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Respiratory Rate Detection Using a Wearable Electromagnetic Generator

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Abstract— **Wearable health and fitness monitoring systems are a promising new way of collecting physiological data without inconveniencing patients. Human energy harvesting may be used to power wearable sensors. In this paper, we explore this zero-net energy biosensor concept through sensing and harvesting of respiratory effort. An off the shelf servo motor operation in reverse was used to successfully obtain respiratory rate, while also demonstrating significant harvested power. These are the first reported respiratory rate sensing results using electromagnetic generators.**

I. INTRODUCTION

Wearable health and fitness monitoring systems are a promising new way of collecting physiological data without inconveniencing patients. These have included portable heart monitoring using Holter ECG [1], shown in Fig. 1a, and more recently wearable fitness monitoring systems, such as Polar FT40 [2], shown in Fig. 1b, and activity based monitoring such as BodyMedia bodybug [3]. Cardiopulmonary monitoring has become more convenient and less obtrusive with smart clothing development [4]. Most of these systems provide physiological data such as heart rates and respiratory rates, and calorie expenditure estimates. Chest belt and smart garment systems use physiological sensing through embedded sensors, in conjunction with a battery operated transmitter that snaps onto the garment to collect data and send it over a wireless link to a battery operated wrist watch or personal communication device.

(a) (b)

Fig. 1. Numetrex smart garments with embedded ECG electrodes (a), and a compatible Polar transmitter and wristwatch (b).

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While smart clothing systems provide an extended operation for fitness monitoring using a watch battery [4], if they are used for continuous health monitoring, the batteries would have to be changed frequently, resulting in a large amount of disposed batteries that present an environmental hazard. In addition, many people tend to stop using such devices once the batteries run out.

Human energy harvesting for wearable and portable electronics was proposed in the mid 1990's [5]. While a number of potential human energy sources were identified in [5], human energy harvesting has mostly been focused on kinetic energy [6-8]. Kinetic energy harvesting has been focused on the gross body motion during walking [6-8], and it has been demonstrated that electromagnetic scavenging is more efficient than piezoelectric [4, 7]. Perhaps the most readily available form of human power is respiration, yet no significant work has been done on energy harvesting from movement of the chest walls due to respiratory effort. On the other hand wearable biosensors have been investigated for remote health and fitness monitoring, including applications ranging from wound healing to athletic training [9]. Wearable sensors have included ring, ear, and body sensors [9-12]. To power these systems, simple batteries and proximity radio frequency (RF) power scavenging [8] have been used. In [13, 14], the concept of self-powered biosensors through sensing and harvesting methods for respiratory effort was introduced. In this paper we present experimental results demonstrating that the peak power of 15 mW can be harvested from the respiratory effort using a wearable off-the-shelf servo motor operating in reverse, while respiratory rate is extracted simultaneously with high accuracy.

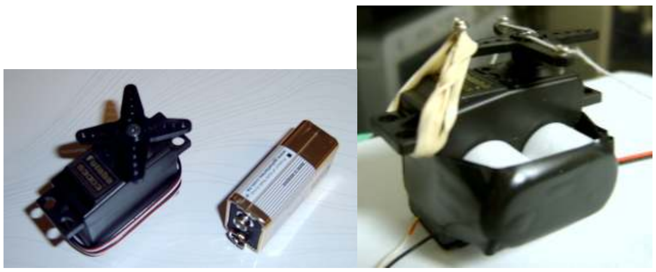
II. WEARABLE SERVO MOTOR DESIGN

Electromagnetic generation is based on Faraday's Law, which states that a changing magnetic field induces an electric field resulting in electric current:

$$\text{Faraday's law} \quad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

A servo motor was used for easy modification into a wearable apparatus, as well as for motor rotational speed increase from the gearbox. The servo motor used is comprised of a permanent magnet DC motor, a gear train, a potentiometer, and some control circuitry [15]. The potentiometer is attached to an armature, which is connected to the gear train, followed by the rotor of the motor. The chest motion turns the armature, which turns the gears and the rotor of the motor. The rotor, which is basically a metal shaft with wire coils, rotates within the permanent magnets inside the motor. A current is induced and collected at the motor's terminals.

The off-the-shelf servo motor is modified into a wearable chest band. The model is a Futaba S3003, a standard servo motor [16]. The servo housing weighs only about 37g, and is about the size of a 9V battery. The armature has four blades and a diameter of 3.8cm.



(a) (b)

Fig. 2. Original (a) and modified wearable servo motor (b).

Plastic spacers are attached to one side of the housing to prevent the protruding armature from hitting the chest. A string is fixed at one end of the armature using a screw. The string is then wrapped tight once around the chest, and the other end of the string is fixed at the opposite end of the armature. A rubber band is also attached between the housing and another blade of the armature. The rubber band provides a restorative force to return the armature to its original position after each breath.

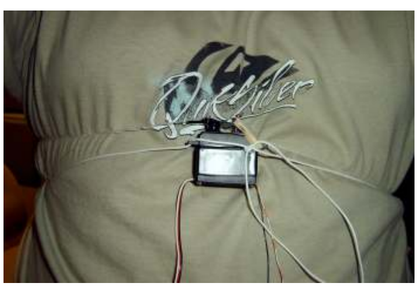


Fig. 3. Modified servo motor attached to the chest – motor placed right on sternum.

The string attached to the armature is wrapped tight around the chest, with the motor placed right on the sternum. Another wire is wrapped around the housing and chest to stabilize the motor, and ensures that only the armature turns during breaths.

When the servo motor is attached to the chest, the armature is positioned as shown on the left in Fig. 4. During inhalation, the chest circumference expands. The fixed ends of the string are pulled in opposite directions, thus turning the armature as well as stretching the rubber band. During exhalation, the rubber band pulls the armature back to its original position.

By observation, the armature will not be able to turn more than ninety degrees. The amount of rotation is proportional to the amplitude of the chest displacement, and it will be demonstrated that even during very deep breathing, the armature theoretically will not turn more than ninety degrees.

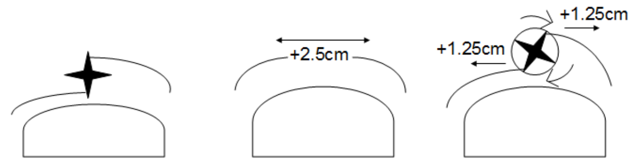


Fig. 4. Top view of chest and armature before and during inhalation.

On average, the chest circumference expands about 2.5cm during inhalation. Because the string is attached to opposite ends of the armature, the total tip displacement, or arc length, will be 1.25cm. The armature has a diameter of 3.8cm. The circumference, C, can be calculated from the armature diameter, d:

$$C = \pi \cdot d = \pi \cdot (3.8cm) = 11.9381cm \tag{2}$$

The amount of revolution (AR) of the armature can be calculated by dividing the arc length (AL) by the circumference, C, and expressing it in degrees:

$$AR = \frac{AL}{C} = \frac{1.25cm}{11.9381cm} \cdot \frac{360^o}{rev} = 37.7^o \tag{3}$$

Thus, during normal breathing, it is expected that the armature will not turn more than 38 degrees. During deep breathing, and assuming a maximum chest circumference increase of 5cm, the maximum amount of revolution is calculated as:

$$AR = \frac{AL}{C} = \frac{2.5cm}{11.9381cm} \cdot \frac{360^o}{rev} = 75.4^o \tag{4}$$

Therefore, the setup allows for full angular displacement of the armature for wide range of respiratory efforts.

III. Servo Motor Performance

The servo motor apparatus was tested on a human subject during three different scenarios – normal breathing, holding breath and exhaling, and fast, deep breathing. The subject is standing in a stationary position. A piezoelectric belt was worn simultaneously as a respiratory effort reference. The voltage outputs of both the servo and the piezoelectric belt were measured and recorded.

The positive half-cycles occur during inhalation, and the negative half-cycles occur during exhalation. The piezoelectric output is proportional to the chest displacement. By Faraday's law, the servo output measures the velocity of displacement. Thus the output of the servo-motor will increase for faster chest motion corresponding to higher respiratory rate.

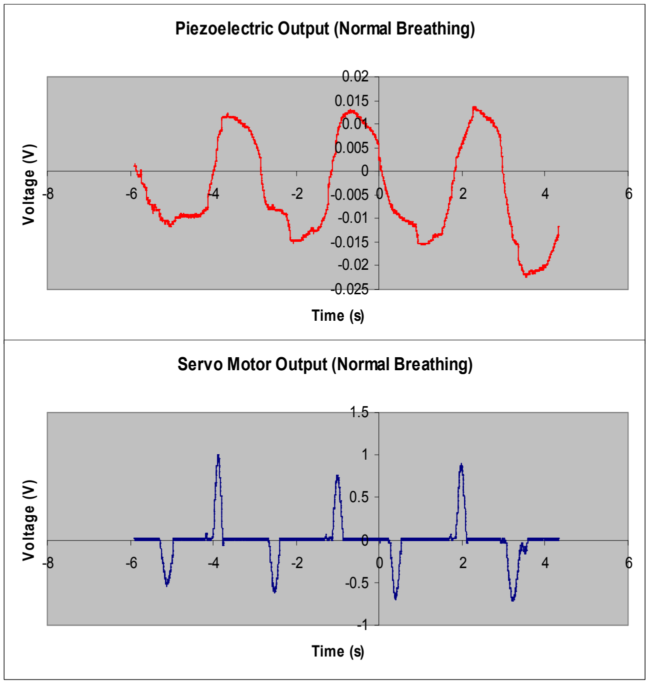


Fig. 5. Piezo Vs. Servo Output, Normal Breathing

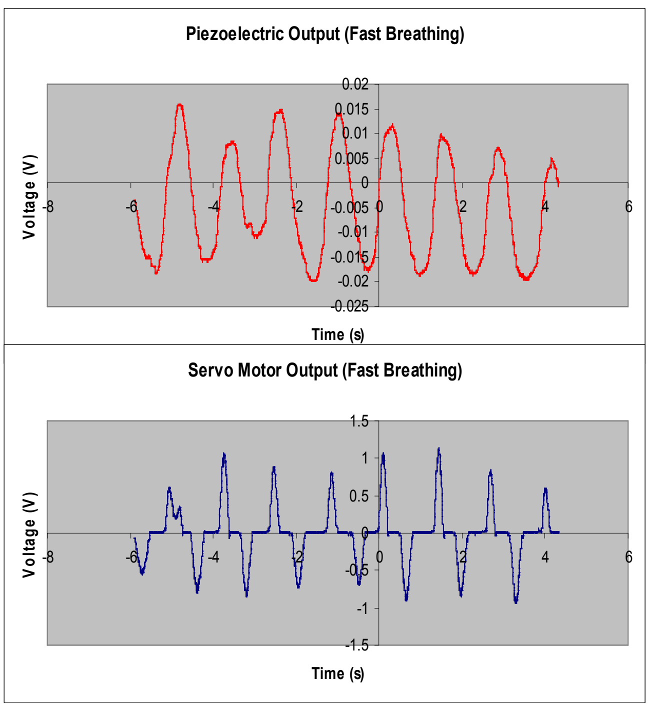


Fig. 6. Piezo Vs. Servo Output, Fast Breathing

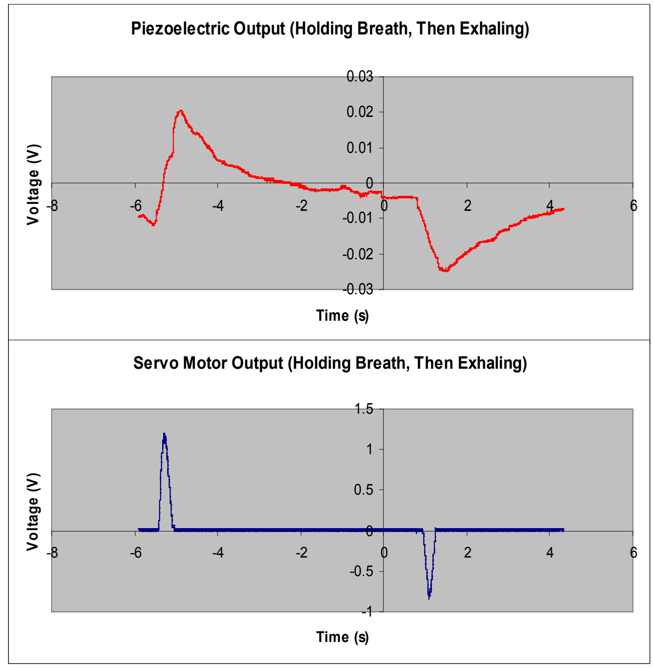


Fig. 7. Piezo Vs. Servo Output, Holding Breath Then Exhaling

The pulse-like waveform output of the servo-motor is due to static friction (stiction) in the motor's gears. Nonetheless, the positive and negative peaks of the servo motor align with those of the piezo-belt for all scenarios. In Fig. 7, the positive and negative peaks of both outputs line up, but while the subject is holding breath, the chest does not move, thus getting no output from the servo. The piezoelectric material discharges, causing the downward slope depicted. A respiratory rate calculation and comparison will be made in the next section.

During normal breathing, the servo outputs a peak-to-peak voltage of about 1.4V. The peak-to-peak current measured is about 84.8mA, resulting in the peak power of about 15 mW.

The output of the servo can be rectified and stored in a capacitor, and the stored energy can be used to power a low-power microcontroller for respiratory rate detection from subsequent breaths.

IV. Respiratory Rate Determination

As shown in Figures 5-7, the servo motor output peaks match those of the piezo-belt reference output. In Matlab, Fast Fourier Transform was performed on the piezoelectric and servo motor signals from Figs. 5 and 6. The maximum points were detected on the resulting periodograms, and the respiratory rate values were extracted, as shown in Figs. 8 and 9.

Under normal breathing, the breathing rate calculated was 23.3 breaths/min for both the piezoelectric belt and servo motor. Under faster breathing, the breathing rate calculated was 46.7 breaths/min for both. Thus, the servo motor apparatus can detect respiratory rates with high accuracy compared to the piezoelectric belt reference.

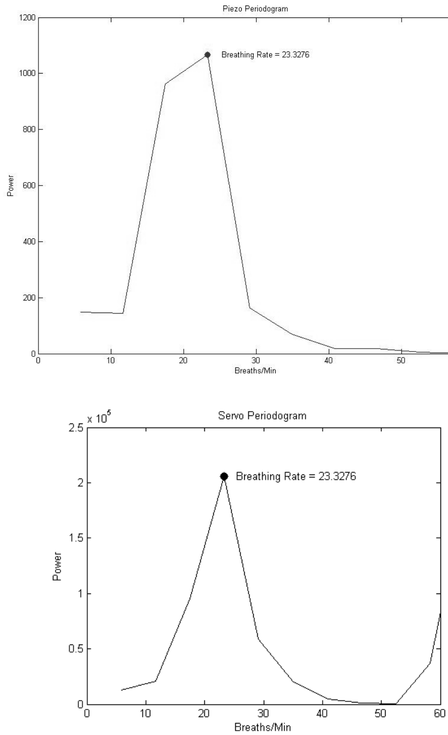


Fig. 8. Piezoelectric and Servo Motor Periodograms, Normal Breathing

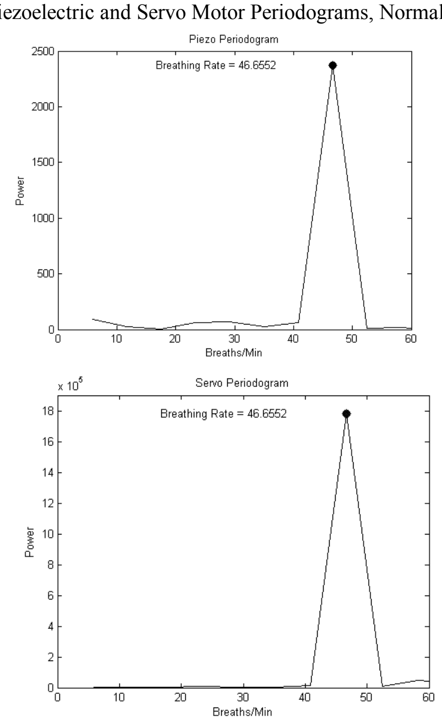


Fig. 9. Piezoelectric and Servo Motor Periodograms, Fast Breathing

V. CONCLUSION

The wearable servo motor is an unconventional design that can be used for respiratory rate monitoring as well as energy harvesting. We have demonstrated the feasibility of measuring respiratory rate using an electromagnetic generator, while providing a significant output power. The respiratory rates are obtained using a servo-motor on a single subject, standing in a stationary position, and closely match the rates obtained using the piezoelectric reference. Further experimentation will be done on a number of subjects in different positions, as well as during movement. Simultaneous respiratory effort harvesting and sensing can be used to create a wearable zero-net energy biosensor, providing an environmentally friendly alternative to traditional medical sensing. Future work will include more ergonomic and comfortable design that could be incorporated into clothing.

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