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Integrated real time bowel sound detector for artificial pancreas systems

Khandaker A. Al Mamun *, Nicole McFarlane

Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, TN 37996, United States

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ABSTRACT

This paper reports an ultra-low power real time bowel sound detector with integrated feature extractor for physiologic measure of meal instances in artificial pancreas devices. The system can aid in improving long term diabetic patient care and consists of a front end detector and signal processing unit. The front end detector transduces the initial bowel sound recorded from a piezoelectric sensor into a voltage signal. The signal processor uses a feature extractor to determine whether a bowel sound is detected. The feature extractor consists of a low noise, low power signal front-end, peak and trough locator, signal slope and width detector, digitizer, and bowel pulse locator. The system was fabricated in a standard 0.18 μm CMOS process, and the bowel sound detection system was characterized and verified with experimentally recorded bowel sounds. The integrated instrument consumes 53 μW of power from a 1 V supply in a 0.96 mm^2 area, and is suitable for integration with portable devices.

1. Introduction

Continuous glucose monitoring (CGM) technology has seen significant progress in the last 10 years. Recent CGMs use multiple sensor systems and feed sensor data to predictive algorithms for insulin control. Clinical trials demonstrate the usefulness of such continuous glucose monitoring systems, where blood glucose levels are well regulated when a CGM is used [1,2]. Complete diabetic management systems consist of a continuous glucose monitor (CGM), process control algorithms and continuous subcutaneous insulin infusion (CSII) unit. The goal of these systems is to function as an artificial pancreas (AP) system, possibly the ultimate preventive solution of diabetes disease. The first part of an artificial pancreas system, the measurement unit, continuously monitors blood glucose levels. The second, the control unit, compares glucose levels with standardized values to regulate the timing and quantity of an insulin bolus. Studies indicate that AP systems still lack information on the variations in blood glucose concentrations associated with dynamic physiological measures such as meals, stress levels, exercise, and sleep patterns [3,4,5]. Glucose level variations with dynamic measures cannot not be tracked using current-state-of-the-art systems due to the absence of real time physiological data. Adding activity sensors and predictive algorithms in the control unit incorporating these physiological measures could thus provide a more accurate picture of a patient's glucose level fluctuations, mimicking the biological pancreas.

With the advent of complex algorithms and multiple sensor platforms, the true challenge now lies in the implementation of the AP in a real life scenario. Non-linear feedback presents challenges to current AP algorithm implementation [5,6]. Likewise, physiological variables such as exercise, meal intake, food type, and sleep pattern induce perturbations in blood glucose levels that need to be addressed. Most current commercially available CGMs demand manual intervention of patients to incorporate this physiological data, and can at best trigger alarms or, stop insulin infusion in case any adverse event is detected. No robust solution has been demonstrated that can provide fully automated physiological feedback with high confidence. Activity monitors, such as accelerometers can provide a dynamic measure of some physiological activity through locomotion data. Abdominal vibration or bowel sound on the other hand could be a useful metric to measure eating instance or gastro-intestinal motility. Clinical studies show that relationships may exist between bowel sound rates with abdominal motility, type of food, and blood glucose levels [7].

Bowel monitoring is a useful clinical measure determining abdominal motility, irritable bowel syndrome, detection of sepsis, small volume ascites, intestinal transit time and assessment of abdominal surface vibration. Bowel monitors for long time digestive motility monitoring has been reported [8]. Methods for bowel sound enhancement, detection and segmentation using wavelet, neural network and estimation algorithm have been also widely studied and reported in literature [9–12]. Change in bowel rates with food consumption and identifying the fasting state have also been demonstrated [13]. Bowel rates show a strong relationship with individual meal intake, and has been proposed to be a useful measure for correlating individual eating instances [14–17]. However, the systems reported so far require

* Corresponding author.
E-mail address: kmamun@vols.utk.edu (K.A.A. Mamun).

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bulky front end interfaces and are costly in terms of signal computation. This reduces the inclusion of such monitoring systems in portable devices.

In this work, we demonstrate an ultra-low power and compact bowel sound measuring instrument which is suitable for integration into portable systems. The ultimate goal is inclusion of an automated meal intake notification feature in the insulin pump of an artificial pancreas system which can better mimic pancreas activity.

The paper is organized as follows, the materials and methods are discussed in Section 2, the results and discussion are presented in Section 3, and the conclusion is summarized in Section 4.

2. Materials and methods

2.1. Detection system

Bowel sound rates can be detected by manual auscultation using stethoscopes, sound cards, and signal processing algorithms [8–10]. Extraction of features in the analog domain could provide precise measurement at low power as opposed to using power intensive digital signal processors for digitization and measurement [18–21]. In addition, piezoelectric sensors could be a low cost alternative to currently used microphone and stethoscopes for manual auscultation.

Bowel sounds have certain unique features. Bowel spectrum shows large peaks and troughs, and exist for short time periods. The frequency of bowel is well below 500 Hz. These features allow a detector system to identify bowels from surrounding noise and interferences. The system requirements are as follows, first, the detector system should be capable of measuring abdominal vibration with high accuracy in the presence of environmental noise. Microphones and stethoscopes have been utilized in prior research, which offer high sensitivity [14,15,22]. However, the sensitivity comes with implementation difficulty in a portable system. Hence, considering our portable application and low cost requirement, we choose flexible piezoelectric sensors. Piezoelectric sensors offer a low cost implementation option and also are available in flexible form. The sensitivity can be tailored by using a variable gain charge amplifier as needed. Second, abdominal vibration contains spread spectrum noise signals dominated by the heartbeat, noise from talking and walking, sliding noise, and other interferences. As our desired signal lies well below 500 Hz, a low pass filter after the charge amplifier can restrict most of the interfering noise sources. However, certain noise sources such as talking, walking and sliding have a similar frequency spectrum to bowel signals and mostly predominate above 200 Hz [16]. Third, it was demonstrated that bowel sounds peaks and troughs are of short duration and can appear randomly with spread spectrum from 1 Hz to 500 Hz. Hence, a low noise feature extraction module is needed to help identify bowels from this noise source. Regularly sustained bowel signals have signal frequency around 500 Hz. As we are focused on detecting the change in bowel rate over time, regularly sustained bowel sounds can be filtered out without much loss of information. By adding a 10 Hz low pass filter, the envelope of the bowel signals can be recorded, and feature extractor can extract the peak, trough and signal width information from the envelope. Fourth, traditional feature extractors are implemented with digital processors which demand costly modules in terms of power and computation. This is not desirable in portable applications. Also bowel sounds need to be processed in real time, demanding data processors that can handle large amount of data and placing extra constraints on implementing feature extractor in portable system. We have adopted an analog feature extractor to relax the requirements and optimized the module for low power operation. The proposed system thus consists of a tunable charge amplifier, analog feature extractor and an algorithmic logic implementation unit [23]. In our proposed system, bowel sounds are transduced into electrical signals via a commercially available piezoelectric sensor coupled to charge amplifier (Fig. 1). The charge amplifier amplifies the input signal and forwards the signal to an analog feature extraction block. The feature extractor extracts key bowel features, such as peak, trough, pulse width, signal slope rates, sign bits. The extracted features are then fed into a control logic module. The control logic unit is responsible for generating empirical thresholds based on recorded bowel signals and synchronizes the bowel events. The peak, trough and pulse width threshold levels were determined using a LabVIEW program with previously recorded bowel sounds. The bowel detection unit detects the bowel pulses utilizing an algorithm implemented in digital logic. Utilizing the extracted features of the bowel sounds, digitized signals are generated which correlate to positive bowel events. The system

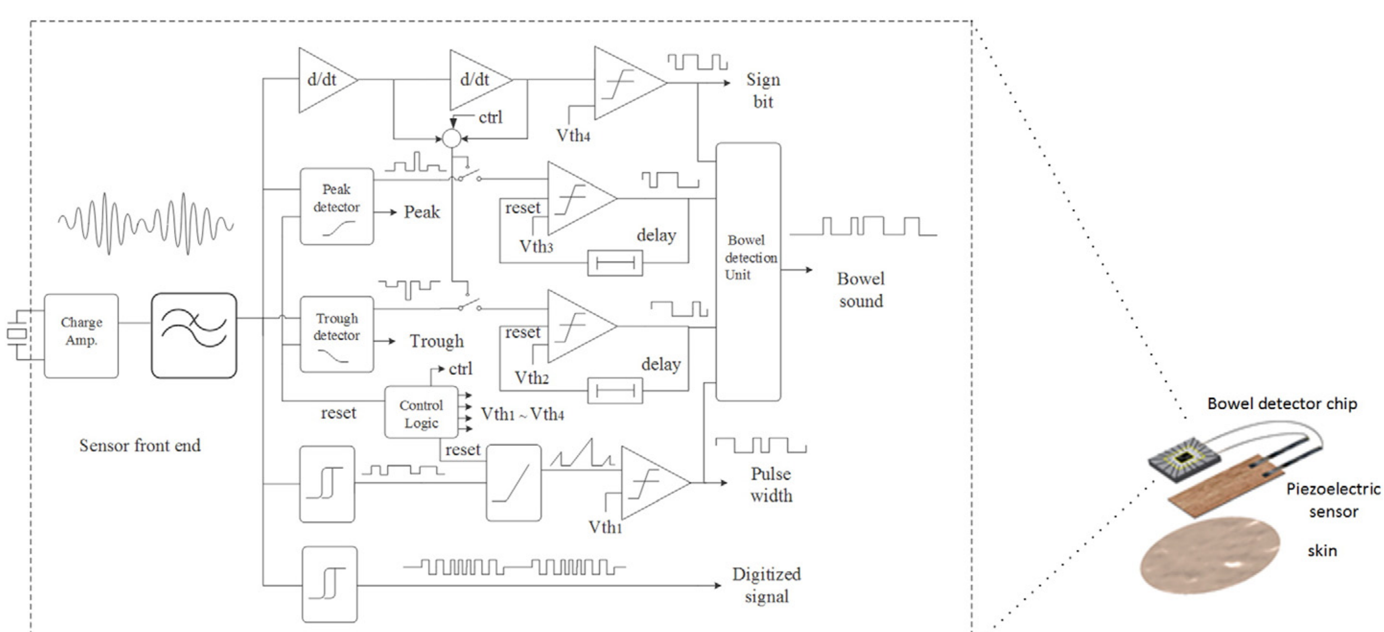

Fig. 1. The bowel sound detector system consists of a charge amplifier, feature extractor, and algorithm and control unit.