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# Improvement to the Data Logging Capability of a Cough Monitoring System

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# IMPROVEMENT TO THE DATA LOGGING CAPABILITY OF A COUGH MONITORING SYSTEM

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**Abstract**

*Data logging capability of a previously developed self-contained cough recorder using an accelerometer as the sensing element is improved by using a secure digital memory card for later retrieval on a computer. Firmware is developed to enhance the functionality of the cough recorder. Existing libraries are modified for increased write rates. Increased writing speed allows 8-bit sampling at rates exceeding 8kHz, allowing for detailed time and frequency domain analysis. Additional features have also been developed to enable easy management of recordings, such as a file system compatibility with Microsoft Windows., and unique file names for each recording.*

## 1. Background

Coughing is a common reflex mechanism to clear blockages of the windpipe. As such, it is also a general indication of unhealthiness. The presence of a cough is a reason for consulting a doctor, purchasing over-the-counter cough suppressing medicine, and visiting a hospital. In 1995 [I], 19 billion dollars were spent on over-the-counter cough and cold remedies. However, studies have shown that the effectiveness of cough medicine is comparable to placebo. These studies often lack uniform and quantitative methods for recording and analyzing coughs in subjects.

Previous efforts towards recording coughing include the system developed by Hsu *et al* [II], which used a unidirectional microphone and electromyograms to determine when the patient was coughing. This method obtained good results in detecting coughs, but with the 50Hz sampling rate, a detailed reconstruction of coughs was not possible. Jaeger *et al* [III] developed a system that correlated data from a microphone, an accelerometer measuring movements and vibrations from the throat, and an electromyogram to sense muscle movements. This system was effective in rejecting interference, but required the patient to be stationary in a laboratory environment. Requiring the patient to stay in a laboratory adds to the cost of a study and reduces the convenience to the patients. Subburaj *et al* [IV] produced a device using an accelerometer attached to a radio transmitter. The RF signal was then received by a large base station for recording. The device allowed the patient to move around, but required a large recording unit to function, and limited the range of the patient's movement. In addition, the transmitting unit was heavy and unsuitable for use with children. The analysis software provided no automation, requiring the user to play back the entire recording to analyze the recorded data.

## 2. Previous Research

To alleviate this need, Jewell [V] developed a prototype compact, self-contained cough recorder with Matlab-based analysis software. The device consisted of a MEMS accelerometer for the sensing of coughs, and a PIC microcontroller digitizing samples and storing the samples to a Compact Flash (CF) memory card. This approach was unique in using a calibrated accelerometer to accurately measure cough effort and magnitude in a self-contained ambulatory unit. The accelerometer was taped to the patient's suprasternal notch. Privacy was maintained for the patient since the accelerometer did not record ambient noise, and a low pass filter removed most components of speech. The device was ultra-portable, and was powered by a 9-Volt battery. The recording time varied based on the memory card used. The minimum size supported - 32 megabytes - allowed about 66 minutes of recording time, while the largest card supported allowed just over 17 hours. Software was provided to enable frequency and time domain analysis, as well as viewing the cough signal envelope. The Matlab software could also automatically remove periods of silence from the recording, and do limited categorization of the remaining signals. The validity of this method of recording was confirmed by Paul *et al* [VI] in a study comparing the accuracy of the cough monitor and a video recording. The result showed good agreement between the cough counts recorded on video and by the cough monitor.

While the recording device was indeed revolutionary, the recorder was not optimized for small size. Only some brands of CF memory cards could be used with the existing firmware, and the product was not "finished." A new cough recording device was developed by Varadan [VII] that was smaller and more versatile than the device designed by Jewell [V], while maintaining compatibility with the Matlab analysis software.

Key improvements included a more compact circuit design, lower voltage requirements, and usage of a physically smaller memory card.

The entire package with sensor weighs less than 50 grams. Because this device is small and lightweight, it is ideal for use in pediatric studies. The accelerometer sensor provides multiple benefits to the system. By only sensing movement of the vocal cords, ambient noise is efficiently filtered out. Also, taping the accelerometer on the superasternal notch of the patient reduces the speech content recorded, which increases the privacy of the patient, and allows for simpler signal processing requirements for automated cough detection. The cough monitoring device is also completely self-contained. This provides an advantage over a wireless transmitter and base station because there is no range restriction, or multiple devices to manage.

The improved cough monitoring system uses a PIC 18F6722 microcontroller to record data from an internal A/D converter, as shown in Figure1. This circuit is fed by a fourth-order low-pass Butterworth filter network and a gain stage. Cough sensing is done through a MEMS accelerometer. Both the filter and the accelerometer circuitry is reused from the previous design. The input signal is sampled at 8 kHz and stored on a SD memory card. The SD card is connected through the Serial Peripheral Interface (SPI) built into the microcontroller.

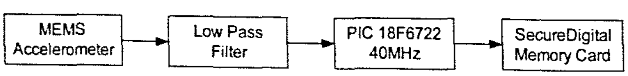


**Figure 1 – Hardware Block Diagram**

### 3. Hardware/Firmware Development

The focus of the research described in this article was the development of the firmware necessary for full operation of the improved cough recording device. This involved performing basic user-interface functions, sampling the output voltage of the accelerometer at a fixed sample rate, and recording all samples to the removable memory card. The functional requirements involved recording analog data at a rate of at least 8000 samples each second, and recording all samples in a format that can be accessed by any computer equipped with a Secure Digital card reader. Firmware programming was done in C using the Custom Computer Services Windows IDE.

In order to write the analog samples to the SD card, the Progressive Resources Flash File library was implemented. This library enables the microcontroller to write data to a SD card through the SPI interface, making a FAT16 file system that is easily accessible by computers. Without modification, the Flash File library lacked the data rates required for the cough monitor. By simplifying the expected running conditions, it was possible to remove several time consuming file system checks and safeguards. These checks are necessary for ensuring that the file system is always updated, and that other files on the SD card are preserved in the event of a sudden power loss, or removal of the SD card. With these safeguards in place, the highest consistent writing speed was 4 kB/s. After removing the safeguards, write speeds between 17 and 22 kB/s are typical. The library was also modified to use four write buffers to allow for potential temporary slowdowns encountered while writing data to the SD card.

The power for the device is controlled by a switch built into the SD card socket. When no SD card is present, power is removed from the circuit. This prevents inadvertent power dissipation while the device is not in use, and also ensures that a SD card is always connected during operation. Power is supplied by two 3.6V Lithium primary batteries, size ½ AA. These batteries are currently estimated to give a battery life between 17 and 24 hours, depending on the model of the battery and the model of the SD card. Three light emitting diodes are visible outside the case, which are used to provide status indication to the user.

The PIC microcontroller uses an on-chip program memory, which starts the execution of the firmware, as shown in Figure2, upon the insertion of a SD card. When a SD card is inserted into the socket, the microcontroller powers on and reformats the SD card. This ensures that the file system is not fragmented and that the maximum amount of space is available. After formatting the SD card, the device generates the file name for the current recording session. The device ensures that all file names are unique, and convey two pieces of information. An example of the file naming convention is: "X_005038.dat", where 'X' is the unique device identifier, and '005038' is a unique recording serial number that is incremented every time a new recording file is created. The file serial number is stored in EEPROM to maintain the data after power is disconnected. We envision each device would be labeled with a letter corresponding to the device identifier in the file name. This would allow easy tracking based on the recording device for statistical purposes. Since no recording will have the same name, this makes the file name a viable primary key in a database. No file renaming will be necessary if the recording files were placed in the same directory. Unfortunately, to achieve this flexibility for the end user, each device must be uniquely programmed with a device identifier. After the file name is generated, interrupts are allowed, and the main program loop is activated. This loop writes buffers to the SD card as soon as the buffers are full, and maintains correct write order of the buffers.

Samples from the accelerometer are taken every 125μs, or at a rate of 8000 samples per second. The sampling routine is run from an interrupt that is generated from a hardware timer overflow. The time delay is easily changed by changing the reset value of the timer register. After reading the value on the ADC, a level shifting is performed on the 10-bit result to

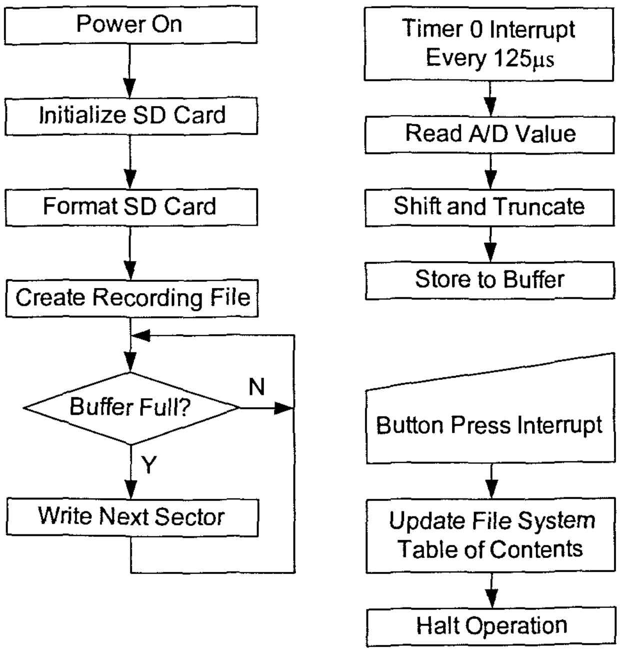


**Figure 2 – Flowchart of Firmware operation**

center the steady state value to 128. After this level shifting, the result is checked for values outside the range of 0 to 255, and any samples falling outside the window are stored as either 0 or 255 to indicate a clipping condition. If the sample falls within the sample value window, the two most significant bits are removed, and the result is stored as a 8-bit sample. Using an interrupt to initiate recording from the analog to digital converter allows the lengthy write routine to process in the background without missing any samples. The minimum amount that can be written to a SD card at a time is 512 bytes. Data is buffered in 512-byte sectors for direct writing to the SD card. Four buffers are allocated in memory, allowing for a temporary interruption lasting up to 0.25 seconds. This level of buffering was found to be necessary to maintain certain levels of file system integrity. The current SD cards are 512 megabyte units, which are able to hold over 17 hours of recorded data.

After the recording session is completed, the user is instructed to press the button located on the circuit board. The button is accessible from the exterior of the case via a hole above the button in the plastic shell. This prevents accidental pressing of the button, which would prematurely end the recording. After the button is pressed, the Table of Contents of the file system is updated to reflect the current file size. The system is then suspended, and the SD card is safe to remove. If the SD card is removed before the button is pressed, the data file will have a length of zero, and recovery of the data will be difficult.

One requirement of this device is that the data recorded should be easily accessible by a personal computer after the recording session is finished. Thus, an implementation of the FAT16 file system was chosen for simplicity. After a file is created on a FAT16 file system, data is written in 512 byte sectors, and 16 consecutive sectors make up a cluster. The number of sectors in a cluster is determined by the size of the SD card. In a 512 megabyte card, 16 sectors are in one cluster, while on a 1 gigabyte card 32 sectors are in one cluster. Each cluster on the SD card must be accounted for in the cluster table of the FAT16 file system. The cluster table maintains a linked list of clusters for every file, and also keeps track of unused clusters. The exact file size is stored in the Table of Contents of the file system. This is the value that Microsoft Windows uses to determine the file size to display. If the cluster table and Table of Contents are not in agreement, the file will be corrupted. To date, we have been unsuccessful in performing updates to both the Table of Contents and the cluster table in real-time recording conditions. The compromise employed maintains the cluster table in real time, and updates the Table of Contents of the file system after the recording is finished. Only one brand of SD card has been tested successfully so far.

Current management of recordings is manual. Ideally, data management software would be used to automatically log times and dates associated with recorded files. Additional data, such as subject ID, start and stop times of the recordings, and additional notes and analysis of the recordings could be stored in a database. This would allow easier tabulations of results, as well as providing a simplified software interface for researchers.

**4. Analysis of Output Waveforms**

Previous work by Jewell [V] indicated that coughing is distinct from other signals recorded in this manner. To demonstrate that the input signals are distinct, three waveforms are given for three separate actions. The actions performed include speaking, clearing the throat, and coughing. The following pictures show the data recorded using the cough monitoring device.

When the accelerometer is attached to the suprasternal notch, vibrations from speech are minimized. The low-pass filter network also removes many components of voice, which is necessary to protect the privacy rights of the subject and ensure that no speech is recognizable from the recorded data.

Figure 3 shows a typical envelope for clearing the throat from a signal recorded from the cough recorder. This action is easily distinguishable from silence or speech in a recording. Key features include a sustained envelope of the signal, with a gradual tapering of the envelope. Figure 4 shows a typical cough waveform. As the cough begins, the envelope rapidly increases, followed by a decrease in energy. A second peak follows. Coughs consist of two or more surges, and have rapid rise times on the initial surge. These two indicators assist the automated software in detecting coughs.

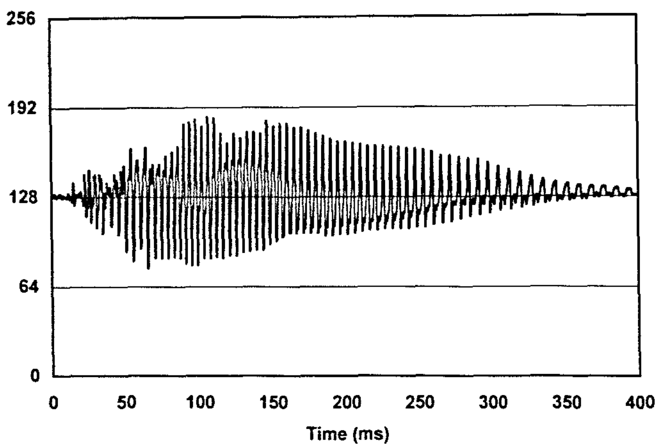


**Figure 3 – Time domain signal of 'Clearing Throat' from the recorded secure digital card data**

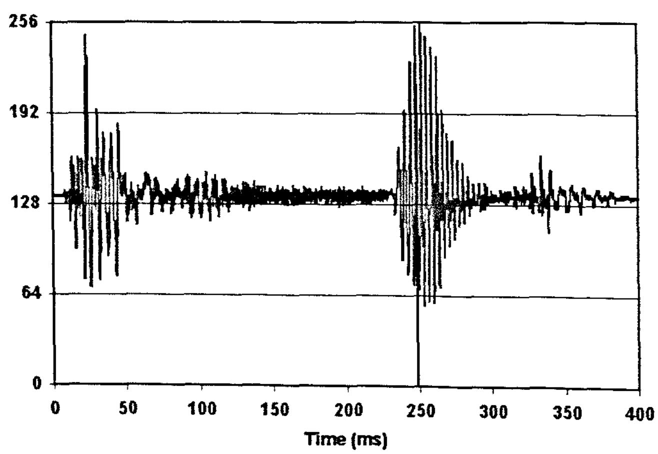


**Figure 4 – Time domain signal of 'Cough' from the recorded secure digital card data**

## 5. Conclusion

Firmware has been successfully developed to achieve the required design objectives. The device correctly filters and samples the accelerometer values. However, recording data has proven to be difficult with the SD technology. Writing non-sequential sectors, such as the file system cluster table and the Table of Contents have caused tremendous slowdowns. This results in gaps in the recorded signal, which is generally unacceptable. Buffering is used to attempt to compensate for unexpected delays while updating the cluster table. This requires the user to press a button before removing the SD card, and unexpected removal of the SD card leads to data loss.

Other problems come from limited storage space. Although currently not a problem, the size of the memory card limits the maximum recording time. One possible solution is a compression technique called run length encoding (RLE). This compression technique takes advantage of fairly constant data when the accelerometer is not moving. This will increase the time between sector writes, which results in lower power consumption and the possibility of automated file system updating. Since the device is battery operated, power consumption is a major concern. The operating frequency of the microcontroller can be reduced, offering lower supply voltages, and less power consumption. Reducing the number of reading and writing operations will also save considerable amounts of power. Furthermore, the device does not work with different varieties of SD cards. Further research and development will overcome these limitations.

## Acknowledgement

We would like to thank Dr. Ian Paul, MD (Hershey Medical Center, PA) for his support throughout the project

## References

I. Parvez L, Vaidya M, Sakhardande A, Subburaj S, Rajagopalan T G, "Evaluation of Antitussive Agents in Man," *Pulmonary Pharmacology* , vol. 9, pp. 299-308, 1996.

II. Hsu J.Y., R.A. Stone, R.B. Logan-Sinclair, M. Worsdell, C.M. Busst, K.F. Chung, "Coughing frequency in patients with persistent cough: assessment using a 24 hour ambulatory recorder," *European Respiratory Journal*, vol. 7, pp.1246-1253, 1994.

III. Jaeger R J, Szidon J P, Doucette P J, "Instrumentation for Measuring Frequency of Cough," Engineering in Medicine and Biology Society, IEEE 17th Annual Conference, vol. 2, pp. 1645-1646, 1995.

IV. Subburaj S, Parvez L, Rajagopalan T G, "Methods of Recording and Analysing Cough Sounds," *Pulmonary Pharmacology*, vol. 9, pp. 269-279, 1996.

V. S. Jewell, "Development of a Self-Contained Ambulatory Cough Monitoring System," M.S. thesis, The Pennsylvania State University, University Park, PA, United States, 2004.

VI. Paul I.M, Wai K, Jewell S.J, Shaffer M.L, Varadan V.V, "Evaluation of a new self-contained, ambulatory, objective cough monitor," Cough, vol. 2, pp. 2-7, September 2006.

VII. Varadan V.V., unpublished, 2006.

## Mentor Comments

Much of the development research that occurs in some engineering disciplines requires teamwork and continuing improvement of products and systems. Professor Vasundara V. Varadan describes how he and Professor Jia Di supervised the unique and important research initiatives of Mr. Barlow.

*As background, I started this project while I was on the faculty at Penn State and worked on this device* *at the request of Dr. Ian Paul, Professor of Pediatrics who wanted a device to undertake clinical trials on the efficacy of cough medicine as prescribed for children today. A prototype, fully functional device was developed at Penn State under my supervision by my graduate student Steven Jewell who wrote his MS thesis on the topic (2003). Since coming to this University, I have developed a more compact, factor of 2.5 smaller and lighter, self contained cough recording system. A secure digital card was designed for use with the system, since it is available more commonly from a variety of vendors and is available with 2-3 GB capacity. However, the standard protocols it uses for data writing make the data logging speed far below the 8 kHz rate that is required for recording high quality cough data. The important contribution that Mathew Barlow has made in its evolution and improvement, is that he bypassed the standard protocols provided by the SD card manufacturer and developed his own software and firmware so that we can still achieve an 8 kHz sampling and writing rate using the SD card. This is described in the paper submitted to Inquiry with output data confirming that his software and firmware are successfully recording signals at the correct sampling rate. Matthew wrote the paper on his own with editorial help only from Prof. Jia Di and myself. One device was sent to Dr. Ian Paul for evaluation and he has responded that it is working satisfactorily.*

*The significance of this device cannot be overstated. Cough is the most common reason why parents take their children to a doctor. Cough medicine is a 19 billion dollar market in the USA. Yet, Dr. Paul's qualitative studies already indicate that cough medicine is no more effective than honey. The media interest in this has been great. Dr. Paul has been interviewed by many newspaper, cable and network TV stations as well as the BBC. I think that the current device will enable a more scientific clinical trial that will firmly establish the efficacy of cough medicine for the prevention and cure of coughing. The device as developed now is commercializable and could also be adapted for other uses.*