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Low-cost and Disposable Pressure Sensor Mat for Non-invasive Sleep and Movement Monitoring Applications

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Abstract—**Sleep has profound effects on the physical and mental well-being of an individual. The National Institutes of Health (NIH) Sleep Disorder Research Plan gives particular emphasis to non-invasive sleep monitoring methods. Older adults experience sleep fragmentation due to sleep disorders. Unobtrusive non-contact monitoring can be the only realistic solution for long term home-based sleep monitoring. The demand for a low-cost and non-invasive sleep monitoring system for in-home use is more than before due to an increasingly stressful life style. Cost and complexity of current sensor elements hinder the development of low-cost sleep monitoring devices for in-home use. This paper presents the design, development and implementation of a low-cost and disposable pressure sensor mat that could be useful for in-home sleep and movement monitoring applications. The sensor mat design is based on a compressible foam sandwiched between two orthogonal arrays of cPaper capacitance sensors. A low-cost conducting paper has been developed for use as the capacitance sensor electrode. Typical mat design uses a 3 mm thick foam with 5 mm row/column grid array shows that it has a measurement resolution of 0.1 PSI pressure. The resolution can be controlled by both modifying properties of the conducting paper and the foam. Since this pressure mat design is based on low-cost paper, the sensor electrodes are disposable or semi-durable and hence it is ideal for the use in point-of-care physiological monitoring, pervasive healthcare and consumer electronic devices.**

I. INTRODUCTION

Sleep disorders can cause a variety of medical problems, both in children and adults. It can be potentially very serious, even life-threatening, if not treated properly. Sleep centers diagnose sleep disorders by observing sleep patterns, brain waves, heart rate, rapid eye movements and biopotentials using devices attached to a subject's body. Even though there are several well-known methods available to evaluate sleep in sleep labs, noninvasive and unconstrained monitoring is still an unmet challenge. Known technologies require physical contact of the sensor electrodes with the subject and that hinders the implementation of such a system for in-home settings.

Tactile sensing based on pressure monitoring is one of the rapidly advancing fields in healthcare as well as consumer products. Physiological monitoring and gait analysis require low-cost and flexible tactile sensors [1-3]. Tactile sensors typically map the pressure by measuring the force or change in electric field on a surface. Microsensors based on piezoresistive, piezoelectric, capacitive or optoelectronic technologies are examples of such as approach. Most of these sensors though have high cost, complex manufacturing process, low spatial resolution, limited flexibility or small dynamic range [4]. Tactile sensors for touch applications are designed using capacitance sensors, particularly for higher-end applications. Attempts have also been made to develop flexible tactile pressure sensors based on textiles [5-7] as well as flexible polymers [8-9] with limited success. Even though capacitance sensing technology has been applied in many consumer electronic devices, the relatively high cost and stringent fabrication requirements prevent their use in low-cost disposable applications today.

One of the issues with today's hospitalization is that, though patients are admitted with a view to improve their health, often they contract bedsores and ulcers, particularly in the case of elderly people. This is mainly due to excess pressure against the skin over an extended period of time which reduces the blood flow and eventually damages the skin. Medical complications like bone and blood infections may also develop in such patients. One of the methods to prevent bedsores is to turn the patient's body periodically, which is labor intensive and time consuming [10-12] and is not done regularly. A system that could monitor a patient's status and alert the caregiver if they are motionless for a predetermined length of time is an unmet challenge. A low-cost automated pressure monitoring mat and alert system that could unobtrusively monitor a patient's sleep patterns through movement and other parameters will highly improve today's labor-intensive assisted living conditions.

This paper presents the design, fabrication and implementation of a low-cost and disposable pressure monitoring mat and data acquisition system for non-invasive sleep and movement monitoring applications. The sensor mat design is based on capacitive sensors using low-cost conducting papers (cPaper) [13-15]. cPaper has sufficient conductivity that is required for most disposable product applications. Since the cPaper pressure sensor is designed for disposable /limited use, it is ideal for applications in low-cost physiological monitoring, pervasive healthcare and consumer electronic devices. Since the top and bottom cPaper electrodes are disposable, the pressure sensor mat may be reused by replacing the top and bottom electrodes while retaining the foam.

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II. PRESSURE SENSOR MAT DESIGN

A pressure monitoring array has been designed based on capacitive sensing principles using cPaper. cPaper is a nonwoven material where the electrical conductivity is achieved by loading carbon fiber into the matrix. The conductivity of a single ply cPaper sheet can be controlled by loading carbon fibers at different concentrations onto the base sheet.

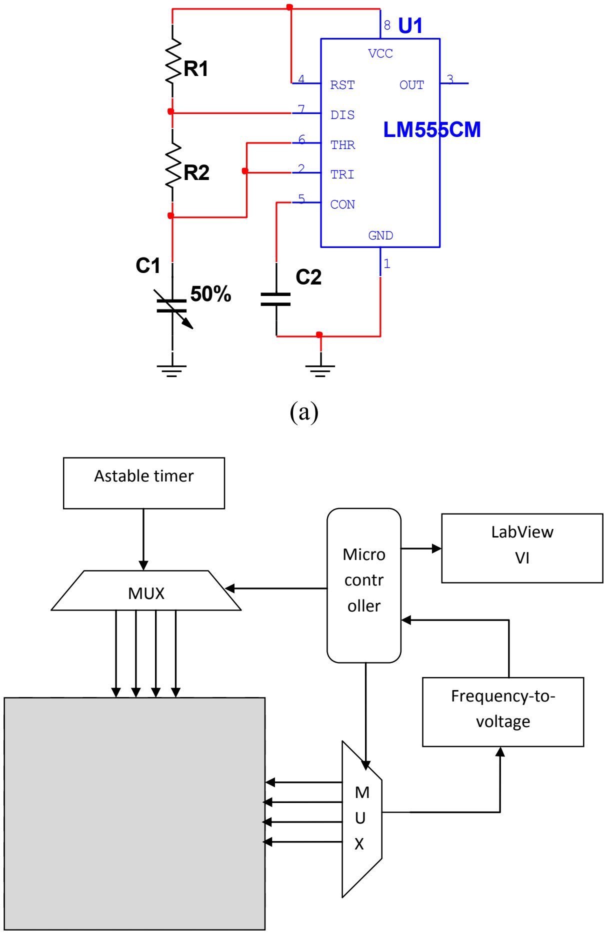
Fig. 1. Photograph of the 8x8 matrix pressure mat tile. Each element in this tile is 5 mm width and 15cm long. Bigger mat can be made by tiling smaller units.

Single ply cPaper strips are made out of rolls of cPaper with 40% carbon fiber loading in this work. A blend of carbon fibers (diameter ranging from 5 to 10 um and length 3 mm) and cellulose pulp is used for cPaper fabrication using a wet laid process. Adjusting the cellulose-carbon fiber ratio yields a range of conductivity. One of the advantages of the cPaper is that, the conductivity can thus be tailored easily. Since conductivity is one of the important criteria for capacitance sensors, cPaper strips with low resistivity (<10 ohm/Sq) are selected for the present design. Strips of width varying from 2 to 12.5 mm are used for the mat fabrication. Hotmelt adhesive is sprayed onto a spunbond nonwoven material and cPaper strips are affixed and glued together using another layer of spunbond nonwoven material. Top and bottom nonwoven encapsulation layers are helpful in isolating and protecting the conducting lines. Electrical connections are made from each column and row electrodes by bonding thin conducting metallic wires directly to the cPaper using ultrasonic bonding. This array acts as top electrode on one side of a compressible foam. The mat is fabricated by arranging second electrode array orthogonal to the top rows at the bottom side of the foam. The foam's thickness and compressibility significantly affects the performance of the mat. High sensitivity applications require thin foams with good compressibility.

Figure 1 presents the photograph of an 8x8 element cPaper capacitance sensor array fabricated using a nonwoven material. cPaper strips of width 5mm and a separation of 5 mm is used as the top electrode (row electrode) for the sensor. The bottom column electrode is made with the same width and spacing. The spatial resolution is therefore about 1 cm.

Any external pressure compresses the foam, which is a dielectric medium separating the capacitor plates and hence changes the capacitance due to the displacement of the electrodes at the selected location of the mat. Since the compression of the dielectric medium reduces its thickness and hence the spacing between the plates, the array exhibits a local change in capacitance with applied pressure.

III. FRONT-END ELECTRONICS



(a)

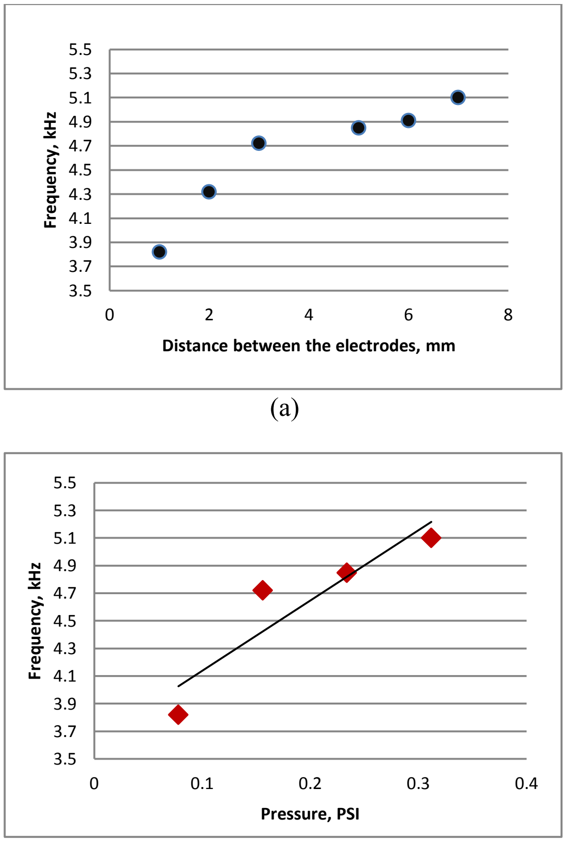
(b)

Fig. 2. (a) Astable multivibrator circuit; (b) Schematic diagram of the pressure monitoring mat. The row and column vectors decide the selection of element. Microcontroller selects the row/column and read the value of the capacitance.

Figure 2(a) presents the schematic diagram of the capacitance measurement circuit. The output frequency of the astable multivibrator changes due to change in capacitance C1. The function generator, based on an astable timer circuit changes the frequency due change in applied pressure on the mat. The output frequency of the astable multivibrator can be calculated from:

$$f = \frac{1.44}{(R1 + 2R2)(C1)}$$

The duty cycle (ratio between ON and OFF time) is mainly determined by the resistance values R1 and R2. Since the capacitance change is measured by monitoring the change in pulse width, close to 50% duty cycle is highly desirable for the present design. Block diagram of the control and signal detection circuit is presented in figure 2(b). Analog multiplexers are used to select the row/column electrodes of the mat. A PIC microcontroller is used subsequently to read the capacitance values at the various row/column intersections by continuously scanning selected regions of the mat. This process is repeated in a pre-determined sequence so that the capacitance distribution can be measured over a large surface area. An electronic signal generator, row and column selection circuits, frequency-to-voltage converters and LabView functional blocks are implemented for signal detection.



(a)

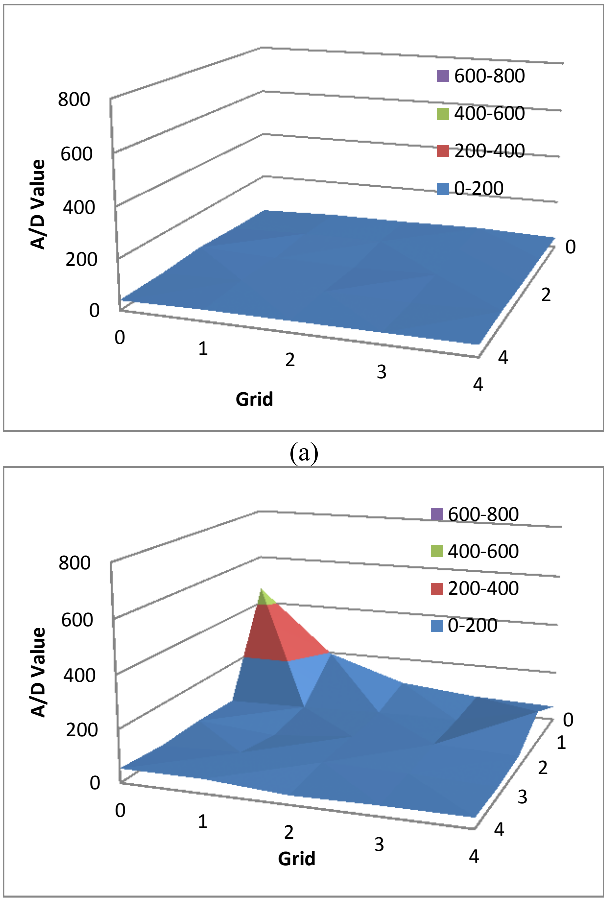
(b)

Fig.3. Change in frequency due to (a) change in separation between the electrodes; and (b) change in applied pressure on a single element.

The signal from the astable multivibrator is amplified and is given to a frequency to voltage converter. The microcontroller reads the DC voltage values and the output are displayed using the LabView graphical interface.

IV. RESULTS AND DISCUSSIONS

The effect of change in dielectric thickness between the cPaper electrodes on the change in oscillator frequency is measured by precisely moving the top electrode using a micrometer. The change in frequency is measured using 8 mm thick foam sandwiched between two cPaper electrodes and moving the top electrode. Figure 3(a) presents the change in output frequency due to the change in separation between the top and the bottom electrodes. The pressure calibration curve is determined by measuring the change in frequency against known static pressure on the mat that has 3mm thick foam with 5 mm cPaper row/column electrodes. Measured change in frequency due to the applied static pressure is shown in figure 3(b). It can be seen from figure 3 (b) that small changes in pressure (~ 0.1 PSI) can be recorded using a cPaper-based pressure monitoring mat made up of a highly compressible foam.



(a)

(b)

Fig. 4. Measured change in output due to various pressure; (a) no pressure on the mat; (b) pressure applied on element number (0,0)

Data acquisition and display interfaces are developed using LabView VI. The multiplexer scans row/columns with scanning frequency of 20 Hz and the microcontroller reads the values. Figure 4 presents the measured output from a 5x5 element cPaper mat. Figure 4(a) shows the output without any applied pressure and figure 4(b) shows the change in output voltage due to a small pressure applied on element (0,0).

Since the capacitance change is dependent on the compressibility of the foam, any desired pressure measurement is possible by designing foams with required pressure-deformation characteristics.

The resolution of a pressure sensor mat element depends on the width of each row/column element since the capacitance depends on the area of the electrodes at the interface. cPaper strips with electrode width of 2 mm to 12.5 mm were explored in this work. A 5 mm strip width is more than sufficient for sleep as well as movement applications in terms of spatial resolution.

cPaper arrays can be fabricated in any desired size and shape and used as a bed sensor for long term pressure and position monitoring. This could also be used as a fall monitor mat for elderly or a child monitoring system to prevent sudden infant death in a crib by periodically monitoring subject's movement or any abrupt changes in the movement.

V. CONCLUSIONS

Design and development of a low-cost and disposable pressure monitoring mat and data acquisition system that is ideal for sleep medicine and movement monitoring application is presented in this paper. This non-invasive sensor allows clinicians to gather data from in-home and community settings without disturbing routine sleep. The advantage of using cPaper pressure sensors for in-home sleep monitoring is that it could be used as a disposable mat, which improves overall hygiene. It is easy to make large mats by tiling various cPaper mats, which is also cost effective. The preliminary results show that the cPaper capacitance elements provide sufficient sensitivity to enable the design of low-cost pressure monitoring arrays.

Disposable and low cost pressure sensors could also be used for imaging and pervasive healthcare applications. One of the critical components in robotic surgery is a tactile sensor. The cPaper sensor can be miniaturized to integrate as a disposable tactile sensor array to use in minimally invasive surgery. Since the conductivity of cPaper depends on the carbon fiber loading, it could be tuned to a desired conductivity that is required for the tactile sensor applications. There are other opportunities in physical medicine and rehabilitation for miniature sensors that can be unobtrusively attached to a subject for various monitoring applications.

The electronic signal detection and data acquisition systems can be easily integrated to Wi-Fi systems for real-time remote monitoring, particularly for point-of-care use. The results of this study encourage further efforts towards non-invasive sleep and movement monitoring assessments in clinical settings.

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