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e-Nanoflex Sensor System: Smartphone-Based Roaming Health Monitor

The growing need and market demand for point of care (POC) systems to improve patient's quality of life are driving the development of wireless nanotechnology based smart systems for diagnosis and treatment of various chronic and life threatening diseases. POC diagnostics for neurological, metabolic, and cardiovascular disorders require constant long term untethered monitoring of individuals. Given the uncertainty associated with location and time at which immediate diagnosis and treatment may be required, constant vigilance and monitoring are the only practical solutions. What is needed is for a remote cyber-enabled health care smart system incorporating novel ideas from nanotechnology, low power embedded systems, wireless networking, and cloud computing to fundamentally advance. To meet this goal, we present e-Nanoflex platform, which is capable of monitoring patient health wherever they may be and communicating the data in real time to a physician or a hospital. Unlike state-of-the-art systems that are either local sensor systems or rely on custom relaying devices, e-Nanoflex is a highly nonintrusive and inexpensive end-to-end cyber-physical system. Using nanostructured sensors, e-Nanoflex provides nearly invisible monitoring of physiological conditions. It relies on smartphones to filter, compress, and relay geo-tagged data. Further, it ties to a backend cloud infrastructure for data storage, data dissemination, and abnormality detection using machine learning techniques. e-Nanoflex is a complete end-to-end system for physiological sensing and geo-tagged data dissemination to hospitals and caregivers. It is intended as a basic platform that can support any nanostructure based flexible sensor to monitor a variety of conditions such as body temperature, respiration air flow, oxygen consumption, bioelectric signals, pulse oximetry, muscle activity, and neural activity. Additionally, to address the cost of manufacturing sensors, e-Nanoflex uses a low cost production technique based on roll to roll gravure printing. We show the efficacy of our platform through a case study that involves acquiring electrocardiogram signals using gold nano-electrodes fabricated on a flexible substrate. [DOI: 10.1115/1.4003479]

1 Introduction

Chronic disease management and in-hospital patient care are two major contributors to healthcare costs. The former consists of patients in need of repeated tests to assess disease progression or protocols for drug dosage adjustments. The latter consists of patients recovering from surgeries or in need for constant observation for diagnosis. They contribute to approximately 30% ($690 billion) and 20% ($460 billion) of the annual healthcare costs, respectively, in the United States of America. Cardiovascular diseases and neurological disorders form the majority of diseases that need constant or periodic medical attention. For example, consider the following: chronic diseases, such as *asymptomatic myocardial ischemia*, a decrease in blood supply to the heart, appear as episodic events that do not leave any diagnostic evidence behind, making them difficult to identify [1]. Detection of cardiac arrhythmias from continuous electrocardiogram (ECG) recordings is an important tool that physicians use to adjust medication for post myocardial infarction patients. Common chronic neurological disorders, such as epilepsy and Alzheimer disease, can be identified from electroencephalogram (EEG) recordings. Furthermore, in various circumstances, changes in brain function may occur several hours before any clinical manifestation in patients with progressive brain ischemia or in patients suffering from vasospasms after a subarachnoid hemorrhage [2]. The detection and recording of these events are important parts of a patient's health history and play a key role in the risk stratification process used by physicians to plan treatment. Thus, continuous real time monitoring is a valuable tool that can help both diagnosis and treatment planning. Continuous monitoring in a hospital is extremely expensive, if not infeasible. This fact has motivated innovative research into healthcare solutions that are targeted toward shifting the delivery of healthcare to point of care (POC), i.e., the patient's home or remote location, to reduce the need for repeated hospital visits. Remote monitoring systems have emerged as the widely proposed solution for this problem, where the patient wears biomedical sensors and the system sends data to a hospital or stores it locally on a wearable device.

Currently available systems for POC monitoring consist of

Manuscript received November 23, 2010; final manuscript received January 7, 2011; published online February 16, 2011. Assoc. Editor: Linfeng Chen.

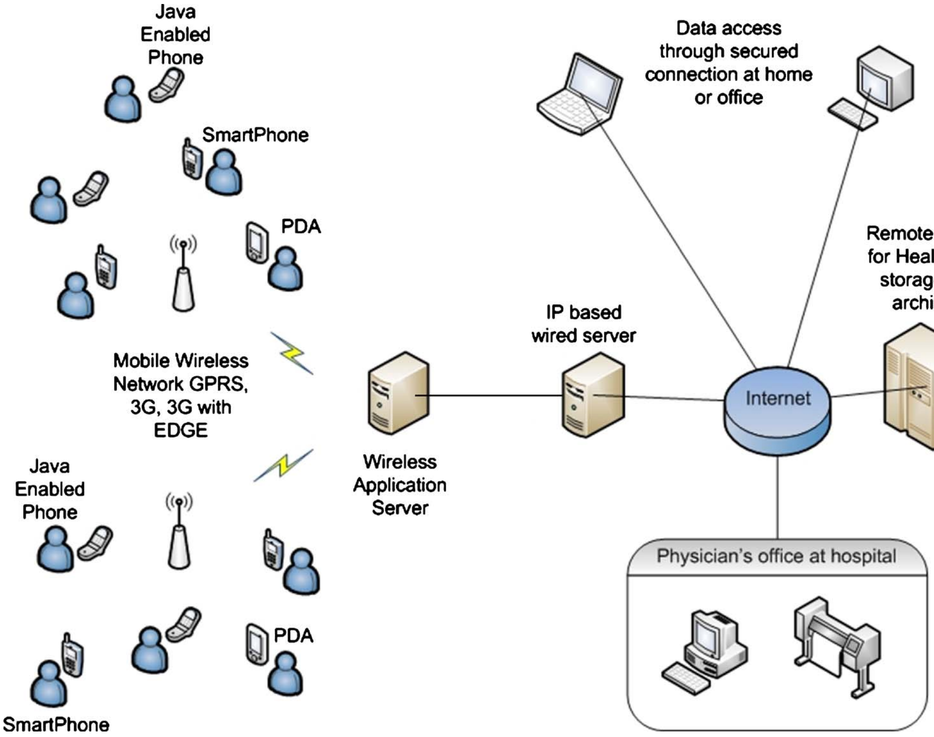


Fig. 1 Data flow from e-Nanoflex sensors to remote storage servers

wired sensors that the patient needs to manually mount [3,4]. Such systems are not pervasive due to three major reasons. First, complete health monitoring needs multiple sensors, bioelectric signals, such as ECG, electromyogram (EMG), EEG, electroculogram (EOG), light absorption based sensors for pulse oximetry, pressure flow sensors for air flow measurement, and strain sensors for respiration effort measurement, and wiring a multitude of such sensors to one monitoring unit is cumbersome and highly intrusive. Second, these sensors use customized data transmission hardware and software that do not easily integrate into a patient's quotidian life; an individual has to carry a special device for data collection. Third, to the best of our knowledge, the sensors used in a majority of these systems are not wearable.

Advances in medical nanotechnology coupled with rapid development in smartphone and cloud computing offers significant advantages over existing systems and helps circumvent most of these disadvantages. Nanosensors offer the unique advantage of small size and high sensitivity that makes them ideally suited for everyday use as they bear no conspicuous presence. Additionally, a smartphone (a device carried by every individual today) can be used to relay health and activity monitoring data from these user worn devices to a cloud resident server. To this end, our proposed platform, e-Nanoflex, seamlessly integrates nanobiosensors with smartphone relays and backend cloud services to provide anytime health diagnostics to patients (see Fig. 1 for overall architecture). It is designed as a basic platform that can support any nanostructure based flexible sensor for a variety of sensors, including nanostructure based flexible gas sensors [5], carbon nanotube (CNT) based flexible sensors for strain, and temperature sensors [6–8].

1.1 Research Contributions.

e-Nanoflex advances the state-of-the-art through four complimentary yet tightly integrated research contributions. *First*, the system advocates the use of highly nonintrusive nanotechnology based sensors that are wearable; such a system is invisible and intertwines with a patient's daily life that will lead to better social adoption. *Second*, the platform addresses important data transmission problems using smartphones such as compression, security, and filtering. *Third*, it provides novel backend cloud services that can store a user's location and data that hospitals and caregivers can have easy and real time access to in the event of a medical emergency. *Fourth*, for inexpensive production of such sensors, e-Nanoflex uses a novel and efficient roll to roll manufacturing technique.

The e-Nanoflex sensor system integrates a Bluetooth™ radio module, amplifier, and sensor in a compact medical plaster form. The system is easy to use and can be simply placed on the skin at the appropriate position (such as the limb lead positions for ECG). The data from the sensor are streamed to a backend cloud through a smartphone. While initial filtering occurs locally at the smartphone, most of the complex processing is delegated to the cloud. Such a partitioning approach has a twofold advantage. First, sophisticated computationally intensive signal conditioning algorithms, such as adaptive filters, are best implemented on a compute capable cloud server. Second, in anticipation of a large scale deployment, there will be multiple users sending data simultaneously and cloud storage is indispensable to handle such large volumes of data. Additionally, an alert message to a physician's phone or a message to the nearest emergency response service can be sent if any anomaly is detected by the cloud server. The smartphone can also be programmed to automatically capture a *video* during a cardiac episode so that paramedics can be better prepared.

As a case study for e-Nanoflex, we have acquired ECG signals using gold nanowire electrodes. We chose bioelectric signals for our first demonstration because heart rate, sleep/wake analysis, and muscle tremor identification can all be derived from bioelectric signals. For example, the inverse of the interval between two consecutive **R** peaks of the ECG waveform provides the heart rate. Thus, it is an information rich modality. Moreover, ECG is the first diagnostic test carried out by a cardiac physician to diagnose any cardiac ailment. Another salient and distinguishing feature of our ECG case study is the use of *dry electrodes*. Bioelectric signals, such as ECG, are usually acquired using conductive electrode patches placed on the skin at precise positions. The problem with currently used electrodes is that they use a conduc-

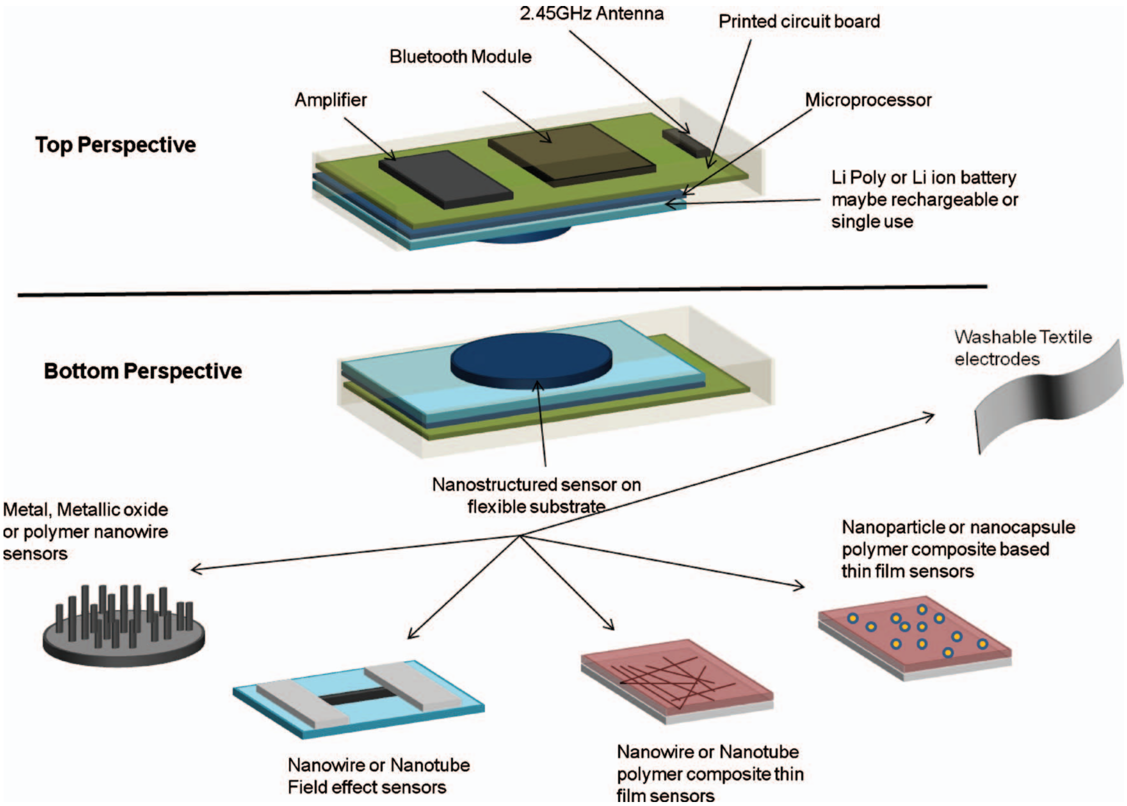


Fig. 2 Top and bottom perspectives of the e-Nanoflex system

tive gel between the skin and the conductor (*Ag/AgCl* disk) to make a low impedance electrical contact with the skin. These gels dry out and change the impedance of the electrode, leading to erroneous or noisy signal recordings. Additionally, they have also been known to cause skin irritation in some patients. We have previously proposed the use of gold nano-electrodes [9], which do not require any gel and can acquire signals through hair without the need to clean the skin with alcohol swabs. These electrodes also have an unlimited shelf-life and are reusable after sterilization because of the inert nature of gold. Therefore, our e-Nanoflex system uses dry gold nano-electrodes and is ideally suited for minimally intrusive ECG monitoring.

The large scale and high throughput manufacturing of such a system plays a key role in keeping the final cost for the end user low. For ECG monitoring, the gold nanowire is made on flexible metal foil substrates and thus compatible with production techniques such as roll to roll manufacturing. Printed circuit traces on flexible substrates have recently emerged on flexible substrates such as polyimide. Consequently, they are also compatible with roll to roll manufacturing technology. A means of incorporating the large scale production of gold nano-electrodes with flexible circuits needed to achieve this goal is presented in this paper.

The rest of this paper is organized as follows. We first present the e-Nanoflex sensor system architecture with a description of the necessary functionalities for true remote health monitoring. We then describe the first prototype system fabricated for ECG signal acquisition. We then describe the design of a manufacturing setup for large scale manufacturing of the e-Nanoflex sensor systems.

2 e-Nanoflex Sensor System Architecture

The e-Nanoflex system consists of two building blocks: (1) the sensor system and (2) the data transfer and backend analysis component. We use data enabled smartphones as a surrogate for relaying healthcare data to backend cloud servers. We first describe the sensor system and its components. We then describe the components involved in the data relaying and backend data storage and analysis.

2.1 Hardware Architecture. The e-Nanoflex sensor comprises of a sensor and the supporting hardware peripherals that are used for data acquisition. The sensor, amplifier, and filter circuits to condition the sensor signal, a microcontroller to convert the analog output of the amplifier into a stream of digitized numbers, and a bluetooth radio module for transmission of the acquired data are all combined into a single, double-sided printed circuit board (PCB) module. The stacking of various components combined with nanostructured sensors result in a small form factor that can be used for various wireless sensor applications involving physiological health monitoring. A schematic for the e-Nanoflex sensor system is shown in Fig. 2.

2.2 Components. Flexible thin film sensors for many biological parameters, such as organic light emitting diode (OLED) and organic photodiode (OPD) based pulse oximetry, polymeric piezoelectric based respiratory air flow, respiration effort and flexible electrode for bioelectrical signals, such as ECG, EMG, EOG, and EEG, can be interfaced with the e-Nanoflex system. Moreover, nanostructure based sensors on flexible substrates can also be leveraged for the above process.

The signals obtained from the sensors are usually *weak* and noise inflicted. For example, 60 Hz interference noise is common in the acquired electrical signals. Therefore, the bioelectric signals need to be amplified selectively to enhance the *signal* and *reject* the noise. The amplifier and filter circuits determine the quality of signal obtained by the sensor. Hence, they play a vital role in maintaining the integrity of the biosignal.

The sensor and the amplifier constitute the analog front end. The amplifier output is then digitized by a microcontroller. The microcontroller is used to fix the sampling rate of the analog to digital conversion (ADC) process. The data processed by the mi-

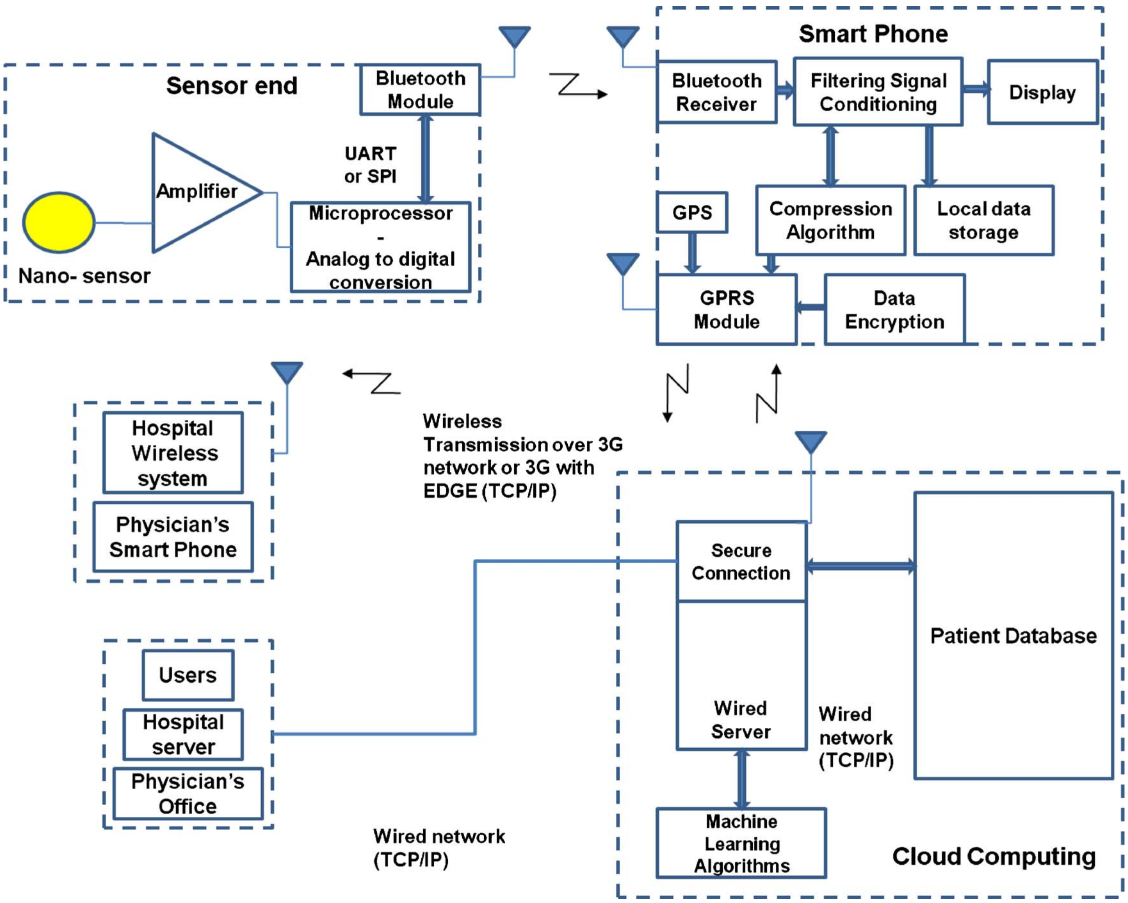


Fig. 3 Schematic of sensor data flow

crocontroller and presented as a string of digital numbers are ready to be transferred to the smartphone. The smartphone first scans for the e-Nanoflex sensor system and establishes a secure connection through a 16 character pin code for device pairing. As soon as a connection is established with the e-Nanoflex system, the microcontroller on the sensor end starts relaying the data from ADC outputs to the bluetooth module. A detailed description of the components for the e-Nanoflex prototype for ECG is provided in Sec. 3.

2.3 Data Transfer and Backend Storage. The data sent from the e-Nanoflex sensors are first received by the smartphone, which act as a base station from where the data are relayed to a remote server. Smartphones have been used as a base station in previous work [10] to detect simple anomalies, such as arrhythmias, or problems such as myocardial infarction. However, implementing computationally intensive abnormality detection services locally on the smartphone can be a huge energy and CPU drain; a research challenge not addressed by state-of-the-art systems. To this end, e-Nanoflex provides a partitioned approach, where computation is divided into two components: (1) low overhead simple computation on the local smartphone device and (2) intensive abnormality and filtering techniques at the backend. Such an intelligent division of computation between the smartphone and the backend cloud provides several advantages. First, the system is germane to the resource constraints on the mobile device. Second, it makes complex adaptive filtering, mandatory to the removal of motion artifacts, possible at the backend cloud. Figure 3 presents a schematic representation of the sensor and its association with the backend cloud services. Here, we describe each component of the system in detail.

2.4 Processing on Smartphone. All smartphones are bluetooth enabled and hence bluetooth offers a ubiquitous medium for data transfer between the sensor and the mobile device. Therefore, in e-Nanoflex, we use bluetooth as the radio for data communication between the sensor module and the mobile phone. The data received from the sensor using the bluetooth module need filtering since several motion artifacts cannot be effectively removed in the hardware. To ameliorate the above issue, the smartphone runs simple filtering algorithms. Note that computationally intensive filtering schemes are executed on the cloud since the mobile device lacks the compute capability to execute such algorithms. The filtering process on the phone uses simple digital filters, implemented as linear difference equations. This signal is then stored on the local storage device or displayed upon request by the user. Consequently, the data are relayed to a backend cloud service using http over a 3G or WiFi connection.

2.5 Data Relaying Through Smartphones. The sensor samples and transfers data at a high frequency: For biomedical application, this frequency is of the order of hundreds of Hertz. For example, for ECG, the sampling rate is 200 Hz. If the data in its raw form are relayed to the backend cloud, it can potentially choke the cellular channel. Currently available 3G networks cannot support such high volumes of communication at all times due to channel sharing. Therefore, data compression algorithms are required to keep the amount of data transmitted to a minimum. Data from biomedical sensors, such as ECG, are periodic and predictable and hence e-Nanoflex uses a simple differencing-based algorithm, followed by entropy based compression techniques, to minimize data transmitted [11,12]. The data transmitted to the remote server are geo-tagged. The onboard global positioning system (GPS) on a smartphone provides the current latitude

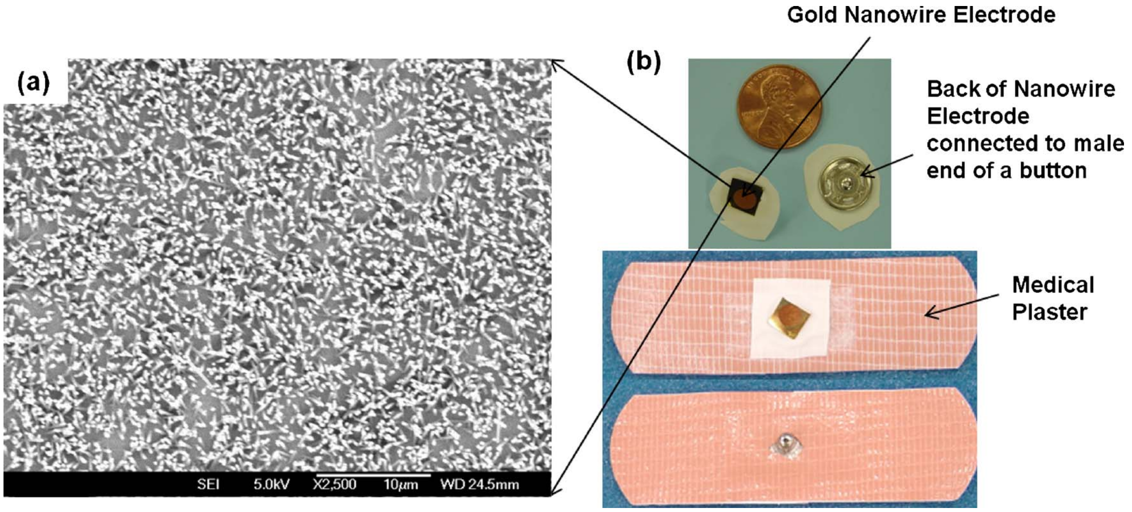


Fig. 4 (*a*) Scanning electron microscope image of vertical gold nanowires. (*b*) The gold nanowire electrode packaged in a medical plaster.

and longitude of the patient. At the remote server end, e-Nanoplast stores the geo-tagged sensor data in a secure database.

2.6 Data Security Considerations. Since the e-Nanoflex platform continuously streams critical healthcare data to a back-end database, security and data integrity are critical issues to maintain patient data confidentiality [19]. The data transfer channel between the sensor and the mobile phone as well as the back-end cloud is susceptible to pernicious security attacks. For instance, the e-Nanoflex sensor wireless channel is susceptible to "sniffing attacks," where a malicious entity can tap into the channel and access the data using a tuned off-the-shelf software radio [13]. Once the information is extracted, the captured data can be placed back on the network or replayed. Additionally, battery powered devices are vulnerable to denial of service (DoS) [14] attacks, where legitimate users are denied access to the remote server by malicious programs that block service, and battery-drain attacks, wherein a malicious user pretends to be a sensor and continuously sends data to the smartphone and drains its battery. Finally, data stored at the back-end databases should be accessible to authorized hospitals and physicians only.

In e-Nanoflex, we tackle sniffing attacks using standard data encryption over bluetooth [15,16]. Second, DoS attacks are avoided using power analysis [17]. Finally, at the backend, we use standard authentication measures implemented on web servers to assure that the data communication link between the caregivers and the backend database is secure [18].

2.7 Cloud Services. Once the data are offloaded to a remote server, they are stored in a large scale patient centric secure database. In anticipation of large scale deployment of e-Nanoflex sensor systems with continuous monitoring, the sheer volume of data to be analyzed will require automated signal analysis and anomaly detection techniques. Therefore, e-Nanoflex implements simple machine learning algorithms [20], such as discriminant analysis, to extract features from the collected data. The type of features depends on the disease class being studied, for example, simple features, such as the empirical mean, are sufficient for diabetes but more complex features, such as interwave width, are required for heart disease analysis. These features can be used to detect abnormalities in the data collected. The cloud services, upon determining a state of emergency, can send an alert message in the form of a short messaging service (SMS) or a multimedia message with an image of the abnormal data and the location of the patient to the attending physician's smartphone. A SMS can also be sent to the nearest emergency medical service team, based on the current location from GPS reading.

3 Case Study: ECG Acquisition

3.1 Hardware System. The current e-Nanoflex prototype is targeted toward acquisition of bioelectric signals, namely, ECG. The prototype e-Nanoflex system was made with detachable gold nanowire electrode pads mounted on a wound dressing plaster to facilitate easy testing. ECG signals need two electrodes and the positions of the electrodes span a large area of the chest. In our design, we connected the female part of snap buttons to the inputs of the instrumentation amplifier. One button lies on the e-Nanoflex module itself and the other is connected to the module through a conductive thread (*SparkFun Electronics*, Boulder, CO) to ensure maximum flexibility and minimal obstruction to movement.

Bioelectric signals, such as ECG, at the level of the skin, are of the order of hundreds of microvolts. An amplifier is used to enhance the signal strength. The amplified analog signal is then digitized by the ADC on the microprocessor at a fixed sampling rate of 200 Hz. The microprocessor then communicates with the bluetooth module using the universal asynchronous receiver/transmitter (UART) interface. The bluetooth module continuously sends the data from the microprocessor to the data logging unit and the received data are then stored or processed by the host microprocessor, which is either a smartphone or a personal computer (PC).

3.1.1 Nanowire Electrodes. Nanowire electrodes were fabricated on a flexible titanium foil, as described previously in Ref. [9]. Figure 4(*a*) shows a scanning electron microscope image of the nanowire structures on the electrodes that were used for the ECG results shown later, and Fig. 4(*b*) shows how the electrodes were mounted on a standard medical plaster used for superficial wound dressing. The nanowires were of an average height of $\sim 1\ \mu$m.

3.1.2 Amplifier. The ECG is a differential signal, i.e., the signal is perceived as the difference in potential between two points on the skin, wherein one of the electrodes acts as the reference for the other. Large common mode rejection ratio (CMRR), small input offset voltage, and low input power consumption are key attributes to be considered in the choice and design of the ampli-

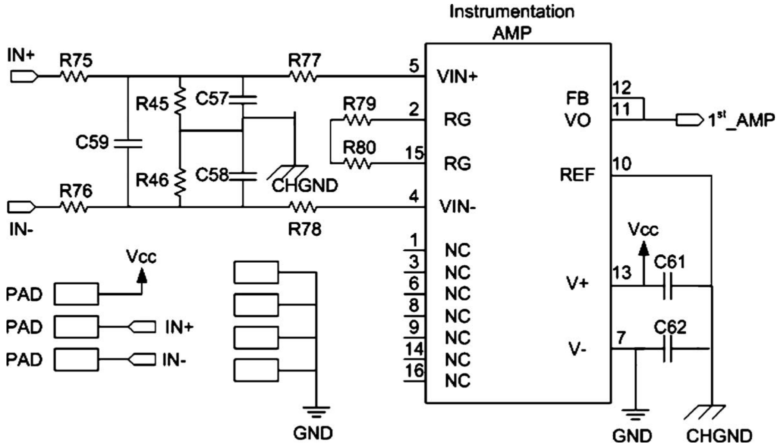


Fig. 5 The schematic of the first stage instrumentation amplifier

fier. A large CMRR makes the amplifier immune to noise interferences that are common to both electrodes such as power line interference. A small input offset voltage is important to maintain signal integrity, free from drifting voltages at the output.

The contact impedance for dry electrodes is known to be higher than wet electrodes when first applied on the skin. However, the contact impedance has been observed to reduce to a range similar to wet electrodes after duration of time [21]. The potentially large impedance mismatch that can occur at the beginning of recording, between a pair of nanowire electrodes, has to be taken into consideration in the amplifier design. We chose to use a multistage amplifier with a small gain of 10 on the first stage to make sure that the first stage output does not saturate due to the impedance mismatch. Figure 5 shows the first stage schematic using an instrumentation amplifier.

The instrumentation amplifier provides the first high impedance stage. Two more stages of noninverting amplifiers are used to further improve the signal quality. Figure 6 shows the schematic of these two stages.

Analog filters with a pass band between 0.2 Hz and 70 Hz make sure the mismatch is not seen by the later high gain stages. The output of the amplifier is then digitized by the microcontroller. The microcontroller writes the data out serially to the bluetooth module, which then transmits it to the data logging unit.

3.1.3 Microcontroller. Most commercially available microcontrollers come with multiple ADC inputs and timer registers. Timer registers are basically digital counters that generate a signal, referred as an interrupt, whenever the register value crosses zero. We can set the upper limit of the timer register when we initialize the microcontroller and based on the frequency of the count. Hence, we can fix the intervals at which the interrupts are generated. We can then use this interrupt to trigger a unit ADC operation. Since the interrupt is generated at a fixed interval, the ADC operation is also done periodically at the same fixed interval, thereby fixing the sampling rate of the digital signal. These ADC values can then be serially output from the microcontroller using two types of interface protocols, namely, UART and serial peripheral interface (SPI). We chose to use UART because it is compatible with most radio modules.

A schematic showing the connections between the microcontroller and the bluetooth module is shown in Fig. 7.

3.1.4 Bluetooth Module. There are several types of connection that can be established between bluetooth devices known as profiles. The profile for a particular connection is chosen based on what kinds of data need to be sent from one device to another. For our application, the data are a series of digits, which are the output of the microprocessor's analog to digital conversion. The serial port profile (SPP) was accordingly chosen since it supports the continuous transmission of data. We used a class 2 bluetooth module from STMicroelectronics, Geneva, Switzerland, with a line-of-sight maximum range of 10 m and small size of 10×13 mm^2. The module basically broadcasts the SPP service and any bluetooth device, such as a phone or a bluetooth enabled PC that comes within range, can connect to this device on that profile and start receiving the data if the correct passkey is entered. The passkey is the first line of security for the data sent by the sensors. The data baud rate was set at 115.2 kbps, which is a standard rate recognized by all microprocessor/microcontroller based devices.

One of the drawbacks of the SPP is that in case the data transmitted are not received by the data logging device, the data are not retransmitted automatically. This problem was considered in detail in Ref. [22]. The additional retransmit feature has to be implemented in software to improve the reliability of a SPP connection.

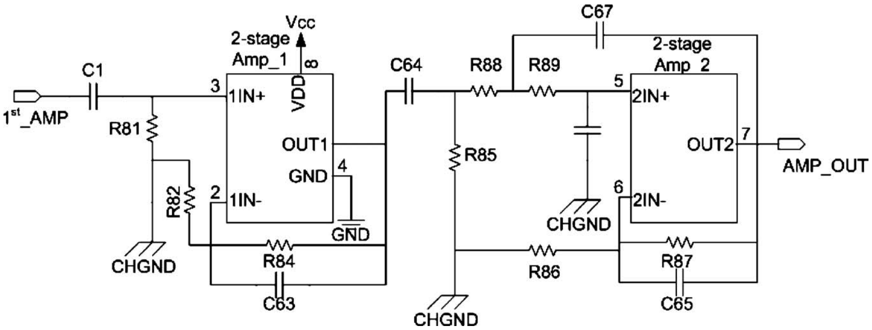


Fig. 6 The schematic of the final two amplifier stages

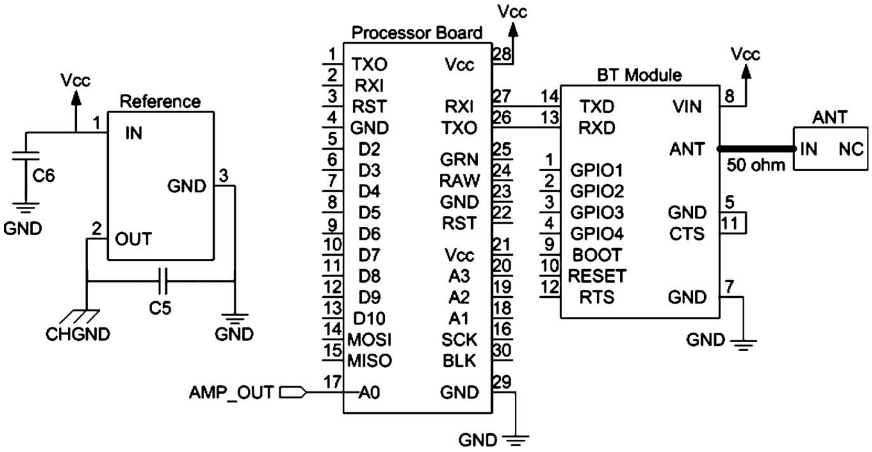


Fig. 7 Schematic for the voltage reference circuit needed for the ECG amplifier (left) and connections between the microcontroller and the bluetooth module (right)

Alternatively, the introduction of a special profile for health devices called the health devices profile (HDP), by the bluetooth special interest group (SIG), is expected to be more robust and suitable for this application than SPP.

3.2 Software System

3.2.1 Signal Acquisition. The microcontroller performs two functions. First, it converts analog signals to digital signals at a fixed sampling rate and second, it sends the digital signal serially to the bluetooth module. The flow chart in Fig. 8 depicts the algorithm that runs on the microcontroller. The microcontroller continuously samples the signal at the set sampling rate while power is on.

3.2.2 Data Transfer. The bluetooth module on the sensor, upon power up, broadcasts the SPP service. This makes all other bluetooth devices know that they can connect to it through the serial port profile. The smartphone or a bluetooth enabled PC simply searches for the sensor and connects to it using this profile. For the SPP connection to be complete, the smartphone or PC first needs to enter a 16 character long pin that matches the pin expected by the sensor. This step is known as pairing. This process needs to be performed only once and will ensure that the sensor is recognized automatically by the smartphone or PC as soon as it is within range. Figure 9 shows this process flow in a schematic.

The program to display the acquired ECG data was written in C#, compiled and debugged in the Microsoft Visual Studio integrated development environment (IDE). The sensor has to be first paired with the mobile device and a serial communication (COM) port is assigned to the sensor. The smartphone automatically recognizes the SPP service provided by the sensor and starts receiving data as soon as the assigned port is opened.

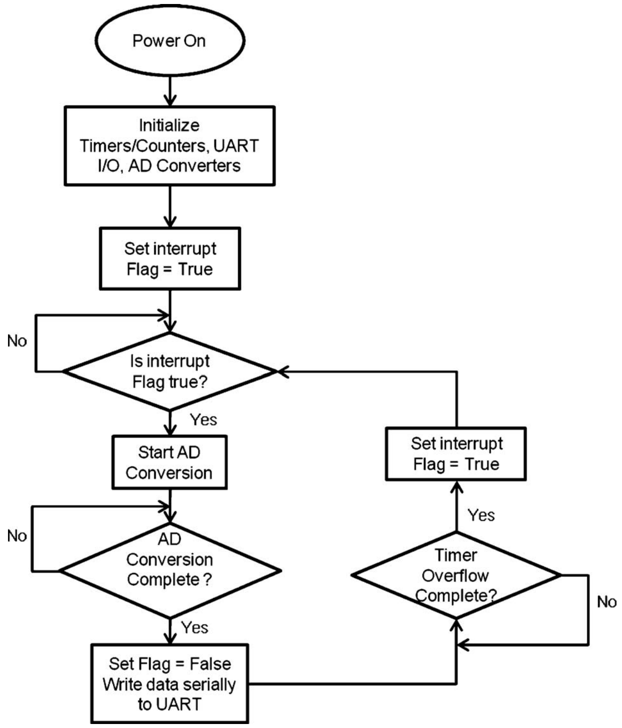


Fig. 8 A flow chart of the algorithm implemented on the microcontroller

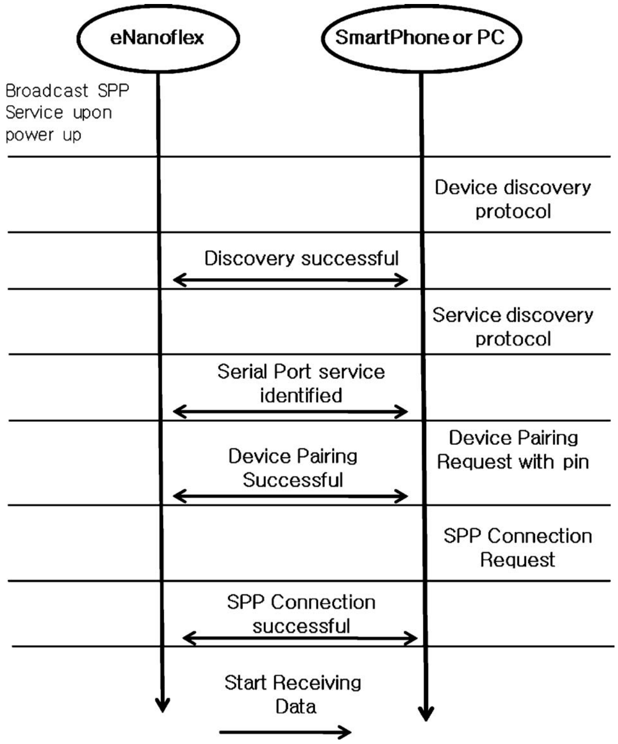


Fig. 9 Process flow for e-Nanoflex sensor discovery and connection

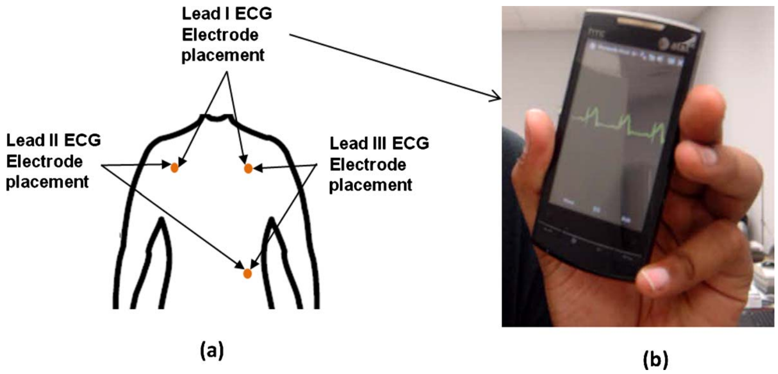


Fig. 10 (*a*) The electrode positions for leads I, II, and III ECG. (*b*) Lead I ECG data displayed in real time on a smartphone.

3.2.3 Data Relaying. The limb lead electrode positioning system is the most common form of clinical ECG [23]. There are three recognized signals acquired as the potential difference across the thorax ad toward the limbs. Lead I is the potential difference between the anatomical right arm and the anatomical left arm while lead II and lead III are potential differences between anatomical right arm and anatomical left leg and anatomical left arm and anatomical left leg, respectively. Figure 10(*a*) shows the electrode positions for the three lead ECG signals. Lead I ECG signal obtained from the sensor was plotted on a smartphone in real time, as shown in Fig. 10(*b*).

The frequency content of ECG is between 0.2 Hz and 70 Hz. The sampling rate was fixed at 200 Hz to satisfy the Nyquist–Shannon sampling theorem. A digital band pass filter with a bandwidth of 0.2–70 Hz was implemented on the data logging device to improve the signal to noise ratio. The three limb lead signals were obtained from commercial wet Ag/AgCl electrodes, *Moore Medical LLC*, Farmington, CT, USA, and from gold nanowire electrode, as shown in Fig. 11. The signals from the two electrodes are observably similar.

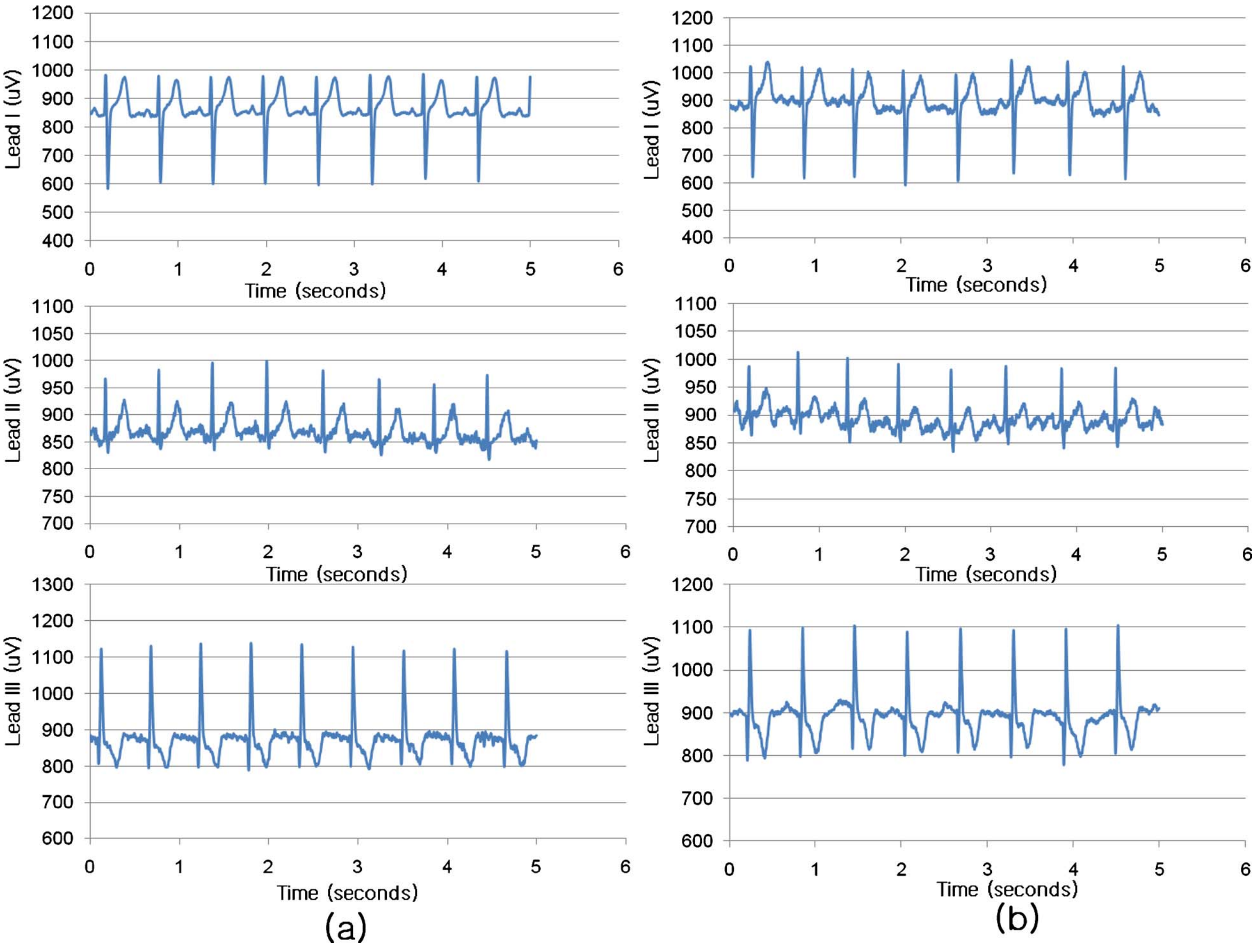
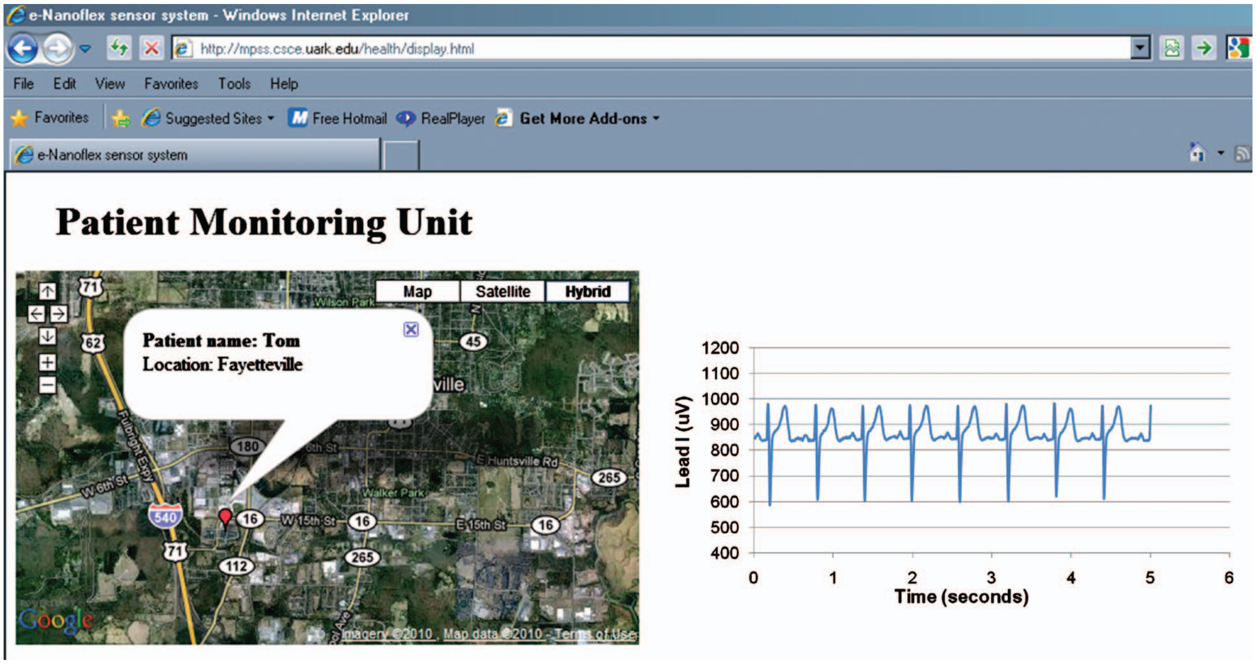


Fig. 11 Three limb lead ECGs acquired from e-Nanoflex sensor using (*a*) commercial Ag/AgCl electrode and (*b*) gold nanowire electrode



Patient Monitoring Unit

Patient name: Tom
Location: Fayetteville

Fig. 12 Snapshot of ECG data stored from the user and the corresponding location from where the data were sent

The data from the e-Nanoflex sensors have also been sent to a remote server through the 3G network. The data were tagged with the current GPS location and the time. In case of an emergency, a message with recorded data and current location and time can be sent to the emergency response team. The snapshot in Fig. 12 shows the location of the user and also the data received from the sensor as recovered from the server.

4 Discussion

Real time acquisitions of bioelectric signals at the level of the skin are susceptible to noise introduced by motion. Although a significant reduction in this noise is possible by firmly mounting the electrodes on the skin, the comfort and *wearability* of this system will dictate the extent to which these electrodes can be firmly mounted. Rather than finding a solution in the hardware, software adaptive digital filters can be used to remove the residual noise from motion.

It is important to note that power consumption for wireless modules restricts the minimum size of the battery that can be used and, in turn, dictates the size of the module. Implementation of ultralow power Bluetooth version 4.0 standards in the near future, by industrial chip manufacturers, will relax the battery capacity requirements. This prospect reflects the potential for further miniaturization.

As mentioned earlier, the cost of e-Nanoflex sensor system has to be as low as possible for large scale acceptance. The wireless sensor platform fabrication can be adapted to a scaled up roll to roll printing/manufacturing system, as described below.

5 Large Scale Manufacturing Using Roll to Roll Gravure Printing

This shall enable economic production of this consumable component for the roaming health monitoring system. The wireless sensor platform is constituted of layer(s) of printed circuit layout and gold nanowire electrode. The manufacturing process involves state-of-the-art gravure printing, and solution based electrochemical nanowire array synthesis.

Gravure printing is used as an alternative to, the widely used, PCB technology. It incorporates printed circuit layout to flexible film in roll to roll manufacturing. The circuit layouts will be printed on different flexible films, laminated and interconnected, to result in a multilayer flexible printed circuit platform (Fig. 13). The lamination process involves punching via lines for interlayer connections, alignment, and lamination, and via filling. Through this technology, an additional layer of titanium sputtered film, for fabrication of nanowire electrodes, can be laminated on to the other (flip) side of this platform.

For nanowire synthesis, the laminated flexible platform is coated with resist polymer on the titanium coated face (Fig. 14). The film roll is moved to the nano-imprint drum. The drum is mounted with a metallic nano-imprint stamp. The polymer film is patterned and cured to obtain a template with nanoscale pores. The roll proceeds to an electrolyte tank for gold deposition. This process takes 15–30 min, during which time the roll conveyor is stopped. After that, the roll is moved and the process is repeated for the next portion of the roll.

Nanostructure based sensor applications can bring about a significant decrease in the size of sensors. The e-Nanoflex system implemented here demonstrates the integration of nanostructured sensors with conventional instrumentation to produce a small form factor health monitoring solution for remote cardiac care. The dry nano-electrode was made using thin film technology on a flexible substrate. Alternatively, nanostructure electrodes can also be implemented on fabric. CNT synthesis can be achieved on a carbon fiber based cloth (carbon cloth), using chemical vapor deposition process [24]. The CNT decorated cloth can serve as multifunctional and/or structural material, integrated with the e-Nanoflex.

Smartphone sales have shown a significant increase in the market share and are slowly replacing regular single function phones in developed countries. However, in developing countries, entry level Java enabled cell phones are more pervasive. It is therefore important to build solutions that are compatible with these phones as well. These phones can already run basic wireless applications and simply need an intermediate wireless application server to handle the data sent from the sensors. Higher functions, such as local display, may not be feasible. This emphasizes the need for off loading the data on to back-end clouds for storage and processing.

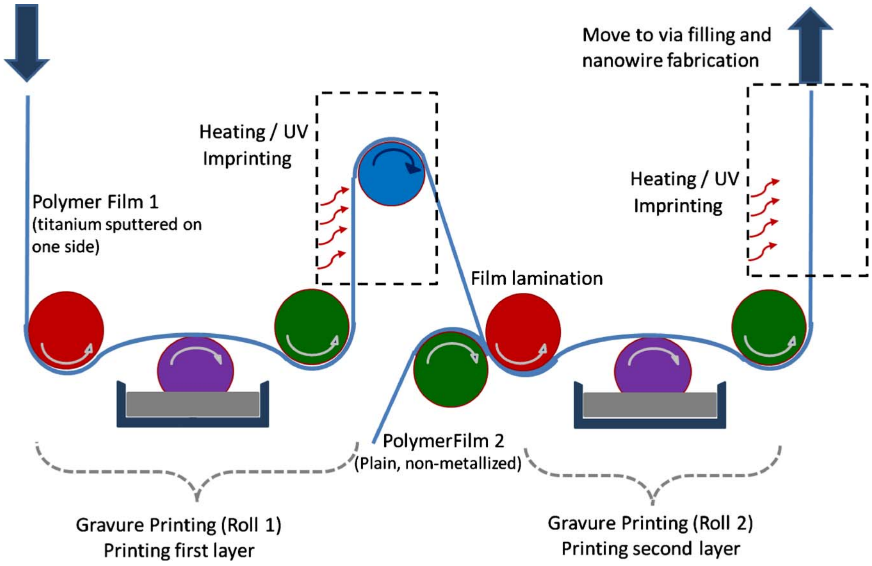


Fig. 13 Roll to roll fabrication for printed circuit flexible platform

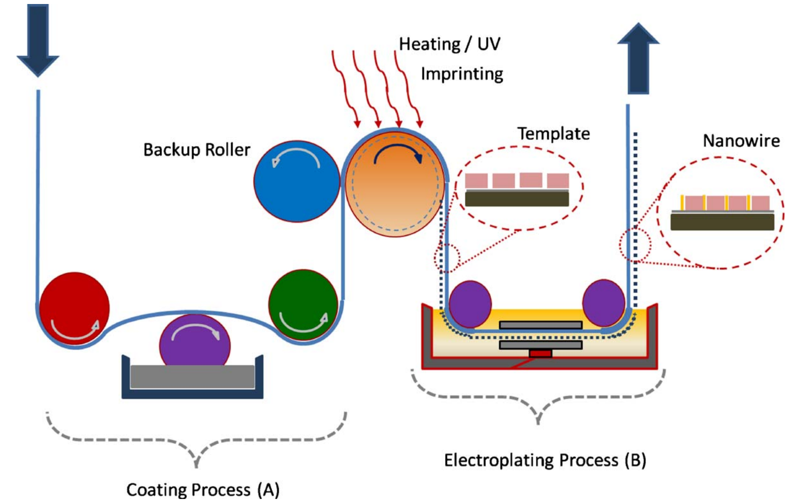


Fig. 14 Roll to roll fabrication for nanowire electrode

6 Conclusion

We have demonstrated a small form factor nanosensor based bluetooth wireless platform for health monitoring called e-Nanoflex sensor system. The e-Nanoflex system addresses the need for a highly portable biological signal monitoring system that is easy to use and can be integrated with existing cyber infrastructure to yield a globally active remote monitoring system. We have described the overall architecture of the e-Nanoflex sensor system and ECG acquisition has served as a case study for its capabilities. We have acquired the sensor data on a smartphone as well as on a bluetooth enabled PC, in real time. We have also sent the acquired ECG data along with GPS information through general packet radio service (GPRS) or 3G network to a remote server in real time, where it can be stored as the wearer's health history. Additionally, we have also described a myriad of higher level functionalities and options available by leveraging cloud computing. We have addressed concerns about information security both at the sensor end and at the backend server end. Mobile network bandwidth has also been considered from a data volume point of view. We have further discussed a solution to make such systems large scale manufacturing compatible to keep the cost as low as possible to the end user. In conclusion, this work reflects the development of a platform for the integration of nanostructured sensors with state-of-the-art wireless instrumentation to achieve continuous remote health monitoring systems for use in real world applications.

Acknowledgment

This work was supported by the Global Institute for Nanotechnology in Engineering and Medicine. Additionally, the authors would like to thank Ashwin Whitchurch for valuable discussions during the course of this work.

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