Assessing the feasibility of a breathing sensing and registration system based on open source equipment for use with respiratory-gated imaging systems

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Aims and objectives

We worked to develop a flexible and customizable breathing sensing and registration system based on open source hardware and software aimed primarily to be used in medical imaging research involving respiratory-gated technique. Although respiratory-gated CT is already a well established technique the lack of affordable and readily accessible breathing sensing systems makes the technique restricted to a small number of institutions. Hospitals and imaging departments are hesitant to spend the budget needed to purchase certified/vendor-approved hardware before knowing if the technique will fit the institution’s needs. We believe this gap could be filled by means of developing an affordable breathing sensing and processing system that could be used attached to the CT scanner along with the respiratory gating software package for research studies involving respiratory-gated technique, allowing for the institution to weight the pros and cons before committing to spend more significant resources to purchase the proprietary, vendor-approved breathing sensing and processing system.
Methods and materials

When considering the development of a breathing sensing and registration system to be used along with a respiratory gating package on a CT scanner there are two main components that have to be put together:

Breathing sensor

A few options do exist. One of the vendor-approved breathing sensing systems is based on histogram analysis of a video feed which will register the breathing cycle based on movement of the thorax or abdomen. The other well-known system currently available consists of a pressure sensor attached to a belt to be positioned around the patient's thorax.

Aiming for affordability and simplicity we tried out two sensors:

- An air pressure sensor with a Pitot tube attached to nasal prongs, which measures the pressure during the breathing cycle. This is commercially available and can be purchased for approximately 25 US dollars as of the writing of this poster.

- A chest expansion sensor which was built by our team using information available in the medical literature. It basically consists of a light emitter (LED) and a light receptor (photo resistor) which measures the oscillation of light intensity after traveling through a fixed length of optic fiber which is sewn onto an elastic fabric band in a zigzag pattern. This band is worn as a belt by the patient around the thorax and as it stretches it changes the angle of the points of deflection of the sewn optic fiber, hence changing the amount of light that reaches the photo resistor during the breathing cycle. The parts necessary to build this sensor can be purchased for less than 5 US dollars as of the writing of this poster.

Processing unit

The processing unit will software-analyze the voltage received from the sensor and define which phase of the cycle it pertains to, and whether there is apnea or not, either inspiratory or expiratory.

The processing unit will send a continuous analog voltage to the CT scanner throughout the breathing cycle representing the phase of the cycle in real time. This signal will be
used by the scanner to show the breathing curve in real time on the CT console monitor. This usually consists of a lower voltage range, and a typical value would be between 2 and -2 Volts.

Depending on desired parameters for the specific protocol in question, the processing unit will also send a triggering pulse during specific phases of the cycle which will be used by the scanner to start or resume scanning. The triggering pulse is usually a square voltage pulse, and typical values are 5 Volts of amplitude and 100 milliseconds of duration.

We developed two versions of the processing unit, using two different control boards, a Raspberry Pi and an Arduino Pro Mini.

Raspberry Pi Version

A Raspberry Pi version B with Python as the programming language was used for the first version of the processing unit, chosen mainly due to previous experience of the authors. The Raspberry Pi is a control board the size of a credit card, developed by a non-profit organization, the Raspberry Pi Foundation (Cambridge, UK). Its suggested price is around 40 US Dollars in North America as of the writing of this poster. It operates at 3.3V logic so we needed to add a Schmitt trigger to achieve the necessary 5 Volts for the triggering pulse. Also, the Raspberry Pi needs a separate analog-to-digital converter which also had to be added to the circuit to be able to interpret the sensor's readings. These two components added complexity and cost to the setup.
Fig. 1: Raspberry Pi version B+ (85 x 56 mm); Canadian quarter for reference. The Canadian quarter measures 23.81 mm in diameter, very similar to the American quarter (24.26 mm) and the One Euro coin (23.25 mm).

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Programming is done directly in the Raspberry Pi, which runs Linux. Although programming in other languages is possible, we opted to use Python, which is recommended by the board developers for interfacing with the in/out pins.

The extra cost of the Raspberry Pi is fair given the fact that it has resources that do not exist on the Arduino, for example the ability to be connected to a video monitor and wireless connectivity.
Aiming for a simpler and more affordable solution we also tried out a similar setup using an Arduino model Pro Mini as the core of the system, with Arduino's own proprietary programming language for the code. This model of board can be purchased in North America for around 13 US dollars as of the writing of this poster. The Arduino series was developed as a prototyping platform for students and is currently considered open hardware. This board does have built-in analog pins and thus does not need a separate analog-to-digital converter. Also, it operates at 5V logic, able to generate the 5V triggering pulse without extra circuitry. It's also much smaller than the Raspberry Pi, which allows for a much more compact project box to be used.

The code is built on a separate computer and then uploaded to the Arduino. It then will run the code independently from the computer.
Fig. 2: Arduino Pro Mini (18x33mm); Canadian quarter for reference. The Canadian quarter measures 23.81 mm in diameter, very similar to the American quarter (24.26 mm) and the One Euro coin (23.25 mm).

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Results

Assembly of the processing units was straightforward with information available on creators’ website and on community-based forums for both Raspberry Pi and Arduino.

The Raspberry Pi needed two extra components that the Arduino did not demand, namely an (1) analog-to-digital converter to be able to read the voltage provided by the sensors, and a (2) Schmitt trigger in order to generate the 5V triggering pulse, since the digital pins of the Raspberry Pi can only generate a maximum of 3.3V by default. This added to cost and complexity of the circuitry.

The characteristics of each version are listed below:

**Raspberry Pi Version**

- Runs on Linux native system (Raspbian)
- 700 MHz
- Allows extra software to be installed
- System is stored on an SD card; card size can be found up to 64 GB, so in practice virtually no limit to programming code length
- Same unit can be used for multiple simultaneous projects, each stored on a different SD card, which has to be swapped for testing of each of the projects
- Ready to accept peripherals (Video, Wi-fi dongle, etc.)
- No built-in analog-to-digital converter
- 3.3V logic with 5V rail available; for our project that means we had to add extra circuitry (Schmitt trigger) in order to be able to achieve the 5V trigger pulse.
Fig. 3: Real time video feedback on Raspberry Pi - simultaneous registration of pressure sensor (nasal prongs, top) and chest expansion sensor (bottom); the solid blue lines correspond to detected apnea.

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**Arduino Version**

- No operational system
- 16 MHz
- Programmed on proprietary language (Arduino IDE)
- No extra software allowed
- Limited storage (maximum 30 kilobytes of code allowed)
- Can be used for multiple simultaneous projects, each stored on a different SD card, which has to be swapped for testing of each of the projects
- Not ready to accept peripherals; serial interface only.
- Built-in analog-to-digital converter
- Available both in 3.3V and 5V logic

The two processing units worked satisfactorily, with good registration of the sensor's signals and able to recognize breathing cycle phases and periods of apnea. Both units are
efficient in sending triggering pulses to the CT scanner at the desired/pre-programmed phase, as well as the voltage representing the breathing cycle position in real time through a different channel.

The end result at the CT scanner console is identical. The two setups vary slightly in price and resources and rather than being one better than the other we prefer to say they are just different, as both have peculiar characteristics that are advantageous depending on the use scenario.
Fig. 3: Real time video feedback on Raspberry Pi - simultaneous registration of pressure sensor (nasal prongs, top) and chest expansion sensor (bottom); the solid blue lines correspond to detected apnea.

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Conclusion

It is feasible to build a breathing sensing and processing unit meant to be used for research with respiratory-gated CT technique using only very affordable control boards as the hardware and open source software. We were successful in building two different versions using two different control boards, the Raspberry Pi version B and the Arduino Pro Mini, both with same functionality, able to recognize the different phases of the breathing cycle and able to produce the necessary voltages in two different channels to interface with the CT scanner.

The setup is vendor-independent, and minimal changes are necessary to comply to different requirements from different CT scanners.

It provides an affordable option to institutions willing to start research with respiratory-gated techniques, but unable or unwilling to purchase the vendor-approved hardware for clinical use before having the technique experimented with in a research environment first.
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