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Contactless energy transfer at the bedside featuring an online power optimization strategy

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ABSTRACT

This paper introduces the principle of contactless energy transfer to wearable bedside electronics. As a proof of concept, a platform containing a matrix of magnetic energy transmitters has been developed and integrated into a mattress. This system is able to feed one or more wearable sensor nodes, attached to the patient, with the purpose of wirelessly recording vital signals over an extended period of time. Each of these power transmitters is designed to transfer up to 10 mW of power over a maximal distance of 300 mm. Moreover, the platform embeds online optimization software to deal with vertical as well as horizontal sensor node movements. The position and orientation of each freely moving sensor node can be dynamically determined and a local magnetic field, with a matching radiated power level, can be selectively induced in the area where the sensor nodes are positioned. This approach therefore limits the radiation exposure to the patient to the minimum viable level. The prototype is successfully tested in a laboratory set-up.

1. Introduction

Emerging technologies such as cloud computing and the Internet of Things have made the world increasingly connected. Ubiquitous wearable devices are spanning an ever increasing range of applications. Such sensor networks are helping athletes to break records, patients to become more aware of their disorders, gamers to have a better virtual experience and employees to develop their careers [1].

The promising global impact of these technologies and the constant research progress in the field of vital signal acquisition promote clinical application of these devices [2–4]. Wearable health systems outshine classic, bulky bedside monitors and bypass wires that hamper the patient's freedom to move. This technology therefore greatly emphasizes an increase of comfort and facilitates long-term bio-signal acquisition. Moreover, these devices enable an effective rehabilitation period in a home environment. Home health is not only beneficial to the patient's well-being, but also stimulates cost-effectiveness in global health [5]. This promise of a revolutionized health care has made wearable electronics one of the most appealing areas in biomedical research [6–9].

Modern diagnostics, however, require long-term, high-quality data acquisition. Moreover, a multitude of algorithms for online bio-signal extraction and automatic pathology detection, are ready to be integrated in such a medical body sensor network but are in need for high performance, ergo they consume abundant energy [10–12]. On the other hand, the patient's comfort level is affected by the device's dimensions. Today the energy density level of commercially favorable lithium-ion batteries is typically limited to 0.75 Wh/cm^3 [13]. Innovative batteries that are expected to exceed these conventional lithium-ion batteries are attracting much attention in both the academic realm and industry. Recent research has indeed demonstrated energy density improvements up to 2.7 Wh/cm^3 when using lithium-sulfur technology [14]. Although, because many practical issues with these technologies remain unsolved, it is expected that lithium-ion batteries will prevail over other batteries at least within a few decades [15]. Therefore, the use of battery-powered sensor networks in the field of medicine is hindered by a challenging trade-off between functionality, miniaturization and autonomy.

Inductive power transfer is a viable alternative to batteries to overcome this shortage of on-board available energy and is efficient enough to avert such a compromise. This technique was already introduced in the 1960s [16,17] and has been widely used in the field of medicine to bias medical implants [18–20]. In case of implantable devices, this technique is accordingly referred to as transcutaneous energy transfer (TET). But also wearable

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electronics, used for bedside monitoring, could benefit from such a wireless magnetic link. In that case, we propose a system that consists of a fixed, base coil in the bed, and one or more remote monitoring units attached to the patient.

In contrast to transcutaneous energy transfer, which in most cases can be performed with a relatively high and fixed coupling factor, inductive powering at the bedside implies loosely coupled coils with significant variations due to patient and sensor movement [21].

In previous work, a life-sized clinical setup based on a Helmholtz configuration was devised to deal with similar coupling fluctuations [22–24]. This topology produces a magnetic field that is more uniform and stronger than a solenoid topology for the same excitation current [25]. The resulted field strength was proven to be homogenous within a constrained working volume of 0.18 m^3 and to be big enough to power the sensor at every position and orientation within this space. Nevertheless, two potential complications, concerning the safety norms of human body exposure to alternating electro-magnetic fields, have arisen. Firstly, to cope with high coupling variations, such a magnetic link is typically optimized for a worst-case scenario, leading to excessive power consumption during nominal operation. Secondly, in this manner, the full upper body part is exposed to the induced magnetic field, which may conflict with the specific absorption rate standards [26,27].

In the consumer market, similar energy transfer systems are rapidly gaining momentum. These contactless energy transfer (CET) platforms enable a convenient new way to charge mobile consumer products [28–30]. A popular choice in literature to increase the freedom of CET device placement and to allow the charging of several devices simultaneously, is by using multiple primary windings [31]. To increase the platforms efficiency, in some systems the primary coils can be individually activated so that only a few primary windings closest to the load device are turned on [32].

This resulted in the establishment of the Wireless Power Consortium and the introduction of the Qi standard for charging mobile electronic devices through magnetic induction [33]. Regulation of the output voltage is provided by a digital control loop where the power receiver communicates with the power transmitter and requests more or less power. The combination of the CET platform topology and the power regulation strategy, utilized by the Qi standard, could cope with the aforementioned obstacles; only a local magnetic field is induced in the area where the power receiver is positioned and excessive power consumption is reduced by regulating the voltage level dynamically.

Nevertheless, this standard has several shortcomings when applied to bedside patient monitoring. Firstly, the Qi standard is devised for a close and stable inter-coil spacing, which makes it possible to use backscatter modulation as a communication technique [21]. The loosely coupled coils, prone to contactless energy transfer at the bedside, makes inductive downlink communication infeasible. Secondly, in case of mobile device charging, we can assume that the inductive coupling will remain constant after an initialization phase. To deal with the aforementioned continuous coupling variations, the transferred power needs to be continuously adjusted. And lastly, this standard uses a relatively low operating frequency between 110 kHz and 205 kHz. Increasing this frequency goes along with efficiency boosting and higher inter-coil distance endurance [34]. Moreover, the induced electromagnetic field diminishes and consequently patient safety increases. Faraday's law indeed states that for a higher frequency a similar electromotive force can be derived for a smaller magnetic flux.

This paper describes the required adjustments to the CET platform model in order to cope with wearable bedside electronics. As a proof of concept, a wireless energy transfer platform consisting of a matrix of identical base coils, integrated at the bedside, has been constructed. The implementation of the system and the measurement results will be discussed.

2. Materials and methods

The proposed contactless energy transfer platform consists of three parts. The first element is the targeted wearable sensor network. This system consists of several custom-made sensor nodes that are in charge of vital signal acquisition. The second component is a grid of inductive power transmitters, which are optimized to transfer abundant energy over a considerable distance. The third item is a centralized management unit that processes the gathered bio-signals and supervises the matrix of power transmitters. Fig. 1 illustrates a block-level schematic of this architecture.

2.1. The remote wearable sensor node

On one hand, a signal acquisition system is only as good as the data it delivers, on the other hand, these devices need to be made as small and unobtrusive as possible to enhance patient comfort. Therefore a custom-made sensor network for wearable bio-signal acquisition has been developed in house. The system architecture of each node is modular and consists of two circuit boards. The sensor interface circuit board contains a dedicated analog front-end, such as an amplifier to record biopotentials, an inertial measurement unit to measure patient movement or a pulse oximeter for photoplethysmography applications. The data and power circuit board subsumes the general-purpose data acquisition and power management blocks. Consequently, the nodes are easily adaptable for miscellaneous vital signs acquisition by tailoring the sensor interface circuit board. Both circuit boards also serve as battery contacts for a rechargeable coin cell battery of 10 mAh. The two electronic circuits are interconnected through the case wall as is explained in

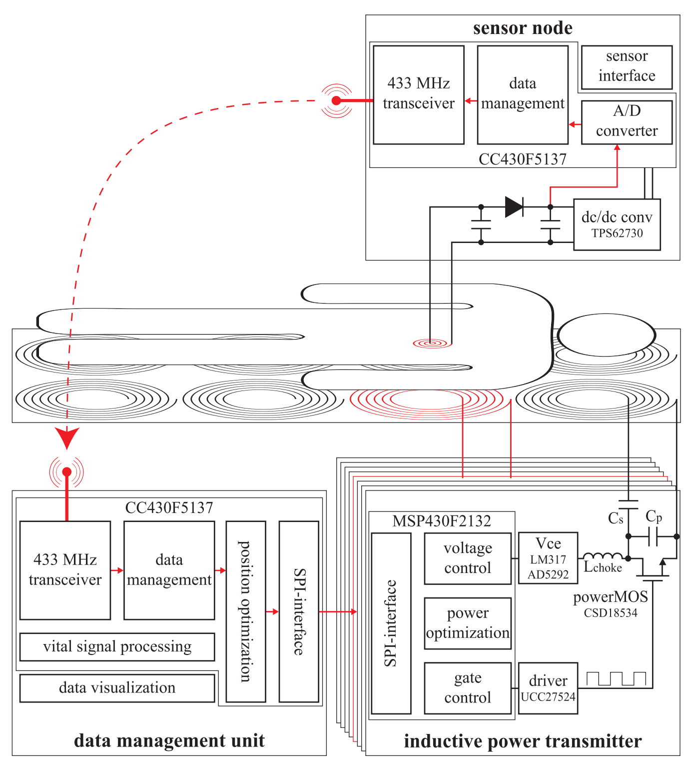

Fig. 1. A block-level schematic of the contactless energy transfer platform, integrated at the bedside. The power feedback loop is marked in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)