and displacements (pistonning) for the swing phase. This sensing scheme provides a means for measuring the socket fit as it relates to accommodation strategies and interventions, and patient prosthesis use.

Another study in [58] delves into the alterations in magnetic field coupling occurring in space due to planar coil deformations, aiming to implement a novel direct transduction strategy termed Soft Inductive Angle Sensing (SIAS). There, a numerical analysis tool has been devised

to thoroughly examine the inductance fluctuations resulting from the bending, folding, and folding with a slight arc of planar coils. Copper or liquid metal coils of various shapes, pitches, and sizes have been constructed and evaluated. Findings indicated that SIAS exhibits qualities such as hysteresis-free operation, velocity independence, high sensitivity, ultra-stability, and rapid response, ensuring precise measurements with increments as small as 0.1° in folding angle change. Moreover, it demonstrated insensitivity to coil materials and the behavior of embedded soft materials, and scalability across a tenfold range.

Lastly, in [59], a systematic design approach has been proposed that merges the fabrication of conductive fibers using surface nanotechnology, optimization of device assembly processes, signal acquisition and analysis, and theoretical simulations. This novel multidisciplinary strategy integrated material science, textile technology, electromagnetics, and electronic engineering. The resulting magnetic inductance sensing system demonstrated an approximately six-fold change in inductance in response to joint bending motions during rehabilitation exercises. This integrated design strategy introduced a new concept—a comprehensive sensing system design—for wearable technologies in real-time health monitoring applications.

In Table 2, we compare the major works related to motion tracking and monitoring systems, which are mainly based on inductive sensing. We compare them in terms of sensor type (configuration or physical structure), sensing method, data processing approach in each work, and the application targeted in each work. Fig. 3 shows some examples of the relevant systems.

B. BIO-SIGNAL DETECTION SYSTEMS

In this section, we go through the inductive bio-signal sensing technologies that are widely used in healthcare and sports. Compared to other bio-signal sensing technologies, inductive sensors offer better wearability, continuous monitoring, user comfort, and low power consumption.

Overall, wearable bio-signal detection systems can collect high-fidelity bio-signals for a relatively long time. Thus, they are a promising solution for building advanced diagnostic tools for monitoring in daily environments. A good example of such a device is presented in [60], which can be used to monitor the respiration and pulse of a user. The system, called MAIN Shirt, consists of four non-contact inductive sensors, three located at the front and one on the back of the shirt that are used to perform pulse and respiratory monitoring. The sensing principle is based on the Eddy currents as discussed before. The induced Eddy currents into the thoracic by the excitation coil cause the change in the secondary magnetic fields, which in turn, are translated into the change of the reflected impedance of the receiver coil. Similarly, in [61], another telemonitoring system has been developed for respiration monitoring. There, coils wound on plastic forms and with various parameters were positioned at of the lungs.

TABLE 2. Motion tracking and proximity sensing systems.

Reference	Sensor type	Sensing method	Data processing approach	Applications
[49]	An array of planar inductive coils	Proximity sensing, due to the conductivity of the hand as it gets close to the array of sensors to perform different gestures	MLA	Hand gesture recognition
[50]	Textile-based inductive soft strain sensors	Physical deformation, strain, and mutual inductance	MLA	Fast frequency movement and their application in wearable devices, measuring multiaxial hip joint angles during running
[51]	Inductive sensors on the glove	Self-inductance changes due to the hand movements	MLA	Hand gesture recognition
[52]	Inductive textile sensor	Self-inductance and mutual inductance change	no MLA	Real-time monitoring wearable device for sensing arm joint
[53]	Knitted 3D helical coils	Physical deformation, strain, and mutual inductance change	Real-time monitoring, no MLA	Ambulatory monitoring
[54]	Inductive fiber-meshed strain and displacement sensor	Physical deformation, strain, and mutual inductance change	Real-time monitoring, no MLA	Respiratory measuring systems and motion-capturing systems
[55]	Inductive textile sensor	Physical deformation, strain, and mutual inductance change	Real-time monitoring, no MLA	Wearable device for monitoring back movements
[56]	Inductive textile sensor	Physical deformation, strain, and mutual inductance change	Real-time monitoring	Wearable motion tracking
[57]	Custom-designed flexible coil	Proximity sensing	Calibration, no ML	Measures in-socket residual limb displacements for people using lower-limb prostheses
[58]	Textile-based inductive soft strain sensors	Inductance change due to sensor strain and displacement	Real-time monitoring and MLA	Wearable devices measuring multiaxial hip joint angles during running
[59]	Wearable magnetic induction system	Magnetic mutual inductance and self-inductance change due to physical sensor deformation	Real-time monitoring, no MLA	Wearable magnetic induction sensor for physical rehabilitation

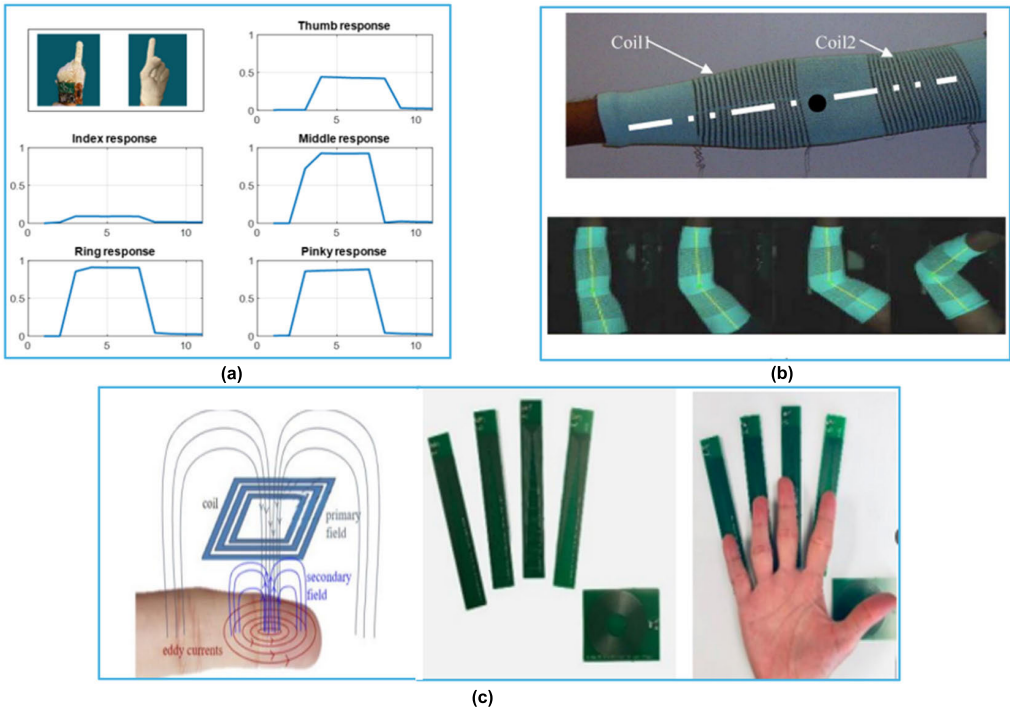


FIGURE 3. Sample Inductive motion tracking systems: (a) GloveSense which is a hand gesture recognition system [51], (b) Inductive fiber-meshed strain and displacement for motion capturing system [54], (c) Hand gesture recognition pad using an array of inductive sensors [49].

Flexible polymeric ferrite sheets were placed between the plastic form and some of the coils to study the effect of

concentrating the magnetic flux toward a thorax. There, the system has been tested with healthy volunteers showing

satisfactory results to monitor respiration rate. However, the adverse effects of the motion artifacts on the captured respiration signals have been emphasized. Also, the notable effect of the variation of the distance of the sensor (coil) from the body has been discussed.

Different from contactless devices, a review of the current available contact-based methods for breath monitoring has been provided in [62] where inductive-based sensors for monitoring the volume and time components of the breathing pattern have been mentioned as well. There, the direct current-coupled inductive sensor can be used to register the change in the self-inductance due to the periodic motion of the rib cage and abdomen.

As the use of respiratory inductive plethysmography modules is growing for breath monitoring, in [63], signal modulation techniques such as amplitude modulation and time division multiplexing are used when the system is built with multiple inductive sensors. All inductive sensors are excited by a high-frequency AC signal periodically and momentarily, and the inductance of each sensor is measured when the AC signal is fed to it. In [63], the sensor performance is tested in terms of the linearity of its response, estimation of lung volume with two sensors, average power consumption of the developed device, and real-time respiration measurement during movement and running. Significant motion artifacts were affecting the sensor responses while running. Thus, the use of adaptive filtering has been recommended to de-noise the responses.

Furthermore, the work in [64] introduces a textile-based strain sensor utilizing embroidery techniques, seamlessly integrating with clothing fabrics. The sensor comprises two embroidered coupling coils, known as coupling planar coils, arranged in series and stacked. The mutual inductance between these coils is contingent upon their relative positions and displacement, rendering it suitable for monitoring human movements and activities, including respiratory rate measurement. Additionally, this configuration can serve as a passive sensor by employing the coils as antennas to interface with RFID/NFC chips. Consequently, sensing data can be wirelessly extracted through RFID/NFC readers. More on respiratory rate measurements, In [65], a new, energy-efficient inductive wearable plethysmography system has been presented. It features highly sensitive 3D knitted helical coils incorporated into a garment, along with an oscillator circuit boasting a high-quality factor. This setup enables extended-term respiratory monitoring through a garment that can be seamlessly blended with everyday attire.

Similar challenges in breath monitoring such as sensitivity to the motion are also faced in cardiovascular-related measurements. A novel inductive sensor for non-invasive arterial pulse measurement has been introduced in [66]. There, the prototype consists of a magnetic elastomer combined with a standard planar coil. Such sensor combinations represent a significant step in the usability of pressure sensors in arterial pulse measurement. Another method based on electromagnetic induction is used for cardiopulmonary signal

detection, based on which the thoracic volume variation affecting the biological impedance, can be detected by magnetic induction [67]. Furthermore, an inductive sensor has been integrated into the cloth in [68] to develop a heart rate monitoring system called WHMIS. There, the inductive sensor is incorporated into the cloth in front of the apex area. Thus, it can assess the cardiorespiratory activity. Another non-contact-based system, called MonitoRing, has been presented in [69], which is in the form of a ring worn on the finger. The sensing method is based on magnetic induction too, providing the possibility of comfortable and unnoticed pulse recordings during daily activities.

Furthermore, human activity recognition (HAR) endeavors to offer insights into human movement and identify both basic and intricate actions within real-world environments. Its objective is to enable computer systems to aid users in their activities, enhancing the quality of life across various domains including senior care, rehabilitation, daily life documentation, personal fitness, and support for individuals with cognitive impairments. Using wearable sensors is one of the main tools that allows the realization of HAR. A good example of the latest advances in HAR has been presented in [70]. There, a wireless system based on magnetic induction is integrated with MLAs to detect a wide range of human motions. Instead of relying on spatial data from inertial sensors, this system captures human body motion by detecting fluctuations in the magnetic induction signals transmitted between a transmitter and receiver during physical activities. This alternative approach addresses various issues inherent in traditional sensor-based HAR systems. It eliminates the necessity for an additional wireless module, decreases power usage, and minimizes bandwidth requirements by integrating data collection and wireless signal transmission processes.

It is worth noting that wireless devices in healthcare have significant applications offering mobility and comfort for the users. In particular, wireless implantable medical devices are used for remote data collection and diagnosis of patients. One of the most preferred methods, as we have also discussed earlier, is inductive coupling, where the power and data between the reader and the implanted device are transmitted via magnetically coupled inductors. In [71], a numerical model has been developed for elliptical inductors, which can be used as wireless implants to monitor the physiological signal from narrow implantation sites. A different approach that incorporates the inductive sensing technique with respect to the swelling of hydrogel samples for implantable biochemical sensing applications has been investigated in [72].

In another interesting development, to measure dental implant stability, an inductive sensing-based technique has been developed in [73] which analyzes the impulse response of the implant. The inductive sensor, along with a specialized adaptor, gauged the movement of the implant. The adaptor's substantial inductance magnified the slight displacement signal emitted by the implant.

In yet another interesting work, a unique system enabling a noninvasive and unobtrusive magnetic wireless

TABLE 3. Bio-signals detection and continuous monitoring systems.

Reference	Sensor type	Sensing Method	Application	Other features
[60]	A textile-integrated magnetic induction sensor array	Magnetic eddy current induction	Monitoring of respiration and pulse rate	Wearable, contactless
[61]	Magnetic induction sensor	Magnetic eddy current induction	Monitoring of respiration	Wearable, contactless
[62]	Inductive sensor	Self-inductance and oscillation frequency	Measuring respiratory rate	Contact-based
[63]	Respiratory inductive plethysmography module	Resonant frequency of the LC tank circuit	Respiratory monitoring and wearable devices	Signal processing, contactless
[64]	Embroidered inductive strain sensor	Inductive coupling	Respiratory rate monitoring	Contact-based
[65]	3D knitted helical coils	Self-inductance change due to displacement, strain and other deformations	Respiration rate monitoring	Contact-based
[66]	High permeability filler-based silicone inductive sensor	The change on permeability of the material in response mechanical stress	Non-invasive arterial pulse measurement	Wearable
[67]	Inductive sensing coil and receiver unit	Magnetic eddy current induction	Cardiopulmonary signal detection	Contactless
[68]	Inductive sensing coil	Self-Inductance changes due to the proximity with the human body	Heart activity monitoring	Wearable
[69]	MonitoRing – a ring coil	Magnetic induction measurement	Pulse plethysmographic measuring.	Contactless
[70]	System of receiver and transmitter inductive sensing coils	Magnetic induction	Human activity recognition	Contactless
[71]	Planar elliptical inductor	Inductive coupling	Wireless implementable devices	Contactless
[72]	Hydrogel bio-chemical sensor	Oscillation frequency	Implantable biochemical sensing applications	Contactless
[73]	Inductive sensing unit	Displacement sensing	Evaluation of dental implant stability	Contact-based
[74]	Magneto-inductive sensor wireless tongue-computer interface	Magnetic induction	People with severe motor disabilities	Contactless

tongue-computer interface system (called “Tongue Drive”), has been presented in [74]. An external system consisting of three-axial linear magneto-inductive sensor modules mounted on a headset near the user’s cheeks is used for sensing the motions of a magnet attached to the tongue. The system can help people with disabilities to have computer access and perform environment control.

In Table 3, we compare the major works related to bio-signal detection and continuous monitoring systems, which are mainly based on inductive sensing. We compare them in terms of sensor type (configuration or physical structure), sensing method, data processing approach in each work, and the application targeted in each work. Fig. 4 shows some examples of the relevant systems.

C. BIO-IMAGING SYSTEMS

Among various screening methods that are used for cancer detection, such as computed tomography (CT), chest radiography, magnetic resonance imaging (MRI), and ultrasound, magnetic induction tomography (MIT) is one of the most cost-effective techniques, even though it is still in the early stages of the development.

In the realm of biomedical imaging, diverse MIT methodologies have been explored, with specific emphasis on

imaging organs like the lung [75], [76], brain [77], [78], heart [79], [80], [81], liver tissue [82], [83], and biological tissues [84], [85]. Gabriel et al. [86], [88] extensively studied various types of human tissues across a broad frequency spectrum. The straightforward characterization of passive electrical properties of biological tissues presents an alternative avenue for tissue imaging. Al-Zeibak and Saunders [89] pioneered the investigation of MIT theory for differentiating between fat and water-containing fat-free tissues.

As discussed in Section II-C, typically, MIT systems are constructed using an array of excitation coils to induce Eddy currents in the target medium, and the magnetic fields produced by the induced Eddy currents are then sensed by the receiver coils [90]. By the measurement of the scattered fields by the object, an image is reconstructed.

In a notable number of works, the sensing system is constructed as a cylindrical tank with excitation coils (for inducing the magnetic fields into the biological object) and the receiving coils (to measure the scattering field from the object) built into that.

In [91], a single-frequency cylindrical holographic electromagnetic induction imaging method including 16 transceiver coils has been presented for small lung tumor detection in human thorax models. The system encompasses a range of

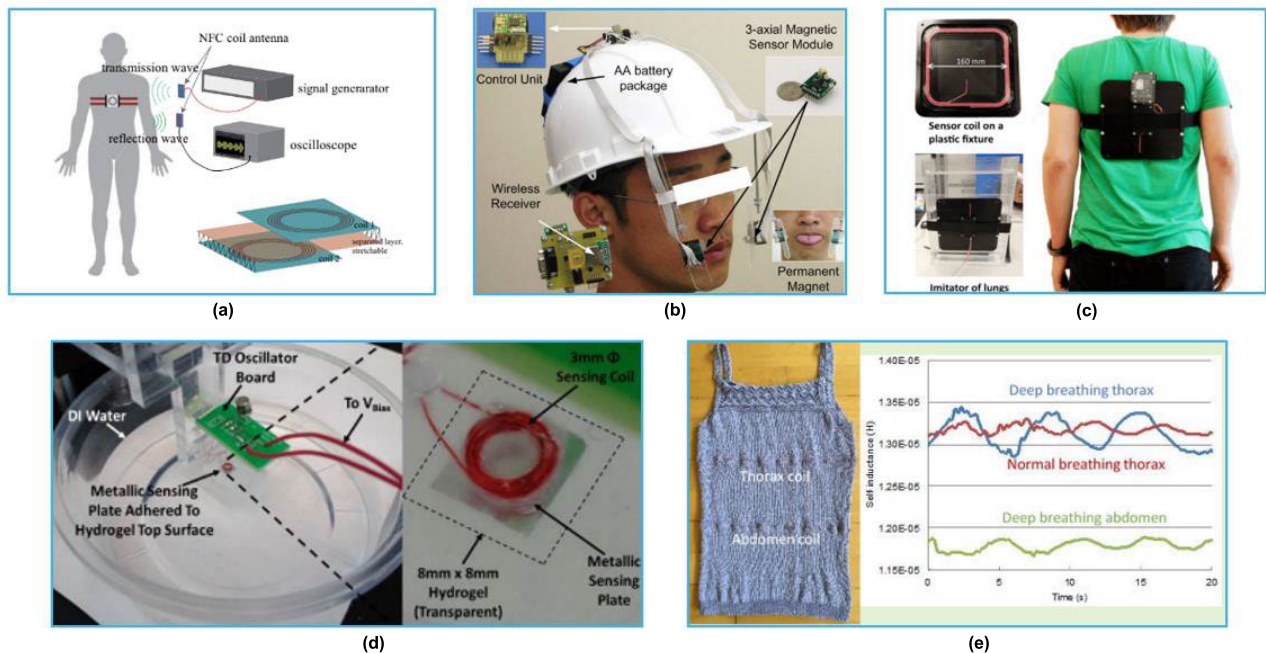


FIGURE 4. Bio-signal detection and continuous monitoring systems based on inductive sensing: (a) Sensor displacement for respiratory rate monitoring [64], (b) Magneto-Inductive sensor tongue-computer interface [74], (c) Magnetic induction-based system for lung monitoring [61], (d) inductive sensing with hydrogel [72], (e) Wearable knitted helical coil system for breath monitoring [65].

lifelike tumors within a thorax model alongside the holographic measurement model. Simulation outcomes demonstrate the capability to detect lung tumors of arbitrary shapes, diverse sizes, and random locations in thorax images. The suggested protocol holds promise for advancing the representation of lung structure. In the imaging algorithm, Born approximation [92] has been utilized which indicates that the magnetic field within the thorax can be roughly modeled as the incident field that would be present at the same location but in the absence of the thorax within the imaging domain. The excitation coil produces the incident field.

In [93], the same research team introduces a theoretical framework for 3D holographic imaging to accurately detect inclusions embedded in biological tissues. The focus of that work has been on assessing brain stroke conditions. A computational setup, comprising a lifelike head phantom, a 16-element excitation sensor array, a 16-element receiving sensor array, and an image processing model has been devised to assess the efficacy of the proposed technique in detecting minor strokes. This initial investigation suggests that the proposed method holds promise for the development of a valuable imaging tool for diagnosing neurological conditions and injuries in the future.

Another MIT system has been presented in [94], where the system with 16 channels working at 1 MHz with a tank filled with water and agar blocks is used to simulate the human brain with edema or hematoma. A similar system but using 56 coil sensors that operate at 1 and 10 MHz for detecting a cerebral hemorrhage has been presented in [95].

In comparison to the previous works, to overcome the limitations in sensitivity and spatial resolution of the MIT devices, a recent technique called optical MIT has been developed. This technique uses optical atomic magnetometers for the detection of the secondary field produced by the induced Eddy currents from the coils. A relevant study in [79] is mostly focused on neurology and oncology applications and, in particular, the technique is used for heart imaging. Similarly, an MIT system with an all-optical atomic magnetometer has been presented in [96]. There, the proposed device generates a conductivity map of conductive objects, accurately reproducing both the shape and size of the imaged samples in comparison to their actual dimensions. Leveraging the potential of all-optical atomic magnetometers for miniaturization and exceptional sensitivity, the proof-of-concept demonstrated in that work offers promising prospects for the advancement of instrumentation in MIT technology.

It is common in MIT techniques to measure the inductance changes of a single coil with the conventional bridge methods. However, these measurements have been consistently affected by noise and drift. Thus, in [97], an alternative approach using the Texas Instruments LDC-1101 chip has been explored. Also, employing infrared (IR) camera technology for coil position tracking, multiple manual scans have been conducted on phantoms crafted from sodium chloride-doped agarose components. This study examined the capacity of single coil scans to depict the corners of square objects, gaps between objects, and adjacent objects with varying conductivity.

TABLE 4. Imaging systems.

Reference	Sensing Method	Applications
[91]	2D holographic electromagnetic imaging	Imaging of lung structure
[93]	3D holographic electromagnetic imaging	Accessing brain stroke
[94]	Multichannel magnetic induction tomography	Brain imaging
[95]	Magnetic induction tomography	Cerebral hemorrhage detection
[79]	Optical magnetic induction tomography	Heart imaging
[96]	Optical magnetic induction tomography	Biomedical imaging
[97]	Single coil magnetic induction tomography	Biomedical imaging

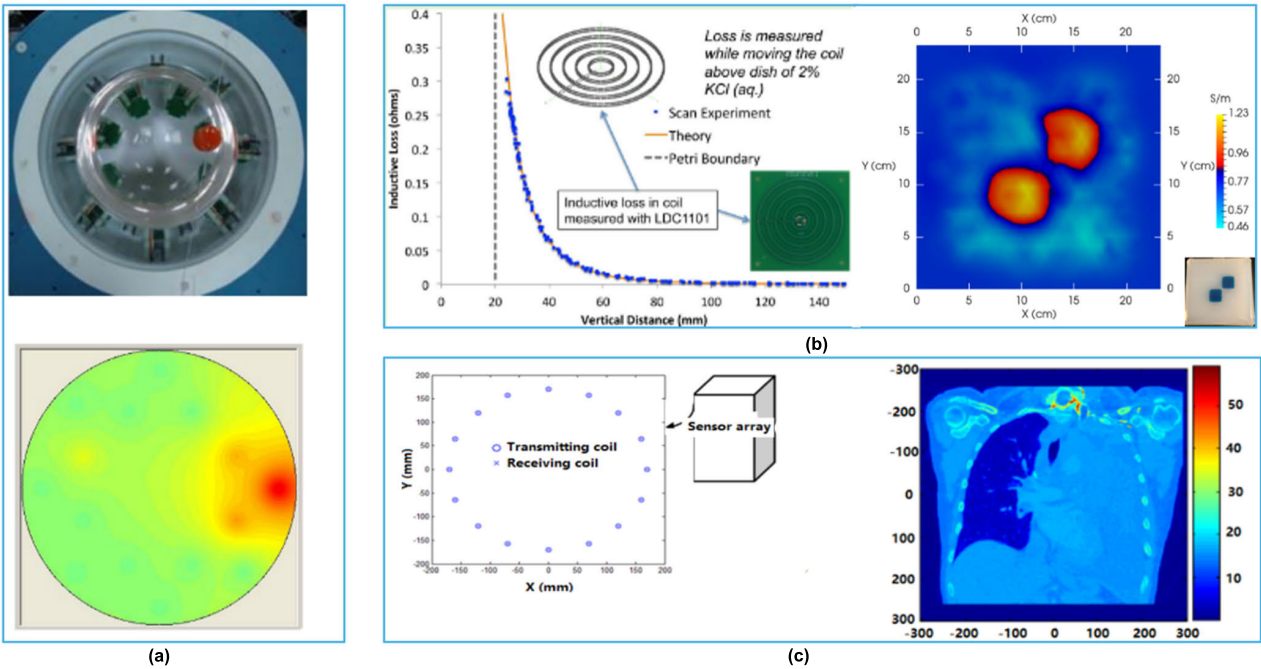


FIGURE 5. Imaging Systems based on inductive sensing. (a) Multi-channel MIT measurement system [94], (b) Single-coil MIT using the LDC-1101 Chip [97], (c) Imaging of lung structure using holographic electromagnetic induction [91].

In Table 4, we compare some of the major works related to MIT systems. We compare them in terms of sensor type (configuration or physical structure), sensing method, and the application targeted in each work. Fig. 5 shows some examples of relevant systems.

IV. DISCUSSION AND CONCLUSION

Inductive sensing is known for its reliability, durability, and ability to operate in harsh environments. It has been commonly used in industrial automation, automotive systems, consumer electronics, and other fields where non-contact sensing is required. In this article, we focused on the healthcare applications of inductive sensors and we identified three main categories of applications based on these sensors: motion-tracking systems, bio-signal detection systems, and

bio-imaging systems. Depending on the application, even though inductive sensing is based on a simple principle, high-precision, and advanced systems can be built using recently developed materials such as durable conductive threads and the recently developed sensitive data acquisition systems. Furthermore, the recent advances in data processing using MLAs allow for the interpretation of the data acquired from the inductive sensors effectively and accurately.

We should emphasize that despite the recent progress in the use of inductive sensors for biomedical applications, there are still certain challenges to be overcome in some areas. In particular, while offering high sensitivity for the measurement of the parameters of interest, these sensors also readily pick interferences caused by the motion of conductive objects, most notably the body parts. Thus, advanced signal

processing and de-noising techniques will help significantly to clean up the responses of the inductive sensors in such conditions.

Furthermore, while the use of conductive threads has made the fabrication of flexible and sensitive wearable sensors feasible and cost-effective, placement of the fabricated sensors on the body parts providing repeatable measurement results is still a challenge in some of the applications discussed. Besides, the use of high-quality stretchable or elastic fabric to mount the sensors is important for the repeatability of the responses and endurance in certain applications such as motion tracking and gesture/posture recognition.

In the realm of imaging, MIT encounters hurdles in its utilization within clinical settings, attributed to factors such as limited image resolution and a lack of extensive commercialization. Nevertheless, MIT's straightforwardness and cost-effectiveness render it an attractive choice for medical imaging.

Overall, we believe that with the rapidly growing progress in the use of inductive sensors for healthcare applications and with the use of more advanced signal processing and MLAs, devices developed based on these sensors will provide cost-effective, durable, and affordable solutions for various diagnostic, therapeutic, and assistive applications in the healthcare industry.

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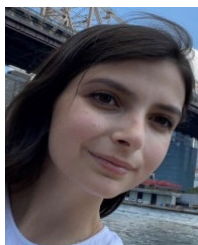


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