Inductive Power Transfer for On-body Sensors

Defining a design space for safe, wirelessly powered on-body health sensors.

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***Abstract*— Designers of on-body health sensing devices face a difficult choice. They must either minimise the power consumption of devices, which in reality means reducing the sensing capabilities, or build devices that require regular battery changes or recharging. Both options limit the effectiveness of devices. Here we investigate an alternative. This paper presents a method of designing safe, wireless, inductive power transfer into on-body sensor products. This approach can produce sensing devices that can be worn for longer durations without the need for human intervention, whilst also having greater sensing and data capture capabilities. The paper addresses significant challenges in achieving this aim, in particular: device safety, sufficient power transfer, and human factors regarding device geometry. We show how to develop a device that meets stringent international safety guidelines for electromagnetic energy on the body and describe a *design space* that allows designers to make trade-offs that balance power transfer with other constraints, e.g. size and bulk, that affect the wearability of devices. Finally we describe a rapid experimental method to investigate the optimal placement of on-body devices and the actual versus theoretical power transfer for on-body, inductively powered devices.**

Keywords—on-body sensing; inductive power; wireless power transfer; healthcare; safety compliance

INTRODUCTION

The popularity of on-body sensing devices is increasing rapidly. Within research there has been a corresponding increase in studies developing and using sensors in areas such as healthcare and activity monitoring, e.g. [1]-[5]. Like many others we believe that the potential of on-body sensing is significant. However, to fully exploit this potential there is a key challenge that must be addressed: that of power. On-body devices are typically powered from a battery that must be replaced or recharged on a regular basis. This basic requirement places significant operating constraints on devices. For example, human intervention is required to recharge or change the battery and this is a well-known cause of frustration. At the very least it leads to down-time between charges. When users place a high value on a device (e.g. a mobile phone) they will generally accept the effort involved in recharging. This is not always the case when devices are considered less important or have been deliberately designed not to play a prominent role in a person's day-to-day routine (e.g. passive health sensors). In many cases people simply forget to recharge devices for long periods or stop using them altogether.

For designers of on-body sensors this leads to a difficult decision. A wide range of power management techniques can be brought to bear in improving the energy efficiency of on-body sensing, such as low-power electronics [6], efficient programming [7], duty cycling communication [8] and data compression [9]. Ultimately however, a trade-off is required. Devices with greater sensing capabilities are likely to have increased power consumption and thus require larger battery capacity or more frequent charging. This paper explores an alternative: the use of 100 kHz inductive power transfer from the environment to on-body sensors. Other wireless powering techniques for body-worn devices exist, using higher frequency regions of the electromagnetic spectrum, e.g. [10], or sonar waves e.g. [11]. Energy harvesting techniques have also been proposed, which generate power from unintentional ambient sources. Inductive power transfer is generally considered to be the highest power option for on-body sensing, as long as proximity to a transmitter can be maintained for at least some of the time, which is the situation investigated here.

If inductive power transfer is effective it would allow us to develop sensing systems that can be worn for longer durations, whilst also having greater sensing and data capture capabilities. Our aim is not to replace other power management strategies, rather it is to explore a new approach that is used alongside strategies such as low-power electronics and efficient programming methods.

While inductive power transfer is well understood in general use, the challenges and constraints involved in inductive power transfer to devices on the human body have received limited attention. This is particularly true with regard to the health and safety constraints. This paper makes several contributions. Firstly, we show how to develop an on-body power transfer system compliant with the International Commission on Non-Ionizing Radiation Protection guidelines on electromagnetic energy exposure [12]. Secondly, our approach takes account of important human factors for wearable devices and defines a design space in which designers can make choices that balance power transfer with factors including the size and bulkiness of on-body sensors. Finally, we describe a rapid and robust experimental approach for estimating the optimal on-body placement of an inductive power transfer devices, based on radio frequency identification (RFID) tags. This approach allows designers to explore how human factors and day-to-day behaviour impact on the theoretical versus actual power transfer of an on-body inductive power transfer system.

Overall, this paper demonstrates that it is feasible to design on-body sensors that use inductive charging, thus enabling more continuous sensing, whilst adhering to the most stringent international safety guidelines and also delivering devices that are wearable and provide sufficient power for use in a wide variety of on-body sensors and healthcare systems.

INDUCTIVE POWER TRANSFER FOR ON-BODY SENSING

Inductive power transfer has received a lot of attention in recent years. Commercial products such as wireless charging plates for mobile phones and other consumer electronics are becoming increasingly popular [13], [14]. It is also widely employed in the medical field to power implanted sensors and devices [15], [16]. Inductive power transfer to wearables has received some interest [17]-[20]. OJAS [20] offers bi-directional inductive power transfer to and from the body, as opposed to the more traditional one way power transfer circuits. However, the compliance of OJAS with international guidelines on electromagnetic energy exposure when used as a body worn system could not be ascertained. No papers could be found on the design, practical aspects and electromagnetic exposure guidelines when creating on-body inductive power transfer systems. Often the state of the art assumes a high familiarity with electronics and physics. Little attention is typically paid to the practical creation of systems, how users' behaviour might impact the power delivered to an on-body system and compliance with international exposure guidelines to minimise electromagnetic energy exposure to users.

A detailed discussion of the theory and electrical design of inductive power transfer systems is beyond the scope of this paper, however it can be found in [21] and [22]. Here, we focus on the physical parameters that underpin power transfer, in order to understand how key features and the geometric parameters of a system influence both the power transfer and safety of devices. Fig. 1 shows a simplified version of an inductive power transfer system. Lines of magnetic flux extend from the transmit coil, through the receive coil and back to the transmit coil. In the on-body scenario, the receive coil and power conditioning circuit are on the user's body. The receive coil is positioned on the body in such a way as to interact with the transmit coil embedded within the user's environment.

$$\oint_C B\, dl = \mu_0 I_C \tag{1}$$

$$V = -N\frac{d\Phi_B}{dt} \tag{2}$$

$$V = -NA\frac{dB}{dt} \tag{3}$$

The power transfer in an inductive system is explained by Ampère's Law (1) and Faraday's law of induction (2), see e.g. [23]. Ampère's Law tells us that passing electrical current I_C in a coil produces a magnetic field B (also referred to as magnetic flux density) around the wire. Similarly, an alternating current creates an alternating field. A second coil with N turns and an area A, positioned into this alternating field experiences an induced voltage according to Faraday's law of induction (2), where Φ_B is the magnetic flux through the coil. Assuming the field to be constant over the area of the coil and perpendicular to the coil allows Faraday's law to be rewritten as (3).

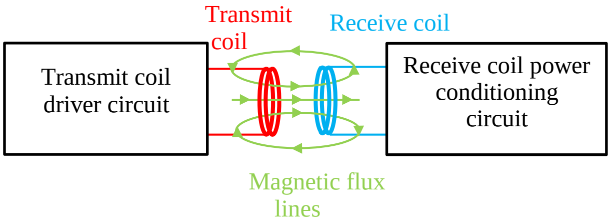


Fig. 1. An overview of an inductive power transfer system.

Equation (3) shows us key parameters to be considered in designing an inductive power transfer systems. V is the induced voltage, which is worth maximising, as this allows for flexibility and high efficiency in the receive coil power conditioning circuit, and ultimately leads to a larger power transfer between the transmit and receive coil. This is achieved by maximising the number of turns N and the coil area A, where the wire gauge needs to be chosen to achieve a suitable trade-off between number of turns and conductivity of the coil. If the receive coil is not aligned with the field from the transmit coil then the magnetic flux through the coil will diminish, decreasing the receive coil voltage. Therefore increasing the area (A) of a circular receive coil, could encompass more lines of flux and lead to an increased receive coil voltage. Here, however we see one of our first major design trade-offs. In the on-body scenario, the receive coil has to fit comfortably on to the body. Large receive coils will be more bulky and may ultimately lead to devices that are less wearable. A balanced approach is thus required.

The final parameter in (3) that the designer can vary is the rate of change of the magnetic flux density, dB/dt, which is increased by raising the magnitude or frequency of the sinusoidal alternating field $B(t)$. These parameters, in turn, are set directly via the magnitude and frequency of the current in the transmitter driver circuit. Thus increasing the amplitude and frequency of the transmit coil current, increases the peak field gradients dB/dt and thereby also the receive coil voltage. The applicable dB/dt is not unlimited however, as strong field changes are known to interact with human tissue. Therefore guidelines exist that limit magnetic field strength magnitude as a function of frequency; these are discussed below as they form the basis of the design method presented here.

NON-IONIZING RADIATION PROTECTION LIMITS

The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has reviewed a range of medical studies in order to produce guidelines [12] on limiting exposure to non-ionising electromagnetic fields. Electromagnetic radiation is classified as non-ionising if it does not carry enough energy per photon to remove an electron from an atom. Non-ionising radiation is typically found below frequencies of the visual light spectrum (750 THz), though different atoms ionise at different frequencies so there is no clearly defined boundary. Most inductive power transfer systems will operate up to MHz frequencies and thus fall under the classification of non-ionising.

The limits set by the ICNIRP are designed to "*provide protection against known adverse health effects*". Two exposure levels are described; occupational and general public. Occupational exposure levels are typically higher (i.e. more lenient) than general public levels and are designed for people who have training to prevent overexposure. The stricter general public exposure levels reflect the broad range of ages and mobility of the general populous. We therefore adopt these general public limits in the design procedure presented here. Other guidelines do exist, e.g. in the US [24], [25] but they are not as stringent as the ICNIRP recommendations, which have been adopted in the EU. To the best of our knowledge no prior paper describes the design of inductively charged on-body sensors that meet these stringent exposure guidelines.

Within the ICNIRP guidelines there are five parameters that are subject to frequency-dependent limitations:

1) Current density J in the frequency range up to 10 MHz; where J is the tissue current in a small area perpendicular to the surface of the body.

2) Current I in the frequency range up to 110 MHz; where I is the tissue current flowing through a control area chosen to maximise the current.

3) Specific Energy Absorption Rate (SAR) in the frequency range 100 kHz-10 GHz.

4) Specific Energy Absorption (SA) for pulsed fields in the frequency range 300 MHz-10 GHz.

5) Power density S in the frequency range 10-300 GHz.

The limitations for each parameter become increasingly strict with frequency, which to some extent counters the benefits of moving to higher frequencies and thus higher dB/dt, which according to Faraday's law of induction (2) increase the induced voltage and power transfer.

Point 3 above highlights a key factor in the design approach adopted in this paper. There is a juncture below 100 kHz at which only the current density (J) and current (I) have to be considered. Above 100 kHz up to 10MHz the specific energy absorption rate (SAR) must be also considered. Typically SAR is significantly more complicated to determine than current density and current alone, which can be inexpensively inferred from measurements using a search coil and oscilloscope. SAR measures typically require computer modelling software or radiofrequency experiments designed to mimic the body tissue. Given this added complexity we have therefore selected an operating frequency of 100kHz for our systems, thus maximising dB/dt for a given B whilst still maintaining the simplicity of calculating just a current density and current. This choice reflects our philosophy that the design of inductive power systems should be as accessible as possible to a wide range of designers; not just those with expertise in computational modelling and RF measurements in body tissue.

The ICNIRP 1998 guidelines provide two levels for electromagnetic protection: reference levels and basic restrictions. Reference levels are taken as an average over the whole body for the electric field strength, magnetic field strength and magnetic flux density. Basic restrictions provide limitations for localised current density and specific energy absorption rate, thus preventing designs in which high fields are used in highly localised regions of the body, for example in close proximity of a small transmit coil. We therefore use the basic restrictions here. Table 4 in the ICNIRP 1998 guidelines [12] set out the basic restrictions for the general public. At our chosen operating frequency, 100 kHz, the corresponding permitted current density in the head and trunk of the body is 0.2 A/m^2 (RMS). The ICNIRP 1998 guidelines do not give current densities for other parts of the body, such as limbs or extremities, so we make the worst case assumption that the head and trunk current densities apply to other parts of the body. In future guidelines, other body locations could be subject to less stringent restrictions.

$$J = \pi R f \sigma B \tag{4}$$

Equation (4) (eqn. 4 of the ICNIRP guidelines [12]) can be used to determine the inductive power transfer systems compliance with the ICNIRP guidelines. To calculate the maximum permissible magnetic flux density, B, at the body using (4) we have to know the transmit coil radius, R, and conductivity of the body, σ. In (4) we assume a homogenous conductivity for human muscle tissue. For example, the electrical conductivity of human muscle tissue at 100 kHz is estimated at 0.362 S/m in the IT'IS foundation database. Using (4), the ICNIRP 1998 guideline value for current density, J, can then be converted to a guideline magnetic flux density, B, which give us the safe magnetic flux density limits for an inductive system.

System geometry and Design Designs

Having decided on an operating frequency of 100 kHz, two key parameters remain to be considered. These parameters relate to the geometry of our inductive transfer system, and as such will be key factors in the wearability of devices. They are: 1) coil radius, and 2) the thickness or bulk of the transmitter and receiver. We consider each of these in turn.

As previously noted, Faraday's law of induction (2) shows that increasing the radius of our receive coil will increase the voltage (and thus power) transfer in our system. However we also noted that larger, bulker coils could make inductive system less comfortable to wear. Equation (4) highlights another reason to constrain the radius of our coils. It shows us that for a given current density, J, and for fixed values of frequency, f, and conductivity, σ, - as is the case in our system - increasing the transmit coil radius, R, will mean the maximum permissible magnetic flux density, B, has to decrease in order to maintain device safety. Decreasing B will result in reduced power transfer, thus partially negating the benefit of a larger coil radius. Overall, then the choice of coil radius should reflect a balance, helping to ensure sufficient power transfer whilst also maintaining safety and the wearability of an on-body system.

In deciding on the thickness of transmitter and receiver – not just the coil thickness, but rather the overall thickness of the transmitter and receiver – it is helpful to begin with basic geometry for an inductive power transfer system as shown in Fig. 2. An on-body receive coil is separated from the body by padding with a thickness Y_R, and a transmit coil is embedded into the user's environment, with a protective padding of thickness Y_T. Fig. 2 also defines the receiver misalignment X_R and transmitter-receiver spacing Y_S.

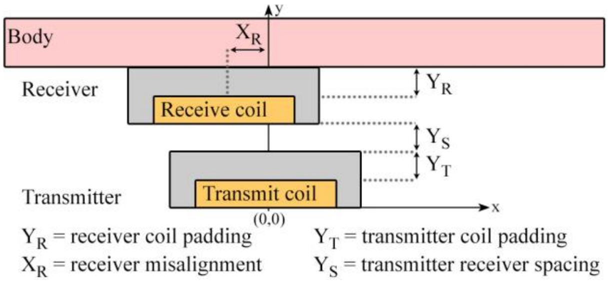


Fig. 2. The overall geometry of an on-body inductive power transfer system, with definitions of parameters and axes.

In this system Y_R and Y_T are key parameters. Both play a large role in determining the amount of power delivered to the receive circuitry. However, they also have a significant impact on the safety of the inductive system, as extra padding helps to reduce the magnetic fields in the body. Optimising Y_R and Y_T based on a trade-off between power transfer and safety constraints thus becomes a key factor in our design process.

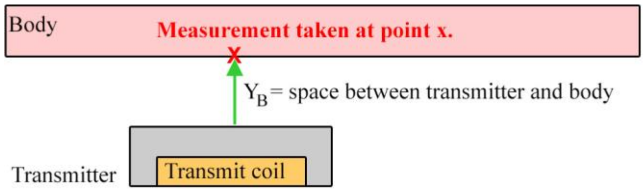
SAFETY CRITICAL SCENARIOS FOR ON-BODY INDUCTIVE POWER TRANSFER

The geometry described in Fig. 2 also allows us to identify the safety critical scenarios for an on-body inductive power transfer system. The scenarios are shown in Fig. 3 a) to c) and represent the worst-case scenarios for magnetic fields in the body. By conducting compliance tests for magnetic fields in each scenario we can assess if an on-body inductive power transfer system adheres to the ICNIRP guidelines.

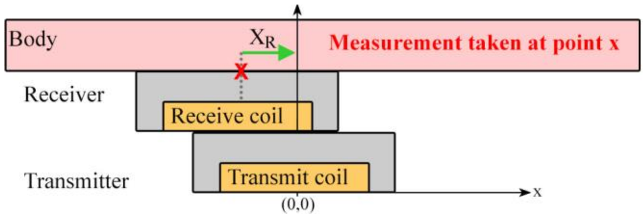
In the first scenario, Fig. 3 a), no receive coil is present. This scenario tests compliance when the receive coil is very far from the transmit coil or for people who may encounter a transmitter in their environment but are not wearing a receive coil. The magnetic flux density at the body is measured for incrementally decreasing distances of Y_B. Measurements are taken at the point corresponding to the centre of the transmit coil, or coaxial, as the maximum magnetic flux density occurs at the centre of a circular coil.

In the second safety critical scenario, Fig. 3 b), the receive coil is present on the user's body, and the transmitter-receiver spacing Y_S is set to zero. The receiver misalignment X_R is incrementally varied. For each value of X_R the magnetic flux density is measured at the centre of receive coil.

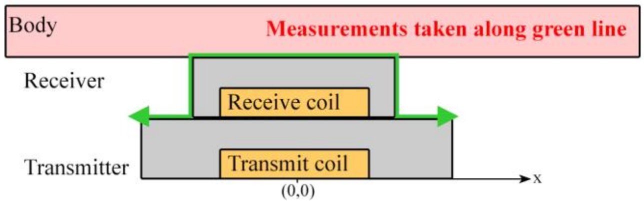
In the third safety critical scenario, Fig. 3 c), the receive and transmit coils are coaxial, and the spacing Y_S is zero. The magnetic flux density is measured over the surfaces that are exposed to the body, as indicated by the green line. This test ensures that body contact with any accessible part of the system complies with the ICNIRP guidelines. Measurements in each scenario can be made using a search coil and oscilloscope, where the search coil records voltage. Using the search coil voltage and the transformer equation ($V_{RMS} = 4.44AB_{Peak}Nf$), we can convert a measured RMS voltage across the coil back to a peak magnetic flux density, B_{PEAK}. This ability to convert an easily measurable parameter back to the ICNIRP guidelines is important. It gives us a method to quickly and simply check the conformity of the inductive power transfer system. To ensure compliance, B_{PEAK} in each of our three safety critical scenarios must not exceed the ICNIRP guideline magnetic flux density.



a) Varying transmitter-body spacing Y_B with no receive coil present. Measurement is at point X using a search coil fully aligned with transmit coil.



b) Varying receiver alignment X_R, at minimum transmitter-receiver spacing. Measurement is at point X using a search coil on receive coil axis.



c) Sweeping the magnetic flux density over the accessible device surfaces. The coils are aligned, with minimum transmitter-receiver spacing.

Fig. 3. Safety critical transmitter and receiver scenarios for magnetic field compliance testing.

DISCUSSION

We have identified a number of important parameters that can be adjusted in the design of an inductively powered on-body sensor. Our key design parameters are:

1) The frequency of our system, (f).
2) The radius of our transmitter coil (R).
3) The number of turns in our coils (N).
4) The amount of padding on our transmitter coil (Y_T)
5) The amount of padding on our receiver coil (Y_R)

What we have seen so far is that developing a guideline compliant system consists of a series of trade-offs. In the remainder of this paper we describe studies to investigate these trade-offs. The overall aim is to optimise the power transferred to our receive circuitry, and thus our on-body sensor, whilst ensuring that the current density in the body remains within ICNIRP guidelines. Many of our parameters, e.g. R and Y_R, will also affect the size and bulk of inductively powered on-body sensors. Thus, a further key aim of our studies is to define an appropriate design space, in which the geometry of systems does not hinder daily wear over long periods of time.

STUDY 1: POWER TRANSFER AND DEVICE GEOMETRY

Our first study investigates the trade-off regarding power transfer and device geometry. Several of the parameters listed above were fixed in this study. As described in Section 0 we operated our system at a fixed frequency of 100 kHz. We chose to use a widely available commercial coil for both our transmitter and receiver, thus fixing the radius and number of turns in our coils. The coil used is part of the Seeed Studio POW0114B wireless charging module and has a mean radius of 17mm, height of 1.65mm, 25 turns of wire, 0.45mm diameter wire, an inductance of 30μH, a DC resistance of 0.25Ω and an AC resistance of approximately 1Ω at 100 kHz. We felt a coil radius of 17mm represented a good compromise in terms of on-body comfort and maximising the receive coil area. Based on this coil size and using equation (4) we can calculate the maximum magnetic flux density, B, allowed for our system as 103.4μT RMS or 146.2μT peak.

Procedure

In order to test performance for different device geometries we made power transfer measurements for the following range of transmit coil padding values (Y_T): 10mm, 20mm, 23mm, 25mm, and 30mm. In each case the transmit and receive coils were coaxial and the size of the padding on the receive coil (Y_R) was varied. For all tests, the load resistor in the receiver circuitry was a decade resistance box connected across the output of a full-wave rectifier in parallel with a smoothing capacitor. The value of the load resistor was varied to maintain a magnetic flux density of 103.4 μT RMS at the body, with a search coil at the red X of Fig. 3 b) and X_R =0mm. The current in the transmit coil was also adjusted to give a maximum magnetic flux density at the transmit coil enclosure of 103.4μT RMS with no receive coil, as shown in Fig. 3 a), and Y_B =0mm.

Results

Fig. 4 shows the load powers achieved in our experiment, with plots for each of the Y_T values tested. Fig. 4 has been plotted for a maximum current density of 0.2 A/m^2 given the geometry of our coils and an operating frequency of 100 kHz.

Analysis

Fig. 4 reveals some interesting trends. Firstly, when Y_T equals 10mm and for all values of Y_R, very little power is delivered to the load, approximately a maximum of 40mW. Increasing Y_T to 20mm, and with Y_R at 0mm, delivers almost 100mW to the load. By increasing Y_R to 8mm and maintaining Y_T at 20mm, the power delivered to the load increases to 188.2mW, almost 5 times as much power as Y_T =10mm. Y_T can be lengthened to increase the power delivered to the load, up to approximately 30mm. At this point the current in the transmit coil gets to 1.68A RMS, the approximate point at which the transmit coil starts to get hot. Increasing Y_T beyond 30mm and thus further increasing the transmit coil current could cause our specific coil to overheat and become unsafe. Beyond Y_T greater than 30mm a different transmit coil with a larger wire gauge would thus be required.

Fig. 4 is very helpful in defining a design space for the geometry of our inductive system. It allows the designer to select a power delivered to the load for their application. A Y_T and Y_R appropriate for their application can then be selected from Fig. 4. Alternatively, the designer can select a value of Y_T and Y_R for their scenario and use Fig. 4 to determine if the power delivered to the receiver is suitable for their application. If a low profile is required, where Y_R must be below 5mm, then values of Y_T from 20mm to 30mm give comparable

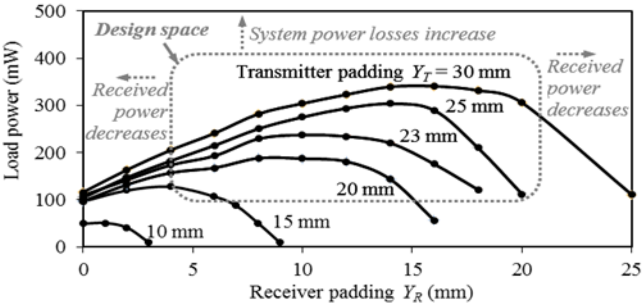


Fig. 4. Power delivered to load against receiver padding Y_R, as a function of transmitter padding Y_T, when a magnetic flux density of 103.4 μT is maintained at the body. Coils' axes are aligned.

performance. At or above Y_R of 5mm, a value from Y_R =5mm to the peak power transfer at a given Y_T can be selected.

Whilst our power curves illustrate the general trend of inductive power transfer systems, Fig. 4 has been specifically plotted for a B_{RMS} of 103.4 μT. If the transmit coil geometry were changed then a new value of B_{RMS} would be inforce and a new set of power curves would have to be plotted. The experimental procedure described here provides a method to generate the necessary plots for any new system.

STUDY 2: COMPLIANCE WITH THE ICNIRP GUIDELINES

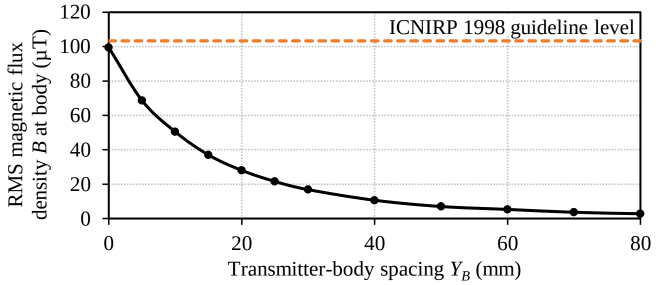
The aim in our second study is to insure that our system can meet ICNIRP guidelines for current density in the body. We used the same set of commercial coils and the 100kHz operating frequency. Based on the results of our first experiment we selected a Y_T of 23mm and a Y_R of 5mm for our on-body inductive power transfer system. We felt that Y_T of 23mm represented an acceptable depth in order to allow an inductive transmitter to be integrated into a user's environment, for example in the arm of a chair or beneath a table. A Y_R of 5mm was selected to allow more power delivery to the load, over a smaller Y_R, whilst still maintaining on-body comfort.

Procedure

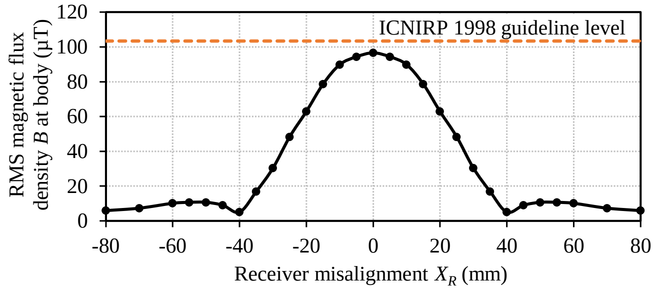
We know the maximum permitted magnetic flux density to conform to the ICNIRP 1998 guidelines is 103.4μT RMS, to give a current density of 0.2 A/m^2. To investigate if our system met this requirement we conducted tests for each of the safety critical scenarios described in Section 0. When taking measurements the body was not actually present, as this could have subjected people to a current density in excess of the ICNIRP guidelines.

Results and Analysis

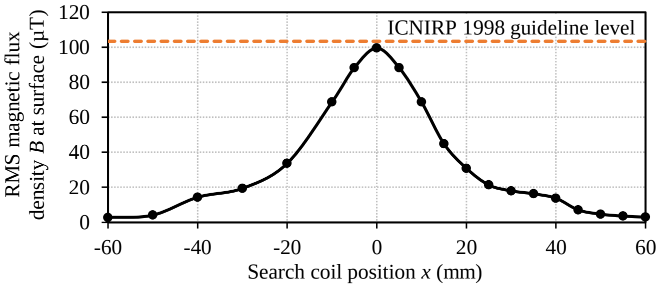
In the first compliance scenario, described in Fig. 3 a), we measured the magnetic flux density without a receive coil present and varying Y_B. Fig. 5 a) shows how the magnetic flux density varied with Y_B for our system. ICNIRP 1998 guideline compliance is demonstrated as the maximum flux density reached is 99.45μT at Y_B=0mm.



a) Measured RMS magnetic flux density B at the body, against spacing between transmitter and body Y_B with no receiver present, as illustrated in Fig. 3 a). Compliance with ICNIRP 1998 guidelines.



b) Measured RMS magnetic flux density B against receiver coil misalignment X_R as illustrated in Fig. 3 b). Compliance with ICNIRP 1998 guidelines.



c) Measured RMS magnetic flux density B against x-position along accessible surfaces as illustrated in Fig. 3 c). Compliance with ICNIRP 1998 guidelines.

Fig. 5. ICNIRP 1998 compliance demonstration of Y_T =23mm and Y_R =5mm inductive power transfer system.

The second compliance scenario is shown in Fig. 3 b). ICNIRP guideline compliance is demonstrated in Fig. 5 b). The maximum flux density reached is 96.61μT at X_R=0mm.

The third scenario is shown in Fig. 3 c). Compliance is again demonstrated in Fig. 5 c). A maximum flux density of 99.50 μT was obtained, when the search coil was coaxial with the transmit and receive coils.

Study 3: Power Transfer

From Fig. 4 we can observe that the peak power delivered for Y_T=23mm and Y_R=5mm is approximately 160mW. In this brief study we conducted a test to understand how out system performed under transmit and receive coil misalignment.

Procedure

The power delivered to the load was measured as the receive coil misalignment from the transmit coil, X_R, was varied.

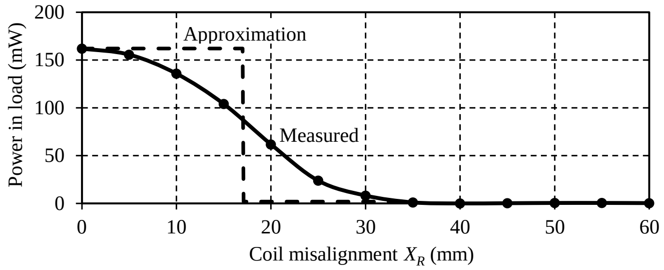


Fig. 6. Variation of power in load against coil misalignment X_R, as defined in Fig. 3 b). The dashed line is a step approximation indicating where 'usable' power is transferred. Y_T= 23mm, Y_R= 5mm.

Results and analysis

Fig. 6 shows the results. We can see that our transfer resembles a step function. Once misalignment has reached 18mm, we have defined a boundary where we consider the power delivered to the load would be too little to charge a storage system such as a battery or supercapacitor.

Study 4: Power Transfer and Daily Routine

Thus far we have shown that it is theoretically possible to transfer power safely to sensors on the human body through inductive power transfer. However, important questions remain. In particular, is this approach really feasible for passive charging in real world scenarios and what impact does human behaviour have on the actual versus theoretical power transfer achieved by inductive transfer systems? Typically, the inductive power transfer literature concentrates on engineering solutions for improving the efficiency of the inductive power system. However for on-body inductive power transfer, human factors are equally significant.

As we have seen the effectiveness of inductive power transfer is highly dependent on the transmit coil being in close proximity and well aligned to the on-body receive coil. Given our aim of passive charging, we cannot expect people to deliberately ensure that their on-body sensors are in close proximity to power transmitters on a regular basis. Instead we suggest it may be possible to charge sensors by taking advantage of the routine nature of much of our lives. We typically carry out specific activities in set locations, such as sitting at a chair while working, watching television on a sofa, or driving a specific vehicle. These activities form parts of our daily routine. Characterising these routines and integrating power transmitters into the environment opens the potential to passively charge on-body sensors.

In this section we describe an experiment to assess the real world feasibility of power transfer to on-body sensors using transmitters embedded in our daily environment. As shown in Fig. 6 the power transferred by our system resembles a step function based on coil misalignment. The behaviour is also characteristic of how radiofrequency identification (RFID) systems work. RFID systems have a transmit coil (RFID reader) and a receive coil (RFID tag). The readers give a binary true or false as to whether a tag is present on a reader. For a tag to be seen, the solid angle of the tag receive window must match with the RFID reader's transmit solid angle. If there is no overlap between the solid angles then the reader will classify a tag seen as false. Our experiment takes advantage of this. To simulate our inductive transfer system we use RFID tags on the body and readers in the environment to measure the time participants' body locations interact with their environmental location. We consider a range of body locations based on sensors locations explored in [5] and three distinct daily activities. The aim is to gain an insight into the potential power transfer of our system in real world scenarios. Our approach can also help to determine the optimal position to place inductive coils in the environment and on-body.

Procedure

RFID tags were placed on participants' bodies as shown in Fig. 7 a). The three everyday scenarios selected for evaluation were watching television whilst sitting on the sofa, washing the dishes and working at an office desk. RFID readers for each scenario were placed as shown in Fig. 7 b) to d). The RFID readers used were Phidgets 1023 readers. The RFID tags were fixed to a participant using surgical tape and their position was adjusted to match up with the position of the RFID reader once they adopted a comfortable position in each scenario. A CSV file was created with the RFID reader ID, RFID tag ID (if applicable) and a timestamp. For each scenario the experiment lasted for 5 minutes for each participants.

Participants

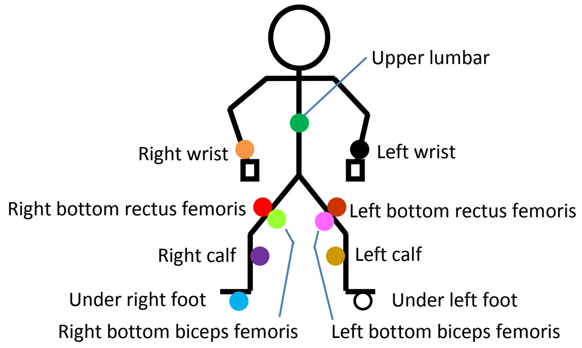
12 participants, aged 18 and 35, took part in the experiment. Each completed all three scenarios.

Results

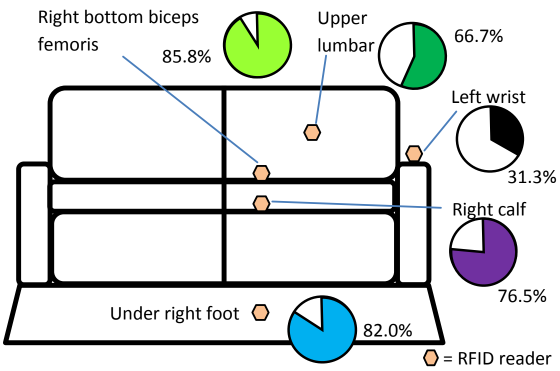
The results shown in Fig. 7 b) to d) are the mean times across all participants that a unique tag spent on a reader during the five minutes of the experiment. For example, the right foot tag performed consistently well over all three scenarios with a mean time range of 55.5% to 83.0%. Other body locations also performed well in their relevant scenarios. The upper lumbar achieved mean contact time of 75.5% and 66.7% in the office and sofa scenarios respectively. The right biceps femoris performed well in the office and sofa scenarios with mean times of 65.2% and 85.8% respectively. In contrast the results for the wrist worn tag we more mixed. It performed well in the office scenario (mean time 69.2%), but less well in the sofa and washing scenarios (mean times of 31.3% and 0.8%). The low mean time for the wrist in the washing scenario is likely explained by our observation during the experiment that participants' wrists were usually inclined when compared to the work surface, with this misalignment reducing RFID tag detection time. This same misalignment would limit the potential for power transfer in our inductive power system.

Analysis

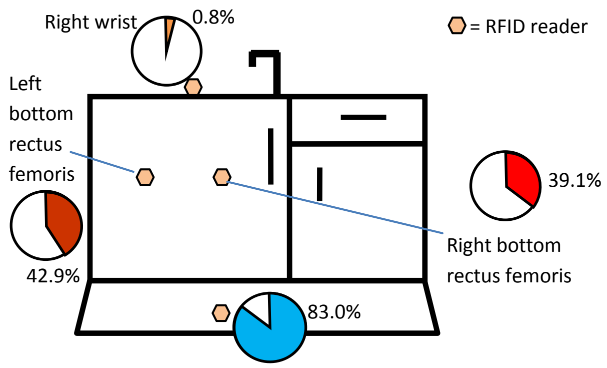
The results provide data on the contact time that can be expected for on-body sensors in a range of body locations across three routine daily scenarios. They show for example that the right foot, upper lumbar and right biceps femoris are promising locations for inductive power transfer, with the mean time seen greater than 50% in two or more scenarios. Other locations, e.g. the wrist, were less successful across our range of routine scenarios, but show promise in specific scenarios, e.g. working at a computer. Our results can be integrated with longer-term behavioural studies analysing how long people spend carrying out various activities and how often.



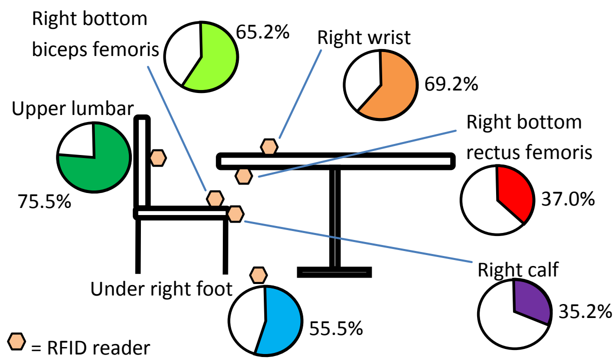
a) Body locations for RFID tags.



b) RFID reader locations and results for watching TV on the sofa.



c) RFID reader locations and results for washing up.



d) RFID reader locations and results for working a desk in an office.

Fig. 7. RFID tag positions on the body, RFID reader positions in the environment and the mean time a unique tag was seen by the reader.

The contact times in this experiment provide the basis for initial calculations for the actual power the can be transferred to inductive powered sensors in real world scenarios. Consider the example of the right biceps femoris, which had a mean contact time of 65.2% when used for five minutes in the office environment. For our system – which has a maximum power transfer of 160mW when the transmitter and receiver are coaxial – over a 5 minute period this would translate into an energy transfer of 48J. In the right biceps femoris example we would expect to see 65.2% of the maximum energy, or 31.3J. To illustrate the potential of this power transfer, consider the ATmega328P microcontroller used in many Arduino boards, including the Arduino Uno. In a low power mode (disabling the brown out detection and using the watchdog timer) a current consumption of 200µA at 1.8V is possible. Assuming all energy from the biceps femoris experiment, 31.3J, can be stored, enough energy is transferred in 5 minutes to run an ATmega328P in low power mode for approximately 24.15hrs. Similar calculations can also be made for other body locations we investigated.

CONCLUSION AND FUTURE WORK

This paper has demonstrated that it is feasible to power on-body sensors using wireless inductive power transfer, thus enabling more continuous sensing, whilst adhering to the most stringent international safety guidelines and also providing sufficient power for use in a wide variety of on-body sensors and healthcare systems. Key choices in our design include the choice of a 100 kHz operating frequency. We have discussed the importance of human factors in affecting on-body inductive power delivery. Our process also allowed us to define a design space for device geometry, which allows designers to consider trade-offs between device geometry and power transfer.

Further investigation is required to understand the human factors associated with on-body inductive power transfer. Whilst the RFID experiments give some indication of the impact on power transfer, further real world use studies of our inductive transfer system are required to fully characterise the power transfer we can expect during a particular domestic routine. However the method described here provides a rapid approach to gain initial estimates of the actual power transfer for systems in a range of daily scenarios. It is a method that can potentially be applied to many more body locations and activity scenarios.

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