Coil Design for Wireless Power Transfer and Communication over Hinges of Smart Glasses

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ABSTRACT

Glasses are a suitable platform for embedding sensors and displays around our heads to support our daily lives. Furthermore, aesthetic features, durability, and portability are essential properties of glasses. However, designing such smart glasses is challenging, because connecting different glass frames both mechanically and electrically, result in smart glasses with bulky hinges. To overcome this challenge, we propose a new design to embed inductively coupled coil pairs adjacent to glasses hinges to deliver power and data wirelessly to the frames. Positioning the coils next to the hinges creates sufficient area for a large transmission and reception coil while maintaining the utility of the glasses. Consequently, we were able to achieve over 85% power efficiency and a communication rate of 50 Mbps between coils that are small enough to be embedded inside the frame of conventional glasses, available on the market.

CCS CONCEPTS

• **Human-centered computing** → **Ubiquitous and mobile computing**; • **Hardware** → *Wireless devices.*

KEYWORDS

wearables, smart glasses, wireless power transfer, wireless communication

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1 INTRODUCTION

Smart glasses, equipped with sensors, actuators, and displays, have promise for naturally incorporating computing around the human head. Therefore, various interactions using smart glasses have been extensively studied [16]. The familiar form factor of *glasses* has significantly contributed to the development of this vision; however, designing smart glasses that are aesthetic, waterproof, and portable (*i.e.*, foldable and small)—as conventional glasses are—is still challenging, which prevents the widespread use of smart glasses.

One notable cause of this challenge is the wiring within smart glasses, which is needed for delivering power and data to integrated electronics. Meanwhile, many applications require electronic components to be placed on different parts of smart glasses [1]. Consequently, when foldable (*i.e.*, portable) smart glasses are designed, these wired connections are established through mechanical hinges, which require bulky hinge structures to maintain the reliability and durability of the connection.

In this work, we propose to cut the cords between hinges by delivering power and data wirelessly through a pair of inductively coupled coils, which are embedded next to the mechanical hinges. Our design enables the coupled coils to be positioned in close proximity, which suppresses the leakage of electromagnetic fields and introduces two significant benefits: (a) higher power transfer efficiency owing to the enhanced coupling, and (b) higher communication rates owing to the availability of a broader frequency band. These benefits meet the needs of various smart glasses, in which the power capacity is limited and large amounts of data (*e.g.*, video

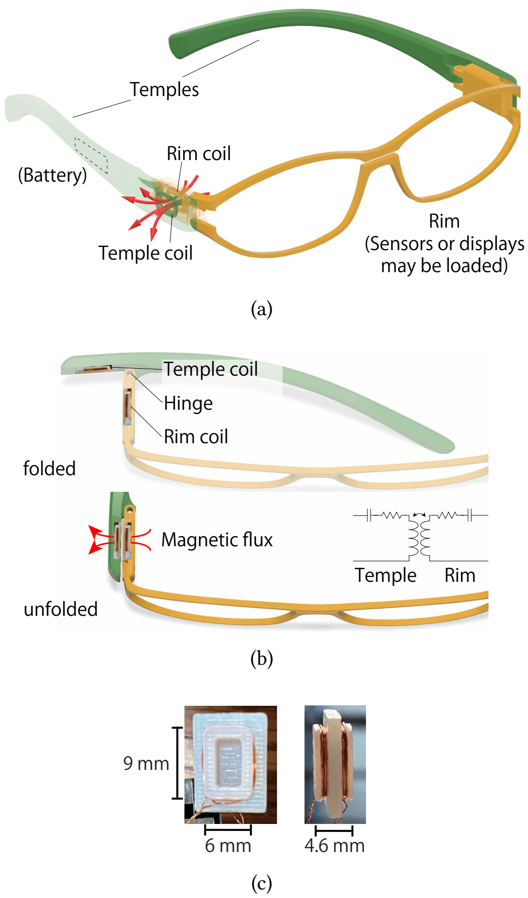

Figure 1: (a) Wireless power transfer and communication between the temple and rim frame of smart glasses are achieved by the interlinkage flux (red arrows) of embedded coils. (b) Top view of (a). The coils are placed next to the hinges, and when the glasses are unfolded, an electrical connection via the magnetic flux is established. (c) Front and top views of the fabricated coil pair measured for analysis.

streaming) must be sent in real-time. To examine the feasibility of our approach, we design a 9 mm × 6 mm coil pair that fits within the frame of commercially available glasses [15] and show through measurements that it presents high power efficiency (over 85%) and a high communication speed (over 50 Mbps).

2 RELATED WORK

Electrically Connecting between Frames

Many approaches for wiring within smart glasses have been explored in previous studies and commercial products. One approach to embed wiring inside hinges [5]; however, reliable hinges with embedded wires require bulky structures. Connections via exposed electrodes such as spring pins [19] have also been investigated, although the connection quality easily degrades due to staining or rusting through contact. Another naive yet promising approach is to make the whole frame rigid [6], although in this approach the glasses cannot be folded and lack mobility. Some smart glasses have all of the electronic components inside one temple [9], although applications such as AR or sound glasses require components on both sides. Wireless links using emitted radio waves have also been used, although the communication speed is limited and they are vulnerable to interference [10]. Moreover, the limited power density is not suitable for delivering power.

Delivering Power and Data Via Inductive Coupling

Power delivery and communication can be established through a pair of inductively coupled coils; the transmitter generates an oscillating magnetic field, whereas the receiver picks up this field to retrieve power and read out modulated bits [12]. This technology has been applied in various domains such as power delivery over mechanical joints in robotics applications [20], and power delivery and communication via coils fabricated on wearable media for charging wearable and mobile devices [13, 14].

We also note that there exist several established standards for this technology. Qi is the most commercially successful power transfer standard, enabling power delivery efficiency of greater than 80% over very short ranges. However, the coil size are typically larger than 30 mm, because mobile devices are their target application. Standards for communication, such as near-field communication (NFC) and near-field magnetic induction (NFMI), have also been established. However, the communication speeds of these standards are limited to several hundred kbps, owing to electromagnetic interference with nearby devices.

3 DESIGN

As shown in Figure 1 (a)(b), a pair of inductively coupled coils are embedded within the edges of the rim and temple of the glasses, whereby power and information are transferred through the inductive link. The design requirements in terms of coil size, power efficiency, and communication speed are described in the following sections:

Size. For smart glasses to be aesthetic, the embedded coils must be sufficiently small; the constraints of the coil size are such that it can be embedded within the outline of the frame size, leaving a margin for the minimum shell thickness of the frame fabrication process (typically 0.8 mm).

Power efficiency. Because the available power capacity in smart glasses is limited, high efficiency is preferred. The factor that correlates with efficiency is the product of the coupling coefficient k between the coil pair and quality factor Q of the coils (kQ). A high k can be achieved when the distance between the coils is small and when the axes of the coils are aligned. Moreover, the quality factor Q of a coil is proportional to the inductance and inversely proportional to the copper loss [12]. Consequently, larger coils with thicker wires improve the quality factor.

Communication speed. Many smart glasses have cameras and displays, which require a high bit rate of communication. According to the well known Shannon–Hartley theorem, a large bandwidth and high signal-to-noise ratio lead to larger channel capacity (*i.e.*,communication speed) [2]. However, the bandwidth and signal strength should be determined carefully, to ensure that surrounding devices are not affected. We also note that the usable bandwidth will expand if the exposed field is small, owing to the small interference with nearby devices [7].

Implementation

To satisfy the size requirement, we designed the coil to fit inside the JN-466 glasses from Boston Club [15]. To achieve sufficient power efficiency, the placement of the coils must be considered carefully. One naive approach to maximize the coupling coefficient k between the coils is to place the coils concentrically to the rotating shaft of the hinge. However, to increase the quality factor Q, the diameter of the coils must be increased, thereby resulting in a larger hinge and failing to meet the size requirement. To fit large coils within the natural form factor of glasses, we leveraged the fact that high efficiency is only needed when the glasses are in use (*i.e.*, unfolded) and placed the coils on the overhang of the temples as shown in Figure 1 (b). With the coil placement addressed above, the dimensions of the rectangular coil that fits inside the glasses were 9 mm long, 6 mm wide, and 1.5 mm thick. The coil core was printed by using a stratasys Objet260 Connex3 3D printer using VeroWhite Plus RGD 835 material. To form the coil, polyurethane magnetic wire with a diameter of 0.2 mm was wound 10 times around the core. The distance between the coils will be approximately twice the shell thickness of the frames (*e.g.*, 0.8 mm shell thickness corresponds to 1.6 mm coil distance). Series capacitors were connected to the fabricated coils as shown in Figure 1 (c), such that they resonate at the operating frequency 13.56 MHz, which is one of the Industrial Scientific and Medical (ISM) bands; these frequency bands are commonly used for wireless power transfer. In the evaluation presented in the following section, the gap between the coils was adjusted from 0.8 mm to 2.0 mm to evaluate the effect of the shell thickness on power transfer efficiency and communication performance.

4 MEASUREMENTS

Power Transfer

We calculated the power transfer efficiency between the coil pair through the S-parameters of the coil pair measured using a vector network analyzer (VNA) under different coil gaps. The measurement was conducted using the operating frequency of 13.56 MHz and the load impedance value was set to the value that maximizes efficiency, based on maximum efficiency point tracking mechanisms [8]. Figure 2 shows the power transfer efficiency with different coil gaps. The efficiency decreases as the distance increases, and over 80% was achieved under every condition; this roughly corresponds to the efficiency of Qi [4]. In particular, when the coil distance was 1.6 mm, corresponding to a shell thickness of 0.8 mm, which is typically needed for the fabrication process, the efficiency was 87%. We note that the efficiency is independent of the power level, as the output power linearly changes with the input power.

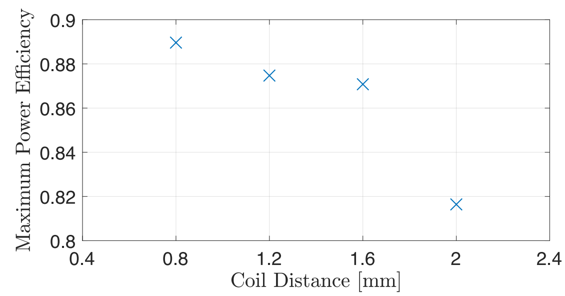

Figure 2: Wireless power transfer efficiency between the coils with different distances. The efficiency was 87% when the coil distance was 1.6 mm, which corresponds to the typical distance necessary due to the glasses frame fabrication process.

Communication

The bit error rate of communication, based on amplitude shift keying (ASK), was calculated from the measured S-parameters of the coils with a distance of 1.6 mm, which describes the power attenuation between the coils [17]. The noise floor was calculated from the thermal noise under 300 K and the noise figure of the receiver (10dB). Notably, 10dB was derived from the noise figure of the Ettus Research Universal Software Radio Peripheral (USRP) N200, which is commonly used for wireless communication in research, with a 5dB margin. ASK was chosen because the power consumption required for modulation/demodulation is small compared to relevant approaches [21]. The source and load impedance of the coils were fixed to 50 Ω.

Figure 3 shows the relationship between the bit error rate and output power when ASK modulation with different bit rates was used. It can be observed that a bit error rate of 10^{-6} can be achieved when the bit rate is 50 Mbps and the TX power is −60 dBm (1 nW), whereas 10^{-5} or lower is considered sufficient for Wireless LAN [18]. The benefits of

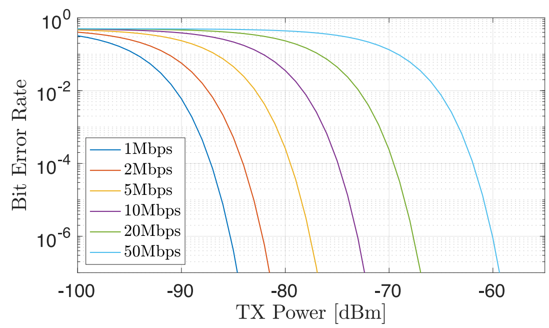

Figure 3: Bit error rate and transmission power of the communication system using amplitude shift keying (ASK) modulation, as calculated by applying the measured S-parameters of the 1.6 mm **spaced coils to [17].**

communicating with low power are that the leakage electromagnetic field is weak, resulting in less interference with nearby devices, as well as the reduced likelihood of the signal to be eavesdropped.

5 POTENTIAL APPLICATIONS

Activity Monitoring

Various sensors such as microphones, cameras, and accelerometers are embedded inside smart glasses to monitor the user's daily activities [1, 3]. Sensors are placed optimally according to their monitoring targets. Our method can be applied to these devices to eliminate the wires between different frames, thereby achieving a more reliable structure of the glasses. Note that even when multiple sensors are used, they can share the same coil pair for power transfer and data communication by performing time- or frequency-domain multiplexing.

Wearable Eye Trackers

Eye trackers are devices that track eye movement using cameras placed on the frames on smart glasses. These devices are commonly used to support industrial workers performing tasks in factories [11]. However, the current implementations, which employ wires connected between the temple and rim, are prone to errors in harsh environments, as they are often vulnerable to water and dust. This is because the cameras are placed on the rim, whereas the processor and battery are usually placed on the temple, to balance the weight and efficiently utilize the limited space in the glasses. By integrating our technology to eliminate the wires between the frames, such smart glasses could easily be designed to be waterproof and dustproof, which would their enhance reliability for industrial applications.

6 LIMITATIONS AND FUTURE WORK

Power conversion loss and dielectric loss. We measured the transfer efficiency between the coil pair to explore the fundamental features of the system, but we did not consider the power loss with respect to the AC-to-DC and DC-to-AC conversion required at each port. For instance, 20% of power is lost for this conversion in Qi devices [4] and the conversion loss in our system must be evaluated in future work. Additionally, the dielectric loss of the coil core material can affect the transfer efficiency; therefore, investigating the use of different materials is another potential research direction.

Power consumption for communication. We evaluated the bit error rate and the signal power for communication, as low signal power is important to prevent the leakage of electromagnetic fields. Meanwhile, the power consumption of signal processing integrated circuits in specific implementations must also be considered in future work to evaluate the power consumption correlated to communication.

Electromagnetic compatibility. Excessive electromagnetic field exposures may affect nearby devices or cause health issues; therefore, we need to further investigate the maximum amount of power that can be transmitted according to the applicable radio wave regulations. Additionally, electromagnetic field emitted from other devices may cause a deterioration of data communication. Therefore, the bit error rate under such conditions should be measured in future work.

7 CONCLUSION

We proposed installing a coil pair in the frame of smart glasses to deliver power and data to eliminate the wiring inside the hinges of the smart glasses. We carefully considered the design requirements of the coils to achieve high-performance power transfer and communication while maintaining the utility (*i.e.*, aesthetics, durability, and portability) of conventional glasses. As a result, the coils could achieve over 85% efficiency for wireless power transfer and a communication data rate of 50 Mbps, while the coils were small enough to fit inside the frame of conventional glasses. Although we must further investigate the practical performance and the electromagnetic compatibility by performing case studies, we showed that our approach is promising to eliminate the design complexities of hinges with wires, which will simplify the process of designing smart glasses.

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