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Miniaturised wireless smart tag for optical chemical analysis applications

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ABSTRACT

A novel miniaturised photometer has been developed as an ultra-portable and mobile analytical chemical instrument. The low-cost photometer presents a paradigm shift in mobile chemical sensor instrumentation because it is built around a contactless smart card format. The photometer tag is based on the radio-frequency identification (RFID) smart card system, which provides short-range wireless data and power transfer between the photometer and a proximal reader, and which allows the reader to also energise the photometer by near field electromagnetic induction. RFID is set to become a key enabling technology of the Internet-of-Things (IoT), hence devices such as the photometer described here will enable numerous mobile, wearable and vanguard chemical sensing applications in the emerging connected world. In the work presented here, we demonstrate the characterisation of a low-power RFID wireless sensor tag with an LED/photodiode-based photometric input. The performance of the wireless photometer has been tested through two different model analytical applications. The first is photometry in solution, where colour intensity as a function of dye concentration was measured. The second is an ion-selective optode system in which potassium ion concentrations were determined by using previously well characterised bulk optode membranes. The analytical performance of the wireless photometer smart tag is clearly demonstrated by these optical absorption-based analytical experiments, with excellent data agreement to a reference laboratory instrument.

1. Introduction

The past decade has witnessed significant advances in chemical sensing modalities, not least of all where technology improvements have allowed miniaturisation of chemical sensors and closer integration with electronic instrumentation and wireless communication technologies. Proponents of the Internet of Things (IoT) predict that there will soon be a vast number of connected devices, including chemical sensors, able to monitor and sense their ambient environment and to share this data with the internet and cloud-based computing services. At a system level, wireless data transmission clearly offers benefits for certain chemical sensors in certain applications. The main advantages of wireless sensing, which arise from the elimination of extensive wiring, are improved mobility, unobtrusiveness, lower installation costs and higher nodal densities [1]. Wireless chemical sensors and biosensors are destined to have ever greater application in healthcare diagnostics, environmental monitoring, process monitoring, food quality monitoring and security [2].

To meet the growing demands for in situ monitoring of different chemical analytes in these diverse application areas there is a need for reliable, low-cost, low-power devices that are compatible with wireless communications systems. In the last few years there has been an upsurge in wireless chemical sensing devices due to the availability of ubiquitous wireless standards, including the global system for mobile communications (GSM), Bluetooth, ZigBee, WiFi, radio-frequency identification (RFID) and more recently near field communication (NFC). The general availability of wireless technologies based upon open standards has provided a technology push for wireless chemical sensors (WCSs) and chemical sensor networks (WCSNs). This phenomenon has been described in detail elsewhere in review articles [3] and in application specific reviews of the agri-food [4], chemical process monitoring [5] and homeland security [6] sectors.

RFID/NFC is an interesting short-range radio technology for integration with chemical sensors due to the ultra low-power consumption, low implementation costs and relative low-level complexity. The predictions are that RFID is set to become a key technology of the Internet of Things (IoT) [7].

Several RFID-based chemical sensors have therefore been developed, including RFID tags with integral gas sensors for monitoring

Abbreviations: RFID, radio-frequency identification; NFC, near field communication; WSN, wireless sensor network; IoT, internet of things.

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food quality [8], with olfactory sensors (electronic noses) for integration with low-cost printed RFID tags [9,10], and for disinfection control in hospitals [11]. Potyrailo et al. have developed multi-analyte gas sensors from RFID tags for the detection of organic vapours [12] and also for use in food logistics [13].

Optical detection modalities can bring certain advantages over other methods of detection in chemical sensing systems. Optical sensors are generally non-destructive, easily miniaturised, not affected by electrical or magnetic interference, and are relatively inexpensive [14]. There have been significant advances made in the development of low-cost optical chemical sensors due to improvements in performance, availability and cost of optoelectronic components, especially light emitting diodes (LEDs) and photodiodes. Light emitting diodes were first used in optical sensors in the 1970s [15], and have been used abundantly since. This is mainly due to their relatively low power consumption (compared to laser or laser-diode light sources), low cost, small size, robustness, and their availability over a broad spectral range (from ultraviolet to near-infrared) which makes them appropriate for the determination of a wide range of analytes. LEDs have thus been implemented in a number of low-cost and portable analytical devices [16–18]. Recent examples include low-cost optical detectors for protein determination [19], the development of portable colorimeters based on multiple LEDs for the determination of interferents in blood serum [20] and concentrations of common food dyes in food products [21]. Systems using LEDs as both light sources and detectors have been constructed for the detection of gases [22], as well as glucose in human serum [23].

Due to the advances made in both wireless sensing and optosensing, wireless optical chemical sensors as hybrid devices have evolved. For instance, LED-based sensors incorporating pH sensitive dyes have been integrated with commercially available transmitters to form a wireless chemical sensor network [24]. A colourimetric assay comprising a pH sensing strip with a wireless video camera on board a low-cost robotic fish has been developed for environmental sensing applications [25]. There are also several examples of RFID-based optical chemical sensors the first of which was a planar optical detector for the determination of pH by sensitive dye immobilised in a thin sol-gel film [26]. More recently, Yazawa et al. at Hitachi Central Research Ltd have reported ultra-miniature optical RFID circuits for use in genetic analysis [27].

In order to address the growing need for integration of diverse chemical sensing techniques with RFID tag technology, we are developing an RFID sensor platform that is compatible with different types of (bio)chemical sensors – including optical, conductometric, potentiometric and amperometric (Fig. 1). Appropriate transduction mechanisms and interfaces for various sensor types are being implemented directly on the tags. So far, an RFID smart card for conductometric sensors [28], an RFID/NFC resistivity and temperature probe for monitoring the microenvironment in aggregate materials [29] and an RFID chemical sensor for measuring pH by optical absorption spectroscopy [26] have been developed. More recently, the RFID potentiometric measurement of pH was reported by us [30], and latterly a diverse range of cations relevant to *vanguard* monitoring [31] of water quality with solid-contact ion-selective electrodes were successfully measured with our RFID potentiometer [32].

In the work presented here, we demonstrate the characterisation of an ultra low-power RFID wireless sensor tag with an LED/photodiode-based photometric input.

The performance of the wireless photometer has been tested through two different model analytical applications. The first is photometry in solution, where colour intensity as a function of dye concentration was measured. The second is an ion-selective optode system in which potassium ion concentrations were determined by using bulk optode membranes.

2. Materials and methods

2.1. Experimental set-up for smart tag based photometry

The experimental set-up is shown in Fig. 2. The measuring system comprises the credit card sized radio-frequency smart tag, the sample cuvette with LED and photodiode (optical cell), RFID reader and a personal computer. The photometer is wirelessly linked to the personal computer through a commercial RFID reader (Ridel 5001, TAGnology GmbH, Graz, Austria) which energises and communicates with the photometer over a range of up to 10 cm.

2.1.1. Radio-frequency smart tag

The radio-frequency smart tag used here has been described in detail elsewhere [26]. In brief, the credit card-sized tag (Fig. 2) was developed around a commercial microcontroller (PIC12F683, Microchip Technology Inc., Chandler, AZ, USA) based on the ISO15693 RFID standard. Code for the microprocessor was written, developed and programmed into device's flash memory using an integrated development environment and device programmer (MPLAB v8.0 with PICStart plus, Microchip Technology Inc., Chandler, AZ, USA). The circuitry was designed using a schematic capture design and printed circuit board layout suite (EASY-PC Professional v11.0, Number One Systems Ltd., Gloucester, UK). Printed circuit boards were fabricated from standard FR4 materials

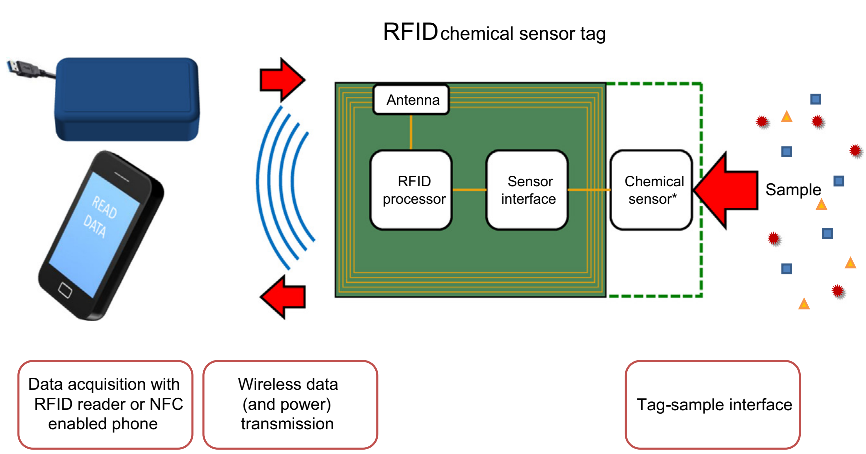

Fig. 1. General schematic of the RFID-based chemical sensor platform. *The chemical sensor can be integrated onto the tag, or may be off the tag. In this work, the optical sensing elements are off tag.