A Wireless Pharmaceutical Compliance Monitoring System Based on Magneto-Inductive Sensors

Xueliang Huo, Student Member, IEEE, and Maysam Ghovanloo, Member, IEEE

Abstract—We have developed a magnetic sensor-based wireless pharmaceutical compliance monitoring (PCM) system using an array of magneto-inductive sensors mounted around the patient’s neck in the form of a tight necklace. This system detects the passage of a pill or capsule embedded with a small permanent magnet as a tracer through the esophagus upon ingestion. As a result, a signal representing a “dose ingestion event” is generated and wirelessly transmitted to a data delivery device (PDA), which is carried on the patient’s body. A software application running on the PDA time/date stamps the event and stores it for later retrieval by a physician. This technology provides a safe, convenient, low-cost, and accurate detection mechanism that helps patients adhere with their prescribed medication regimens. It also helps researchers and pharmaceutical companies conduct more accurate clinical trials on new drugs. A proof-of-concept prototype system using off-the-shelf components and custom PCB has been developed and successfully tested. Preliminary results using an artificial neck showed 94.4% correct detections when the magnetic tracer passed through the detection zone and about 6% false positives for outside areas.

Index Terms—Magneto-inductive sensors, permanent magnets, pharmaceutical compliance monitoring (PCM), pharmacotherapy.

I. INTRODUCTION

P HARMACEUTICAL compliance in a medical context refers to a patient both agreeing to and undergoing taking his/her regular medication as advised by his/her doctor or other healthcare professional [1]. Obviously, even the best drugs do not work in patients who do not take them. It is an established fact that over 50% of patients, especially those assigned to long term treatments, do not comply with their medication plans by taking them at the wrong time, stopping too early, or taking the wrong dosage [2]. Meanwhile, studies carried out in the United States and Europe reveal that noncompliance costs societies billions of dollars each year as a result of rehospitalization, complications, disease progressions, and even death [1]–[5].

There are many reasons why patients do not comply with a certain course of medication. They may think side-effects outweigh benefits, not believe the diagnosis, not understand the directions correctly, not know enough about the side-effects, view the medicine as too costly, or they may use it too much or too little. The most common reason, however, is simply forgetfulness especially among elderly patients [6].

The pharmaceutical compliance monitoring (PCM) devices can help patients remember and their caregivers regularly track their compliance regimens. Using various mechanisms, a PCM device can detect the dose and time that patients have taken their medicine and record that information. Patients will be notified by the device if they do not take their medicine in proper dosage and time. The doctor can also track the patients’ compliance history, compare it with the outcomes and possible side effects, and determine to continue, fine tune, or change the prescription.

The most critical period for PCM, however, is during clinical trials which determine the benefits and efficacy of new drugs. On the basis of the results of such trials, new medications are either licensed for general use or abandoned. They also determine the recommended dosing strategies for specific clinical indications.

Thus, inaccurate data during these clinical trials can result in decisions that will affect millions of patients during an approved drug lifetime [1]. Alternatively, they can result in a potentially effective drug to be abandoned.

So far, the industry standards for PCM have been pill counts returned to the study monitor and medication diaries kept by the patients, none of which are accurate because of their dependence on the patients’ active input [7]. Patients are prone to fill out diaries just before seeing the monitor or “adjust” their medication to compensate for missed doses. Thus, the topic of pharmaceutical compliance has become a key issue due to increasing difficulties in achieving point-of-differentiation and health economic objectives justifying premium pricing and reimbursement. Accurate PCM can help in shortening the new drug approval time by reducing the number of repeated clinical trials due to inconclusive results, cutting the number of recruited subjects and duration of each trial without losing any useful information, and identifying noncompliant subjects for immediate physician intervention or exclusion from the study.

In this paper, we present a new wireless PCM technology based on detection of permanent magnetic tracers embedded in solid medications such as pills and capsules using a body-worn array of sensitive magneto-inductive sensors. This technology, called MagneTrace, is suitable for small- and large-scale clinical trials, as well as individual patients, if integrated as part of the marketed drug concept. The following section reviews the state-of-the-art in the PCM technology followed by an overview of the MagneTrace system in Section III. Sections IV and V describe the prototype MagneTrace hardware and its sensor signal processing (SSP) algorithms, respectively. Experimental results
are depicted in Section VI, followed by concluding remarks in Section VII.

II. STATE OF THE ART IN PCM

Modern PCM systems that do not entirely rely on patients’ active participation can be categorized into two types with respect to their detection mechanism:

a) Noningestion PCM: This type of devices detects the patients’ preparation action before taking the medication. Many of these systems act when the medication is being taken out of its packaging or container. A typical example is SIMpill developed by Clinical Technology Advisors Inc. [8]. When the user opens the bottle during a predefined time window, SIMpill wirelessly sends a message to a secure central computer system through the user’s cell phone indicating that a dose has been taken (out of the container). If the message is not received within the programmed time window, an outgoing text message is sent to the patient’s cell phone reminding him/her to take the medication. If the bottle is still not opened within 30 min, a text message indicating a missed dose can be sent to up to two designated caregivers’ or monitors’ cell phones. Caregivers can then contact the patient by other means and ensure that the medication is in fact consumed. Another example is the Medic electronic compliance monitoring package, developed by Information Mediary Corporation, which has a similar concept built around the medication blisters, taking advantage of the radio frequency identification (RFID) technology [9], [10]. In this case, taking the pill out of its package breaks a printed conductive interconnect and initiates an event.

These kinds of PCM devices are safe, simple, low-cost, and easy to operate. However, they do not really monitor the ingestion of the medication. Therefore, they can be easily deceived by the users either deliberately or unintentionally. These PCM systems are not yet smart enough to indicate who has taken the medication out of the package and what has been done with the medication.

b) Ingestion PCM: The idea behind this type of device is to detect the biomedical change in patients’ body after taking the medication. One example is the Sequella Inc. compliance monitoring wristwatch, which is in the preclinical stage at the time of this publication [11]. In this technology, a light-emitting molecule (fluorophore) is incorporated into the medication as a tracer. When the medication is ingested, the compliance monitor, which should be worn on by the patient on the wrist during the course of the therapy, noninvasively detects the presence of the fluorophore in the bloodstream through the skin and records the fact that the drug is ingested. Compared with the first category, this device is more effective and operates more reliably. However, the potential long-term negative side-effects of the fluorophore tracers on the human body have not yet been well understood. Even though many of these chemicals are considered harmless in short-term applications such as in fluoroscopic imaging, it is not yet clear whether their benefits could outweigh their long-term effects.

Therefore, an entirely noninvasive, unobtrusive, and inert ingestion detection mechanism is required for an effective and accurate PCM system that is preferably wireless and does not interfere in any ways with the human body.

III. SYSTEM OVERVIEW

MagneTrace is a wireless PCM system based on an array of magnetic field sensors placed around the user’s neck on a tight necklace [12]. The user wears this necklace during the period of treatment or clinical trial in order to detect the passage of a small permanent magnetic tracer embedded in a pill or capsule through esophagus upon ingestion. MagneTrace system, which simplified block diagram and cross section are shown in Fig. 1, is composed of the following three major components.

a) Magnetic tracer: A small permanent magnet embedded in the medication acts as a magnetic tracer. The magnet is coated with silicone or other inert polymer-based material, which are insoluble in gastrointestinal (GI) tract. Since human tissue is transparent to static (DC) and low-frequency magnetic fields, the field generated by the magnetic tracer is detectable outside of the body and can provide the magnetic sensor array with the necessary information about the movements of the tracer as it passes through the esophagus upon ingestion [13]. The tracer is small enough to easily pass through the GI tract with no interactions and exit in about 24 hours.

b) Detection device: Consists of a wearable array of high-resolution magnetic sensor modules that are distributed on a tight necklace around the user’s neck in different orientations, as shown in Fig. 1. The detection device is designed such that it
can detect the tracer regardless of its orientation when it passes through the patient’s esophagus. The sensors are driven by a control unit on the same necklace that consists of a power source (battery), power management circuitry, a low-power microcontroller (M/C), and an RF wireless transceiver. The SSP routine that runs on the M/C continuously scans the sensor modules and processes their outputs looking for a “dose ingestion event” (DIE). Upon detection of a DIE, the control unit wirelessly transmits the event to the data delivery device.

c) Data delivery device: We have taken advantage of the commercially available portable computing technology in choosing the data delivery device, which can eventually be a personal digital assistant (PDA) with built-in RF transceiver. The data delivery device is worn by the user on his/her belt or placed in a nearby location (<30 m indoors) while being at home or in the shower. Upon reception of a DIE, the data delivery device sends an acknowledgment (ACK) signal back to the detector and time/date stamps the event. All the received events are stored in the PDA for later retrieval by a physician or clinical trial staff either directly from the PDA or over the internet through a wireless local area network.

The MagneTrace PCM system is noninvasive, inherently wireless (permanent magnet), and low-cost. The tracer, detector necklace, and PDA have no chemical effect on the patient’s body and are unobtrusive due to their small size and light weight. The magnetic tracers are safe and harmless as long as the magnet is not too strong. Multiple strong magnets in the GI tract can potentially result in a blockage [14]. As a result, the magneto-inductive sensors should be sensitive enough to detect the changes in the magnetic field resulted from small and so weak magnetic tracers. These fields, however, 5 ~ 7 cm from their source, are comparable to the earth magnetic field (EMF) and its variations when the user moves around. Therefore, the arrangement of the MagneTrace sensor array on the detector necklace and its SSP algorithm, running on the M/C, are designed to be able to discriminate between the magnetic field variations resulted from ingestion of the tracer (DIE) and other sources of electromagnetic interference (EMI).

Since the magnetic force between a pair of permanent magnets sharply decays with increasing their relative distance (see Fig. 2), another solution to reduce the risk of GI blockage of a pole of the magnet, shown in Fig. 2(a), the on-axis magnetic field created by the permanent magnet is removed. Therefore, it is directly proportional to the field generated by the permanent magnet. For a cylindrical magnet, shown in Fig. 2(a), the on-axis magnetic field strength in Gauss at distance $d$ from a pole of the magnet also depends on its size and can be calculated from

$$B(d) = Br \times \left[ \left( \frac{d + L}{\sqrt{4 \times (d + L)^2 + D^2}} \right) - \frac{d}{\sqrt{4 \times d^2 + D^2}} \right]$$

where $L$ is the length and $D$ is the diameter of the magnet, all in cm. In order to minimize the size of the tracer, $Br$ should be maximized. Fig. 2(b), which shows the relative size of the most popular permanent magnets to generate the same output, clearly indicates that NdFeB, also known as rare earth magnet is the material of choice [15]. Table I summarizes the specifications of the rare earth magnet from RadioShack (Forth Worth, TX), which we used in our experiments [16]. It should be noted that the MagneTrace SSP algorithms can be calibrated to any tracer regardless of its $Br$, size, and shape, which could eventually be smaller and weaker than the one we used.

![Fig. 2. (a) Experimentally measured and calculated on-axis normalized PNI magnetic field sensor output and magnetic field strength based on parameters in Table I substituted in (1). (b) Relative size of different permanent magnets that generate similar magnetic field strength at a certain distance [15].](image)

IV. MAGNETTRACE PROTOTYPE HARDWARE

In order to evaluate the feasibility and performance of the proposed approach for PCM, we have developed a proof-of-concept wireless magnetic PCM prototype using only off-the-shelf components. The main hardware components of the prototype MagneTrace system are described in the following.

A. Permanent Magnetic Tracer

The key parameters used to describe characteristics of a permanent magnet are the residual induction ($Br$), coercive force ($Hc$), and peak energy density ($BH_{max}$). $Br$ is a measure of the residual magnetic strength of a permanent magnet after the external magnetization field is removed. Therefore, it is directly proportional to the field generated by the permanent magnet. For a cylindrical magnet, shown in Fig. 2(a), the on-axis magnetic field strength in Gauss at distance $d$ from a pole of the magnet also depends on its size and can be calculated from

$$B(d) = Br \times \left[ \left( \frac{d + L}{\sqrt{4 \times (d + L)^2 + D^2}} \right) - \frac{d}{\sqrt{4 \times d^2 + D^2}} \right]$$

where $L$ is the length and $D$ is the diameter of the magnet, all in cm. In order to minimize the size of the tracer, $Br$ should be maximized. Fig. 2(b), which shows the relative size of the most popular permanent magnets to generate the same output, clearly indicates that NdFeB, also known as rare earth magnet is the material of choice [15]. Table I summarizes the specifications of the rare earth magnet from RadioShack (Forth Worth, TX), which we used in our experiments [16]. It should be noted that the MagneTrace SSP algorithms can be calibrated to any tracer regardless of its $Br$, size, and shape, which could eventually be smaller and weaker than the one we used.

B. Detection Device

High sensitivity, low-power consumption, and small size are the key aspects in design of the detection device, which affect the PCM efficacy and user comfort. Currently, the most popular commercially available magnetic field sensors are the
Table I

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control Unit</td>
<td></td>
</tr>
<tr>
<td>Microcontroller [21]</td>
<td>Atmega32L</td>
</tr>
<tr>
<td>Control unit dimensions</td>
<td>$57 \times 41 \times 20 \text{mm}^3$</td>
</tr>
<tr>
<td>Clock freq</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>11 sample/sec/sensor</td>
</tr>
<tr>
<td>Wireless Transceiver [22]</td>
<td>Nordic nRF2401</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>2.40-2.52 GHz (125 ch. programmable)</td>
</tr>
<tr>
<td>Wireless module dimensions</td>
<td>$15 \times 12 \times 3 \text{mm}^3$</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>3.3 V</td>
</tr>
<tr>
<td>Average current consumption</td>
<td>$\approx 8 \text{mA}$</td>
</tr>
</tbody>
</table>

Magnetic Sensor Module

- Magnetic sensors [19]: PNI magneto-inductive, Micromag2
- Sensor module dimensions: $14 \times 11 \times 2.8 \text{mm}^3$
- Individual sensor dimensions: $6.3 \times 2.3 \times 2.2 \text{mm}^3$
- Sensor resolution / range: 0.015 μT / 1100 μT
- Sensor inductance: 400 – 600 μH @ 100kHz, 1 Vp-p

Magnetic Tracer

- Source and type: RadioShack rare-earth magnet
- Size (diameter and thickness): $5 \text{mm} \times 1.3 \text{mm}$
- Residual magnetic strength: 10800 Gauss

Other Components and Specifications

- Data delivery device: PC or PDA
- Graphical user interface: LabVIEW – National Instruments
- Correct inside detection zone: 94.4%
- False positive outside detector: $-6\%$

Hall-effect, fluxgate, magneto-resistive, and magneto-inductive sensors [17]–[20]. Hall-effect sensors are the smallest solution, while magneto-resistive and fluxgate sensors offer the highest sensitivity. However, when power consumption, interface circuitry, size, cost, and commercial availability were considered together, magneto-inductive sensors turned out to be the best choice for this application. Magneto-inductive sensors consist of an inductive-capacitive oscillator, which output frequency changes with the magnetic flux density passing through the core of the sensor coil in parallel to its axis.

Fig. 3(a) inset shows a MicroMag2 sensor module from PNI (Santa Rosa, CA), which is used in the present MagneTrace prototype [19]. Each module, which specifications are summarized in Table I, incorporates two sensors with perpendicular axes in $X$ and $Z$ directions. Fig. 3(b) shows one of these sensors on a U.S. penny. In these magneto-inductive sensors, the inductance can change by 100% over the designated range of magnetic field measurement. The MicroMag2 module also includes a sensor interface chip with oscillator and counter circuits that are temperature stabilized and provide a programmable sensitivity over a wide range. The chip also includes a bidirectional serial peripheral interface (SPI) bus that can directly send digitized measured magnetic field samples to the control unit and receive control commands.

It takes about 1–3 s for the pill to pass through the esophagus upon ingestion and that is the only time when the tracer is in the vicinity of the detector device. Therefore, the sampling rate must be selected sufficiently high to provide enough information for the SSP algorithm to effectively detect the DIE. On the other hand, higher sampling rates increase the overall power consumption and there is an inverse relationship between the sampling rate and the resolution of the digitized sensor outputs. In other words, higher resolution samples require more time to be taken. Therefore, there should be a compromise between sensitivity, sampling rate, and power consumption of the detector device. A sampling rate of about 10 Hz was experimentally found to be sufficient for the SSP.

In the prototype detection device, three MicroMag2 sensor modules are mounted on a flat ribbon cable to form a necklace and capture the magnetic field variations around the user’s neck, as shown in Fig. 3(c). The modules are equally distanced on the flat cable which forms a shared bus between modules and the control unit, while encompassing the user’s neck and connecting to the control unit from both sides. If the necklace forms a perfect circle around the neck, as shown in Fig. 1(b), the three
horizontal X sensor axes make an equilateral triangle and the three vertical Z sensors axes will be in parallel to the tracer path along the esophagus. Nonetheless, the SSP algorithm does not necessitate the necklace to form a perfect circle. Fig. 3(d) shows sample sensor outputs while passing a tracer through an artificial neck, resembling ingestion (see Fig. 5).

A low-power M/C, Atmega32L [21], is the heart of the control unit, which scans the three sensor modules turning only one of them on at a time to save power. All measurement results are processed within this M/C to detect a DIE. The M/C also controls a low-power commercial RF transceiver (LAI PAC, Canada) operating at 2.4 GHz [22], [23]. The transceiver is first configured as a transmitter to transmit the DIE to the data delivery device and then switches to receive mode to detect the ACK signal. In the absence of an ACK after four transmissions, the control unit notifies the user by turning on a red LED.

Table II summarizes the power consumption of different blocks on the detector necklace at 3.3 V. The wireless transceiver is the most power consuming block on the detector. However, since the DIE is only triggered a few times per day, the detector operates at a low-power monitoring mode except for a total of 1 or 2 s. The operating time of the detector necklace is highly dependent on the size and capacity of the battery used. The current prototype is expected to operate for 3–5 days with two 600 mAh Zinc Air hearing aid batteries or 9–12 days with two 1800 mAh AAA batteries [24]. Using ultra low-power microcontrollers such as MSP430 (Texas Instruments, Dallas, TX) and employing more efficient power management routines, it is possible to significantly reduce the overall system power consumption and enhance its operating time. Eventually, a custom designed integrated control unit can extend the operating time up to several weeks, preferably from one doctor’s visit to the next.

C. Data Delivery Device

A similar control unit with RF transceiver is used on the data delivery side in this prototype version. It captures the DIE message transmitted by the detection device and communicates it through an RS-232 port to a PC, which runs the PCM graphical user interface (GUI) in LabVIEW environment. The GUI, shown in Fig. 5(a), time and date stamps the event and saves it in a spreadsheet file, while showing the ten most recent events. The GUI also includes a calibration and adjustment menu, only accessible to the doctor or professional staff in the final version, through which all the SSP threshold parameters can be wirelessly updated on the detection device. Future versions of the GUI will also include entries for prescription schedules to be filled by the doctors in order to remind the patients to take their medications. Missing a dose will trigger a blinking LED or an audible alarm on the necklace. A “dose missed” message can also be sent to the caregiver or clinical trial monitor if a DIE is not detected in a specified interval.

V. SENSOR SIGNAL PROCESSING ALGORITHM

The software flow of the entire MagneTrace system is depicted in Fig. 4(a). In the rest of this section, we focus on the most important components of this diagram.

A. Detection Algorithm

As mentioned in Section IV, the wireless transceiver is the most power consuming part of the detection device. Thus, we would like to minimize its operating time by limiting it to the DIE transmissions only. Therefore, the entire SSP algorithm should be implemented locally on the detector necklace with no need for information exchange with the PC/PDA. Due to the limited computational capability and speed of a low-power M/C, one challenge is to keep the SSP algorithm as simple as possible without sacrificing its accuracy, robustness against the external sources of interference, and flexibility towards minor changes in position and orientation of the sensors.

In the current prototype, we have implemented an efficient multithreshold-based SSP algorithm. The general idea is to look at the individual and combinations of sensor outputs, as well as their rate and duration of change during ingestion and compare them to different thresholds [see Fig. 3(d)]. These thresholds depend on the size and strength of the permanent magnet used as
the tracer and can be defined through a systematic calibration procedure. Only when all threshold requirements are met, the detection device can conclude that the patient has taken the medication and generate a DIE. Otherwise, the sensor output variations are resulted from external interference and will be ignored.

We do not specify any certain horizontal position for the necklace, i.e., the necklace can be rotated around the neck. Hence, all sensor modules are considered identical and distributed evenly on the necklace. That means all horizontal ($X$) and vertical ($Z$) sensor outputs from three modules are to be dealt with in the same way.

1) Relative Amplitude (RA) Thresholds: These thresholds are set based on the sensors average output. They indicate the maximum and minimum relative amplitudes (RAa) allowed for single or multiple sensors when the tracer is passing inside the detection zone within the expected location of the esophagus, shown as a donut shaped region in Fig. 1(b).

a) Thresholds for individual sensors: Since it is impossible for the tracer to move very close to the modules when passing through esophagus, there is a maximum threshold for each sensor. Therefore, upper RA thresholds for $X$ and $Z$ axis sensors are set to indicate the maximum acceptable response when the magnet is closest to the sensor in esophagus and parallel to the measurement axis of the sensor. There is no minimum threshold for sensor amplitudes because a sensor can give zero output when the magnet is facing the sensors and the magnetic flux is perpendicular to the sensor axis.

b) Thresholds for multiple sensors with the same axis on different modules: Since the relative position and orientation of different modules is almost fixed, the outputs of all $X$ (or $Z$) axis sensors are related. Meanwhile, the magnet cannot be very close to or far from two or three sensors of the same type at the same time when it is passing through the esophagus. Therefore, maximum and minimum amplitude thresholds can be defined for multiple simultaneous outputs. We set upper and lower thresholds for every two and all three sensors of the same axis ($X$ or $Z$). These thresholds can be experimentally measured during calibration by adjusting the position and orientation of the tracer when it is passing through the detection zone.

c) Thresholds for perpendicular sensors on the same module: Similar to part (b), the outputs of the $X$ and $Z$ axis sensors on the same module are related due to their fixed relative positions. The peak outputs of both sensors cannot be smaller than a certain threshold level simultaneously when the magnet is passing through the detection zone. If both $X$ and $Z$ sensors on the same module are below this lower threshold level, the magnet is considered to be outside the necklace.

2) Time-Related Thresholds: The RA thresholds can reject the effects of permanent magnets that are not in the right position or do not have the right magnetic strength. However, they cannot reject the signal variations resulted from the external interference, such as EMF, when the user moves or rotates. Therefore, several additional constraints were needed in the SSP algorithm based on the timing of the sensor outputs and their derivative values (DVs).

By comparing the sensor DV waveforms between a tracer passing through the necklace and the user rotation, we noticed two distinctions. i) The maximum values of $\frac{dX}{dt}$ (or $\frac{dZ}{dt}$) are very similar among all modules when the user rotates. However, those are quite different when the magnet is passing inside...
the esophagus. This is because the field generated by the tracer magnet is so weak that only the sensor closest to the tracer gives significant changes in its output, while the EMF affects all the sensors similarly. ii) The time interval between the peaks of the derivative waveforms $\Delta T$ in rotation is significantly longer than the same time interval when the tracer is passing through the detector during ingestion. Because depending on the orientation of the tracer, some of the sensors outputs’ polarity change rapidly as soon as the tracer magnet passes through the $X$-$Y$ plane of the necklace, which happens quite rapidly during ingestion (see Fig. 7). Of course, the magnitude of the derivative waveforms and the time interval between the peaks are also dependent on how fast the user rotates. Therefore, a combination of both values can provide the best criteria to remove the effects of the EMF and other EMIs during rotations and movements.

a) $\Delta T$ threshold: The positive and negative peaks of the sensor outputs derivatives usually occur around the time when the tracer passes the detector $X$-$Y$ plane and represents how fast the magnetic field changes its polarity. $\Delta T$ resulted from passage of a magnet through the detector by ingestion is much smaller than $\Delta T$ from patient’s normal rotations. Therefore, by setting an upper limit for $\Delta T$, most rotations can be eliminated.

b) $|dV/dt|$ amplitude threshold: This threshold acts as a reinforcing criterion to reject any possible fast rotations with small $\Delta T$. Since the EMF similarly affects all sensors, in the case of a fast rotation, $|dV/dt|$ response of all sensors of the same type will be large and above a certain threshold level. In contrast, in a real ingestion event, at least one sensor output will have a $|dV/dt|$ below that threshold.

B. Wireless Handshaking

A simple but robust wireless handshaking protocol was adopted in the normal operating mode to ensure that the DIE flag is properly transferred to the data delivery device and registered. In addition, a program mode was created to enable modification and adjustment of all detector parameters over the wireless link on the fly, as shown in Fig. 4(b) diagram.

a) Normal mode: The control unit transceiver on the detector sends “0xAAAA” as a notification flag when a DIE is detected. The PC/PDA transceiver acknowledges by transmitting a “0xCCCC.” Detector transceiver sends the DIE flag again if it does not receive the expected response in a designated time period. Otherwise, the SSP continues its normal operation. If the detector transceiver does not receive the ACK, it will repeat the sending and listening cycle four more times before a red LED is turned on to notify the user about the loss of wireless connectivity.

b) Program mode: Every time the detector device starts up, it runs with its default threshold parameters. As soon as a qualified person completes the parameter setting in the GUI and issues a programming command, the PC/PDA sends a specific parameter package with a unique header (0x55 + Parameters) to the PC/PDA transceiver, PC/PDA transceiver switches to the program mode and waits for a DIE from the detector transceiver to start the programming instead of sending an ACK. Several operating parameters including sensor resolutions, sampling rate, and all SSP thresholds can be transmitted to the control unit and saved in its memory. When the programming is complete, the detector necklace restarts the SSP algorithm based on the new set of parameters, and the PC/PDA transceiver switches back to its normal operating mode, looking for a DIE.

VI. MEASUREMENT RESULTS

In order to evaluate the performance of the prototype Magnetic-Trace system, described in Sections IV and V, we built an “artificial neck” resembling an adult neck using a PVC pipe with an inner diameter of 11 cm. The PVC pipe was held vertical and elevated above the surface at a height of 10 cm by three thinner pipes. The detector necklace was then mounted around the artificial neck such that the sensor modules were $120^\circ$ apart looking from the central axis of the PVC pipe. The pipe was then filled with plastic straws, 20 cm in length and 6 mm in diameter, to provide vertical guidance for the passage of the magnetic tracer in parallel to the pipe axis with minor horizontal deviation. Fig. 5(a) and (b) show the measurement setup and a top view of the artificial neck, respectively. To resemble ingestion, a few magnetic tracers (Table I) were attached at the tips of thin wooden dowels in different orientations and moved by hand inside the PVC pipe through vertical straws inside the donut shaped detection zone. Even though these experiments were performed in the air, we expect the results to be similar in
human trials since the magnetic permeability of water and air are very close [13].

Our first task was to experimentally measure and set the SSP thresholds defined in Section V. The common procedure was to find the range of values that each of the SSP parameters could take, while the magnetic tracers were passing through the necklace in different orientations within the detection zone, shown in Figs. 1(b) and 5(b). Considering the fact that magneto-inductive sensors give maximum or minimum outputs when the tracer flux is in parallel or perpendicular to the sensor axis, respectively, makes it easy to imagine in 3-D the extreme orientations in each case and measure them experimentally. Nevertheless, we also checked and approved the results by setting up a finite-element model of the sensors constellation and tracer path using the Comsol Multiphysics electromagnetic module (Stockholm, Sweden).

After setting the SSP thresholds, we measured the probability of the missed DIEs inside the tracer necklace, both within and outside the detection zone, by passing the tracer-attached dowels through each straw in various orientations. Each measurement was repeated at least 20 times, while counting the number of correct detections. Fig. 6 shows the results of this experiment in a 3-D curve based on the location of each straw in the detector X–Y plane. It can be seen that the actual detection zone is more like a complete circle around the center of the neck instead of a donut shaped region since the SSP algorithm cannot discriminate between the ring and the center of the donut. However, this is not a serious concern since it is not possible to pass the tracer from the center of the neck, while wearing the detector necklace. We also moved tracers in random positions and orientations on the outside of the necklace to measure the probability of false positive detections. The probability of the DIE detection inside the circular detection zone and outside the detector necklace (false positive) were 94.4% and 6%, respectively.

In order to observe the effects of rotations and movements on the SSP algorithm, we set up the wireless artificial neck on a rotary chair and turned it in place or moved it in the lab. This experiment was repeated with the artificial neck being vertical, as shown in Fig. 5(a), or laid horizontal on the chair. Fig. 7 compares the first derivatives of the X and Z axis sensor outputs resulted from a 360° vertical rotation and a DIE. It can be seen that the rotation differential outputs are far more extended in time and more homogenous among different modules compared to those resulted from a DIE. This is the basis for the SSP time-related thresholds in Section V-B.

VII. CONCLUSION

We have developed the MagneTrace, a magnetic field sensor-based wireless PCM system to track patients’ compliance with their medication regimens. This system can also help researchers and pharmaceutical companies in conducting clinical trials on new medications by improving the accuracy and reducing the time and the number of subjects recruited for these trials. MagneTrace operates by detecting the passage of a small permanent magnetic tracer that is embedded in a pill or capsule through the esophagus utilizing an array of magneto-inductive sensors around the user’s neck in the form of a necklace. A simple but efficient multithreshold-based SSP algorithm has been implemented to eliminate the effects of the external magnetic fields such as EMF. The SSP thresholds can be experimentally indicated for any specific tracer and wirelessly programmed onto the detector necklace. Robust wireless handshaking mechanism is included to ensure proper registration of the time and date of every “dose ingestion event” in the data delivery device. More advanced SSP algorithms can detect multiple tracers with different magnetic strengths at the cost of heavier computations.

ACKNOWLEDGMENT

The authors would like to thank Dr. K. Mercure from the Dow Chemical Company for his suggestions and support, as well as members of the NC Bionics Laboratory for their assistance.

REFERENCES


Xueliang Huo (S’07) received the B.S. and M.S. degrees in mechanical engineering (instrument science and technology) from Tsinghua University, Beijing, China, in 2002 and 2005, respectively. Currently, he is working towards the Ph.D. degree at the GT-Bionics Laboratory, Department of Electrical Engineering, Georgia Institute of Technology, Atlanta.

His research interests include low-power analog and digital circuit design for biomedical applications, brain-computer interfacing, and assistive technologies.

Maysam Ghovanloo (S’00–M’04) was born in 1973. He received the B.S. degree in electrical engineering from the University of Tehran, Tehran, Iran, in 1994, the M.S. degree in biomedical engineering from the Amirkabir University of Technology, Tehran, in 1997, and the M.S. and Ph.D. degrees in electrical engineering from the University of Michigan, Ann Arbor, in 2003 and 2004, respectively. His Ph.D. research was on developing a wireless microsystem for micromachined neural stimulating microprobes.

In December 1998, he founded Sabz–Negar Rayaneh Company Ltd., Tehran, to manufacture physiology and pharmacology research laboratory instruments. In the summer of 2002, he was with the Advanced Bionics Inc., Sylmar, CA, working on spinal-cord stimulators. From 2004 to 2007, he was an Assistant Professor at the Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, NC, where he founded the NC-Bionics Laboratory. In June 2007, he joined the faculty of the Georgia Institute of Technology, Atlanta, GA, where he is currently an Assistant Professor and the founding Director of the GT-Bionics Laboratory, Department of Electrical and Computer Engineering. He has organized special sessions and served in technical review committees for major IEEE and IoP conferences and journals in the areas of circuits, systems, sensors, and biomedical engineering. He has more than 40 conference and journal publications.

Dr. Ghovanloo is a member of Tau Beta Pi, Sigma Xi, and the IEEE Solid-State Circuits, Circuits and Systems, and Engineering in Medicine and Biology Societies. He has received awards in the operational category of the 40th and 41st DAC/ISSCC student design contest in 2003 and 2004, respectively. He has organized special sessions and served in technical review committees for major IEEE and IoP conferences and journals in the areas of circuits, systems, sensors, and biomedical engineering.