

Design of Readout Circuit for Piezoresistive Pressure Sensor Using Nodal Array Approach Reading Technique

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ABSTRACT

In this paper, we proposed a new readout circuit in order to improve measurement output while reading the grouped resistive value in matrix array form. The purpose of having this circuit is to overcome the main problem in applying piezoresistive pressure sensor array for foot plantar application. This new approach is called Nodal Array Approach (NAA), a modified version of Wheatstone Bridge Circuit based on nodal analysis technique using Kirchhoff Current Law. The NAA calculates the sensors' resistance values by solving simultaneous equations from reading voltages of the proposed readout circuit. Therefore, it is found that the readout circuit connection is of low complexity as it only uses resistive element as the major component of reading technique with only four iterations involved for each voltage nodes. Through simulation results, it shows that NAA is able to achieve high accuracy in obtaining a sensor's resistance value by adhering to several limitations in order to avoid miscalculation (< 5% average calculation error).

Keywords: Resistive readout circuit, resistive sensor array, foot plantar application

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INTRODUCTION

It has been a trend in medical fields to search for an alternative approach to diagnose a patient without having to probe him/her with needles for blood samples. This alternative method should be pain-free while still maintaining the same quality as the traditional technique. For an example, by examining foot pressure patterns doctors can tell whether the person has diabetes or not (Aziz et al., 2012; Boulton, 1983). Abnormal

standing or walking postures may lead to ulcer in the soles, which is a side effect of diabetes (Bacarin, Sacco, & Hennig, 2009; Stess, Jensen, & Mirmiran, 1997; Young, Breddy, Veves, & Boulton, 1994; Veves, Murray, Young, & Boulton, 1992; Duckworth, Boulton, Betts, Franks, & Ward, 1985). Hence, foot plantar measurement system has been developed to help doctors, especially endocrinologist and podiatrist, in analysing a patient’s foot pressure distribution pattern (Rashidi, Hussein, & Hasan, 2015; Almassri et al., 2015; Hussein, Hasan, & Jafaar; Shu et al., 2010; Orlin, & McPoil, 2000; Urry, 1999).

However, the measurement system of this product needs to be improved especially its circuit complexity and reading technique (Shu, Tao, & Feng, 2015). We suggest an alternative method of reading technique called Nodal Array Approach (NAA) which uses iterations rather than the normal scanning approach which is very time consuming for a large network of sensors (Zhang, Zhou, Balasundaram, & Mason, 2003; Liu, Zhang, Liu, & Jin, 2010; D’Alessio, 1999). The proposed readout circuit also has the advantage of low complexity in its circuitry and connections which is achieved by developing it to only have resistive elements as its main components. Due to linearity characteristic of resistive elements, its connections, current flows and electrical analysis will be kept simple and ensure easy calculation. Nevertheless, there are some limitations which need be considered in order for NAA to work flawlessly giving the best accurate results.

This paper will focus on the NAA technique and the efforts made by the authors to make it a reality. A 7-node NAA network was constructed in Proteus ISIS software in order to simulate and analyse its results. The simulation results will be discussed by pointing NAA’s major advantages and limitations. This paper will also discuss the advantages of this new approach as a resistive sensor array’s readout circuit with suggestions for future improvements and recommendations.

NODAL ARRAY APPROACH (NAA)

The NAA consists of a sensory network and a controlling mechanism within the readout circuit. and a reading algorithm to calculate sensor’s resistance value as shown in Figure 1. An applied foot pressure will change the resistivity of the arrayed piezoresistive sensors to produce voltage on each of its node. This analog voltage will be converted into a digital form by using

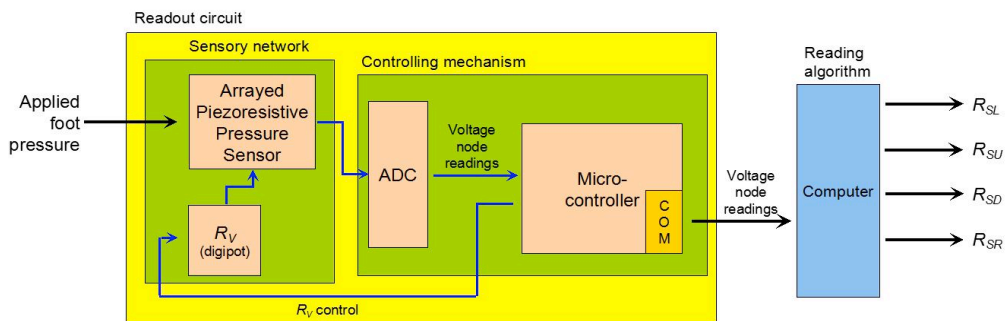


Figure 1. NAA block diagram

Analog-to-Digital Converter (ADC) and stored in a microcontroller. The microcontroller will give command to change the variable resistors value for next iteration. Once all the iteration has been completed, the stored value of each voltage node will be sent to a computer that has been installed with NAA's reading algorithm. The sensors' resistance values will be the end results of this research where they are arranged according to their location in a sensory network.

Sensory network

The sensory network consists of sensors and variable sensors arranged in an array form which looks like a cascade Wheatstone Bridge Circuit. It has a node on each junction that is label as U (up), D (down), L (left) and R (right). The first and last node is special as they only have three junctions of U, D, R and U, D, L respectively. The variable resistors (RV) will be infused in the arrayed piezoresistive pressure sensor as shown in Figure 2. The size of the sensory network depends on Equation (1) and (2), used to calculate the nodes, sensors and variable resistors needed for the whole circuit construction. We have developed a 7-node NAA sensory network which can obtain 20 sensor's resistance values and assisted by 8 variable resistors such as in Figure 2.

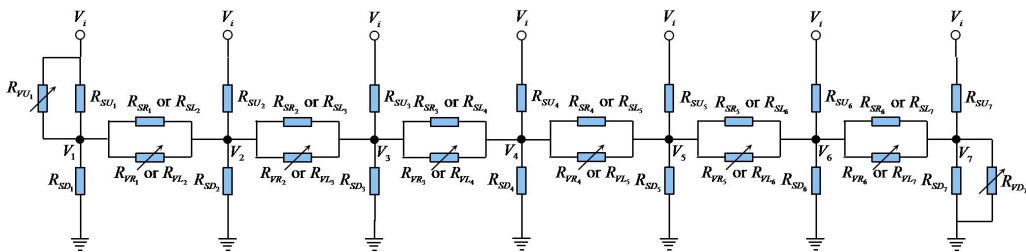


Figure 2. 7-node NAA sensory network

$$s = 3n - 1 \tag{1}$$

$$v = n + 1 \tag{2}$$

- s - number of sensors
- v - number of variable resistors
- n - number of voltage nodes

Controlling mechanism

By observing Figure 1, the voltage nodes readings obtained from sensory network need to be converted into a digital form in order to store them in microcontroller's register. This task is performed by an ADC and seven of them are needed for our experiment of 7-node sensory network. We have selected a 22-bit delta-sigma ADC which has become one of the major factor

affecting NAA's calculation accuracy. In microcontroller, three major tasks are performed during the reading process:

- Storing all the digital values of voltage nodes
- Command the variable resistors to change their resistance values
- Sending all the digital voltage node values to computer through serial communications port

The microcontroller should have at least three I/O ports containing 8 pins where each port represents the task it needs to perform. It also needs to have a large amount of available register for storing all the 22-bit digital representation of voltage node values which is at least 7 (nodes) X 4 (iterations) X 3 (8 bit per register block) = 84 in total. Last but not least, it should have a fast clock frequency in order to perform all the tasks within a second or less to give way for the next foot pressure measurement.

Reading algorithm

As mentioned earlier, NAA implements iteration reading instead of a scanning technique that has been used by many other approaches of resistive readout circuit (Hussein, Hasan, & Jafaar; Shu et al., 2010; Orlin, & McPoil, 2000; Urry, 1999; Shu, Tao, & Feng, 2015; Zhang, Zhou, Balasundaram, & Mason, 2003; Liu, Zhang, Liu, & Jin, 2010; D'Alessio, 1999). Each node will have a specific nodal equation according to the resistive value of sensors and variable resistors attached to it. When the sensory network is given a power supply, voltage can be read at each node while all the variable resistors value will be initially set up. Now, the nodal equation will only have an unknown sensor's value in each of them. As each node only has four sensors (R_{SU} , R_{SD} , R_{SL} and R_{SR}) that is attached to it, it only needs a maximum of four different readings in order to calculate those unknown sensor's value. These four readings will be made through four iterations by varying the variable resistors' resistive values in between. Finally, all these four simultaneous equations are to be solved by using matrix manipulation and the end results will be each sensor's resistance value. This iteration reading procedures can be visualised as a flowchart in Figure 3.

In order to use matrix manipulation for solving four simultaneous equations from each node, Mathworks Matlab was chosen as it is the most convenient and user-friendly software that provides a quick solution. The NAA reading algorithm is kept in a computer's platform rather than burdening the microcontroller with matrix manipulation codes that can decrease its output timing results. These results needed to be processed further to produce useable data using the same platform .

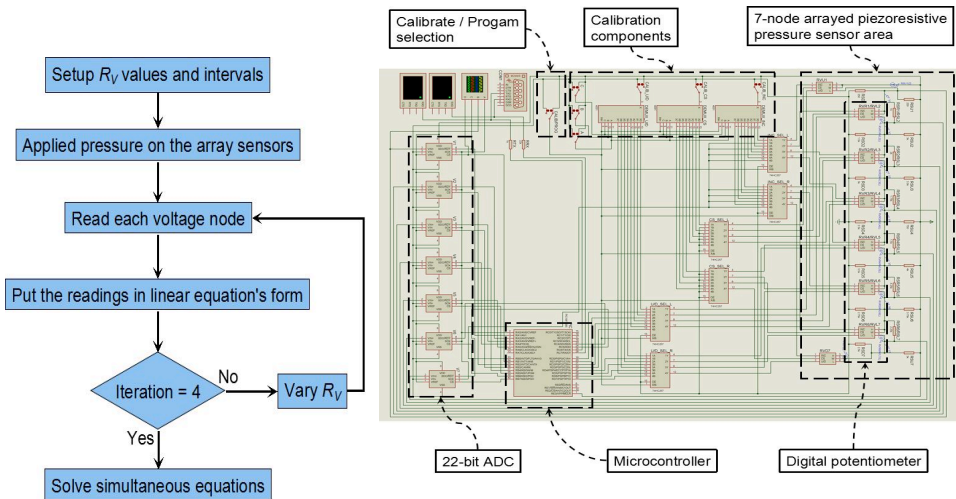


Figure 3. NAA's reading procedures

Figure 4. Schematic diagram of the readout circuit

NAA's limitation

In NAA, each nodal equation from any voltage node needs to have a unique set of variables and values. Several limitations need to be observed in order for NAA to produce the best accurate results and to avoid miscalculation. Three major limitations in NAA are:

- Reading resolution of 5 decimal point
- The uniqueness of each middle variable resistor's value
- The permutation of variable resistors values

The NAA needs to have at least 5 decimal points of resolution because the changes between voltage node value is very small between each iteration. Any attempt on rounding that value less than 5 decimal point might produce the same result with other voltage node which will disregard the unique requirement of NAA. As for the middle variable resistor's value a unique resistance value among each other for the same reason of uniqueness is needed. While iterating, all the variable resistor's value must only be swapped among themselves where there will be no other new value added to the network. This is called permutation.

RESULTS AND DISCUSSION

The readout circuit was successfully developed in Proteus ISIS software while the reading algorithm is implemented in Mathwork Matlab under Windows 10 platform. The overall circuit is also simulated using Proteus ISIS, where the virtual serial communication between readout circuit and computer is established by Virtual Serial Port Driver 6.9 from Eltima Software, while MicroCode Studio from Mecanique served as the PicBasic Pro language compiler tool. As this is only a simulation, all sensors are modelled as standard resistors with fixed resistance value according to the real sensor resistance value. These values are randomly

selected within the minimum and maximum range of piezoresistive pressure sensor resistance values. Voltage supply is 5V in order to supply all the electronic components in the readout circuit. Figure 4 shows the overall schematic of the readout circuit including the calibration circuit. Calibration is needed to set the initial value of each digital trimmer potentiometer as the variable resistors. This calibration process is only done one time as those potentiometers are non-volatile which means that they can lock their resistance at a certain value even after the circuit has been turned off or reset.

Table 1 shows the values obtained from seven voltage nodes where a comparison can be made between the analog values (taken before entering ADC) probed by Proteus ISIS and the final value (taken before entering NAA reading algorithm) retrieved from Mathwork Matlab output results. Through observation, it has shown that the voltage nodes have been successfully digitised by 22-bit ADC with an accuracy of at least 0.00001 from the analog readings. This means that NAA's 5 decimal point resolution requirement has been satisfied, resulting in a very closed sensor's resistive value when compared with the actual one shown in Table 2. Furthermore, the potentiometer's resistive value has been carefully configured in order to follow the uniqueness limitation. However, these potentiometers seem to fluctuate in values during each iteration which does not obey the permutation limitation, just like the example of RVU1 fluctuation values shown in Figure 5. Fortunately, these instabilities very small and only involve values which are beyond the decimal point. As for that, only the integer part of the resistance value is taken (for example $R_{VU1} = 3897 \Omega$) which has only a minor effect on NAA's calculation.

Table 1
Voltage node readings value's in analog and its decimal representations after the conversion

Voltage node	Numbers representation	Iteration 1	Iteration 2	Iteration 3	Iteration 4
V_1	Analog	2.53762	2.52901	2.51912	2.50405
	Decimal	2.537620067596436	2.529008388519287	2.519123554229736	2.504053115844727
V_2	Analog	2.26896	2.26735	2.26534	2.23859
	Decimal	2.268962860107422	2.267348766326904	2.265341281890869	2.238593101501465
V_3	Analog	2.65734	2.66549	2.66955	2.64832
	Decimal	2.657344341278076	2.665491104125977	2.669544219970703	2.648322582244873
V_4	Analog	3.30628	3.30426	3.29652	3.29729
	Decimal	3.306281566619873	3.304262161254883	3.296518325805664	3.297293186187744
V_5	Analog	2.77611	2.76664	2.75754	2.74667
	Decimal	2.776110172271729	2.766637802124023	2.757534980773926	2.746672630310059
V_6	Analog	2.25267	2.24998	2.22165	2.18574
	Decimal	2.252666950225830	2.249982357025147	2.221648693084717	2.185740470886231
V_7	Analog	2.05329	2.03709	1.99547	1.88618
	Decimal	2.053294181823731	2.037088871002197	1.995470523834229	1.886177062988281

Even though almost perfect results have been achieved using NAA, it seems to generate quite a sluggish results time. After careful observation, this low frequency execution process is detected from the 22-bit ADC. This ADC can only have the maximum sampling rate of 60

SPS (sample per second). Based on the availability of current products, all ADCs that are higher than 16-bit use delta-sigma method as their technique of conversion. Delta-sigma ADCs can generate very precise results with high resolution but their drawback is the conversion and data output time. The conversion method uses comparator to sense the voltage difference and then the integrator sums the comparator's output with the input signal (Patel, & Bhatt, 2012; Eshraghi, & Fiez, 2004; Geerts, Steyaert, & Sansen, 2000). This will decrease the sampling rate timing as the oversampling method requires several op-amps and D-type flip-flops as its main components. To fulfil this ADC's requirement, we need to put the command 'PAUSE' of 50 milliseconds for each rising and falling edge of output data clock in our microcontroller. This command is used for all 24-bits output transmission (2 bits for signed overflow indicator which is both '0' for our case) from all 7 ADCs which delays the total execution time by more than a minute as calculated in Equation (3). Unfortunately, this is the only option for

Table 2
Sensor's resistive value compared with the exact value

Sensor's name	Exact value (k Ω)	Value calculated by NAA's algorithm (k Ω)	Percentage of calculation error (%)
R_{SU1}	0.25	0.254790407361186	1.91616
R_{SU2}	3	2.994791273064735	0.17362
R_{SU3}	3.5	3.504383419775587	0.12524
R_{SU4}	0.75	0.749612615444893	0.05165
R_{SU5}	4	3.995045015993616	0.12387
R_{SU6}	3.75	3.749980595404416	0.00052
R_{SU7}	3	2.998251423540472	0.05829
R_{SD1}	0.25	0.256111857812884	2.44474
R_{SD2}	1.5	1.498102302701005	0.12651
R_{SD3}	3	2.997401225484398	0.08663
R_{SD4}	2.5	2.495719723305165	0.17121
R_{SD5}	3.5	3.492461853631187	0.21538
R_{SD6}	2.75	2.746869990611188	0.11382
R_{SD7}	2.5	2.495972627045837	0.16109
R_{SR1} or R_{SL2}	1	R_{SR1} 0.821954472256171	17.80456
		R_{SL2} 1.000864024519932	0.08640
R_{SR2} or R_{SL3}	2	R_{SR2} 2.004099649082407	0.20498
		R_{SL3} 2.000032807596361	0.00164
R_{SR3} or R_{SL4}	1.75	R_{SR3} 1.747678986385587	0.13263
		R_{SL4} 1.750175940401880	0.01005
R_{SR4} or R_{SL5}	1.5	R_{SR4} 1.498726796819304	0.08488
		R_{SL5} 1.500291017297411	0.01940
R_{SR5} or R_{SL6}	4.25	R_{SR5} 4.247567522578707	0.05723
		R_{SL6} 4.250415515986798	0.00978
R_{SR6} or R_{SL7}	2.25	R_{SR6} 2.249973356893091	0.00118
		R_{SL7} 2.252485410403882	0.11046



Figure 5. Fluctuation of R_{VU1} value in each iteration

22-bit ADC that is available in Proteus ISIS. Nevertheless, this issue needs to be solved in the future if NAA's is adopted as a full working prototype of a foot plantar measurement system. A recommendation for high speed delta-sigma ADC can be considered as a solution but which is currently available only as a hardware device.

$$50\text{ms} \times 24 \times 2 \times 7 \times 4 = 67.2 \text{ seconds} \quad (3)$$

(delay) (ADC (rising and (voltage (iterations) (total ADC's output falling edge nodes) delay) bit) of data output clock)

CONCLUSION

A 7-node sensory network of readout circuit to serve the NAA's reading architecture was developed by selecting suitable components in Proteus ISIS which are powerful enough for schematic drawing and simulation analysis. The NAA provides accurate results of sensor's resistive values when its requirements and limitations are satisfied. By only having resistive element as its components, NAA can improve the conventional readout circuit which has too many non-resistive elements resulting in higher circuit complexity. Furthermore, NAA's reading technique that requires only four iterations has a very high potential in higher speed output results. However, Proteus ISIS only provides low conversion and sample rate of 22-bit delta-sigma ADC which has downgraded the speed of NAA's reading technique and become unsuitable for a foot plantar measurement application that needs quicker results. Thus, a hardware readout circuit needs to be constructed in the future in order to have a variety of faster ADCs available in the market.

REFERENCES

- Almassri, A. M., Wan Hasan, W. Z., Ahmad, S. A., Ishak, A. J., Ghazali, A. M., Talib, D. N., & Wada, C. (2015). Pressure sensor: state of the art, design, and application for robotic hand. *Journal of Sensors*, 2015(2015), 1-12.

- Aziz, N. A., Fatimah, A. B., Aznida, F. A. A., Hamid, M. Z. A., Syanaz, M. H., Zuhra, H., & Mustafa, N. (2012). The Association of Various Risk Factors and Plantar Pressures in the Development of Peripheral Neuropathy amongst Diabetic Patients Attending Outpatient Clinics. *International Medical Journal*, 19(1), 1-1.
- Bacarin, T. A., Sacco, I. C., & Hennig, E. M. (2009). Plantar pressure distribution patterns during gait in diabetic neuropathy patients with a history of foot ulcers. *Clinics*, 64(2), 113-120.
- Boulton, A. J., Hardisty, C. A., Betts, R. P., Franks, C. I., Worth, R. C., Ward, J. D., & Duckworth, T. (1983). Dynamic foot pressure and other studies as diagnostic and management aids in diabetic neuropathy. *Diabetes Care*, 6(1), 26-33.
- D'Alessio, T. (1999). Measurement errors in the scanning of piezoresistive sensors arrays. *Sensors and Actuators A: Physical*, 72(1), 71-76.
- Duckworth, T., Boulton, A. J., Betts, R. P., Franks, C. I., & Ward, J. D. (1985). Plantar pressure measurements and the prevention of ulceration in the diabetic foot. *Bone and Joint Journal*, 67(1), 79-85.
- Eshraghi, A., & Fiez, T. S. (2004). A comparative analysis of parallel delta-sigma ADC architectures. *IEEE Transactions on Circuits and Systems I: Regular Papers*, 51(3), 450-458.
- Geerts, Y., Steyaert, M. S., & Sansen, W. (2000). A high-performance multibit $\Delta\Sigma$ CMOS ADC. *IEEE Journal of solid-state circuits*, 35(12), 1829-1840.
- Hussein, O., Hasan, W. W., & Jafaar, A. C. S. H. (2015, June). Investigation on Touch Area of Under Foot Pressure Based-on Weight Measurements. In *7th International Conference on Engineering and Technology ICET-2015*. Phuket, Thailand
- Liu, H., Zhang, Y. F., Liu, Y. W., & Jin, M. H. (2010). Measurement errors in the scanning of resistive sensor arrays. *Sensors and Actuators A: Physical*, 163(1), 198-204.
- Orlin, M. N., & McPoil, T. G. (2000). Plantar pressure assessment. *Physical Therapy*, 80(4), 399-409.
- Patel, J. V., & Bhatt, H. (2012, December). Performance evaluation of different types of analog to digital converter architecture. In *International Journal of Engineering Research and Technology* (Vol. 1, No. 10 (December-2012)). ESRSA Publications.
- Rashidi, F. R. M., Hussein, O., & Hasan, W. Z. W. (2015, August). Investigation on developing of a piezoresistive pressure sensor for foot plantar measurement system. In *Micro and Nanoelectronics (RSM), 2015 IEEE Regional Symposium on* (pp. 1-4). IEEE.
- Shu, L., Hua, T., Wang, Y., Li, Q., Feng, D. D., & Tao, X. (2010). In-shoe plantar pressure measurement and analysis system based on fabric pressure sensing array. *IEEE Transactions on information Technology in Biomedicine*, 14(3), 767-775.
- Shu, L., Tao, X., & Feng, D. D. (2015). A new approach for readout of resistive sensor arrays for wearable electronic applications. *IEEE Sensors Journal*, 15(1), 442-452.
- Stess, R. M., Jensen, S. R., & Mirmiran, R. (1997). The role of dynamic plantar pressures in diabetic foot ulcers. *Diabetes Care*, 20(5), 855-858.
- Urry, S. (1999). Plantar pressure-measurement sensors. *Measurement Science and Technology*, 10(1), R16.

- Veves, A., Murray, H. J., Young, M. J., & Boulton, A. J. M. (1992). The risk of foot ulceration in diabetic patients with high foot pressure: a prospective study. *Diabetologia*, *35*(7), 660-663.
- Young, M. J., Breddy, J. L., Veves, A., & Boulton, A. J. (1994). The prediction of diabetic neuropathic foot ulceration using vibration perception thresholds: a prospective study. *Diabetes Care*, *17*(6), 557-560.
- Zhang, J., Zhou, J., Balasundaram, P., & Mason, A. (2003, October). A highly programmable sensor network interface with multiple sensor readout circuits. In *Sensors, 2003. Proceedings of IEEE* (Vol. 2, pp. 748-752). IEEE.