Adaptive electric potential sensors for smart signal acquisition and processing

To cite this article: R J Prance et al 2007 J. Phys.: Conf. Ser. 76 012025

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Adaptive Electric Potential Sensors for smart signal acquisition and processing

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Abstract. Current applications of the Electric Potential Sensor operate in a strongly (capacitively) coupled limit, with the sensor physically close to or touching the source. This mode of operation screens the sensor effectively from the majority of external noise. To date however the full capability of these sensors operating in a remote mode has not been realised outside of a screened environment (Faraday cage). This paper describes the results of preliminary work in tailoring the response of the sensors to particular signals and so reject background noise, thereby enhancing both the dynamic range and signal to noise ratio significantly.

1. Introduction

The Electric Potential Sensor (EPS) technology developed at the University of Sussex under an RCUK Basic Technology programme has already demonstrated prodigious measurement capability in a wide spectrum of applications. The EPS approximates to an 'ideal' voltmeter and is capable of measuring spatial potential (electric field gradient) in a manner analogous to a magnetometer measuring a magnetic field. The sensors operate via weak capacitive coupling to the source provided by dry insulated electrodes which are recognized as offering significant measurement advantages\(^1\). The sensor approaches the ideal voltmeter using novel feedback and stabilisation techniques to enhance significantly the input impedance of electrometer amplifier circuits. The technology is truly wide ranging and is applicable to medical practice, engineering and the sciences. This spans body electrophysiology, non-destructive testing of metals\(^2\) and composites\(^3\), circuit imaging\(^4,5\), following the propagation of pulses in a saline environment\(^6\) and the acquisition of nuclear magnetic resonance (NMR) signals\(^7\) via electric field sensing, as opposed to the existing magnetic field detection method. In addition the sensors are suitable for integrating into array formats for real-time imaging applications without the inherent cross coupling problems which exist with magnetometers\(^8\). The non-destructive testing applications of EPS utilize a technique analogous to the well known eddy current testing method\(^9\), but will operate with materials exhibiting poor electrical conductivity. Techniques for imaging the electrical activity of circuits relying on a tunneling current\(^10\) suffer from the disadvantage that they require extremely small sample to probe spacing. By contrast the EPS is scalable, allowing data to be collected at any length scale dependent only on the image resolution required. Conventional NMR data acquisition systems are complicated by the cross coupling between the transmitter and receiver coils, with complex protection circuitry\(^11\) a requirement for satisfactory operation. Here the
use of the EPS reduces the direct coupling and obviates the need for special circuitry, considerably simplifying the apparatus.

In particular, we have demonstrated that high quality electrocardiogram\(^{12}\) (ECG), electroencephalogram\(^{13}\) and electrooculogram\(^{14}\) signals can be obtained with no resistive electrical contact to the body. This has enabled us to develop wearable, re-usable sensors suitable for long term patient monitoring. The ability to acquire a full range of high quality physiological signals via insulated surface electrodes creates the possibility of applying them to non-invasive human machine interfaces. The ability of the sensors to operate in a remote mode has been demonstrated by detecting the human ECG from a distance of one metre\(^{15}\). This is currently only possible with the use of extensive shielding (Faraday cage) due to the level of background noise present in the average urban environment. In order to utilize the full capability of EPS technology, such as remote mode sensing, it is necessary to address the signal to noise and dynamic range issues created by external noise sources. The work presented in this paper addresses this issue, with reference to the problems of saturation by external noise and the subsequent reduction in both the dynamic range and signal to noise of the sensor.

2. Adaptive Sensor

The EPS consists of an electrometer grade operational amplifier with an external bias circuit and associated feedback systems which have been described previously in the literature\(^{16}\). The net effect of this combination is to produce a broadband sensor (100 µHz to 1 GHz) sensor with extremely high (~10\(^{18}\) Ω) input impedance and low effective input capacitance (~10\(^{-15}\) F). As referred to in the introduction, this may be used to measure the spatial potential resulting from the electric field associated with a source, and has been demonstrated in a number of novel measurement situations. In all cases except the remote sensing of the ECG\(^{15}\), the sensors are capable of operating in an unshielded open laboratory environment. The proximity of the sensor to the source in these instances where the coupling capacitance is relatively large (1 pF to 1 nF), provides efficient screening from external sources of noise. However, for remote sensing applications where the sensor may be spatially separated from the source by relatively large distances (~1 m) this screening effect is absent. This means that either the sensor must be operated within a screened environment, as in the case of remote ECG detection\(^{15}\), or operate with reduced sensitivity in order to prevent external noise causing saturation. It is worth noting that conventional signal processing, whether analogue or digital, acting on the output of the sensor may improve the signal to noise ratio but cannot recover a signal from regions of saturation.

The work described here is aimed at preventing saturation occurring in the sensor by incorporating filter networks in the feedback loop of the sensor. Using this approach we are able to tailor the response of the sensor to match the frequency components of the signal. This has two immediate advantages over the traditional post processing approach. Firstly, all sources of noise which do not coincide with one of the selected Fourier components are excluded and therefore cannot cause saturation of the sensor. Secondly, the effective signal bandwidth is considerably reduced with a concomitant improvement in the signal to noise ratio. Figure 1 shows a typical schematic for a sensor capable of responding to a signal containing four distinct frequency components. In reality these would normally be harmonically related for periodic signals, thus simplifying the implementation considerably. In this way the bandstop (notch) functions are transformed into a set of bandpass functions in the response of the sensor.

It should be noted that the use of multiple high quality factor (Q) filters, as proposed here, also results in a large reduction in the sensor bandwidth required to acquire a signal with a large number of harmonics. Typically a signal consisting of a fundamental at 1 kHz and harmonics at 3, 5, 7, and 9 kHz would require say 10 kHz of bandwidth. However, it may be acquired using a set of filters (with a Q of 50) centred on these five frequencies with a total bandwidth of;

\[
20 + 60 + 100 + 140 + 180 = 500 \text{ Hz.}
\]
Block diagram showing an Electric Potential Sensor with four bandstop (notch) filters incorporated into the feedback loop.

Figure 1. Block diagram showing an Electric Potential Sensor with four bandstop (notch) filters incorporated into the feedback loop.

This reduction in the signal bandwidth from 9 kHz to 500 Hz corresponds to an improvement in the signal to noise ratio by a factor of:

\[ \sqrt{\frac{9000}{500}} = 4.24 \]

which may also be expressed as 12.5 dB, a significant factor. If the Q of the filters is increased further to say 100, then this improvement is even more marked, with the total bandwidth for the five filters reducing to 250 Hz. This corresponds to an improvement in the signal to noise ratio by a factor of six, or 15.6 dB. The techniques described may allow the Q to be raised to ~1000. This would correspond to a signal bandwidth of only 25 Hz, for the previous example, a signal to noise improvement by a factor of nineteen, or 26 dB. These calculations assume that the background noise is white, which is far from the usual case. As we have already discussed the primary concern is large amplitude noise signals which limit the effective dynamic range of the sensor by driving it into saturation. Attenuation of such signals of up to 60 dB should be achievable with this technique, resulting in an increased effective dynamic range of the same amount, provided that they do not coincide with a selected Fourier component.

In order to explore the possibilities offered by this approach we have constructed a series of notch filters using switched capacitor filter techniques. This allows the centre frequency of the filters to be set by choosing the clock frequency for each filter, and is particularly suitable where harmonically related frequencies are required. In addition, the Q of each filter may be adjusted by means of a digital potentiometer. These filters have been integrated into the feedback loop of a broadband EPS operating over the audio spectrum with an operational bandwidth of 1 Hz to 100 kHz.

3. Intelligent Control

The adaptive sensor described in the previous section is based on the EPS, but this approach may be applied to any electronic sensor where overall negative feedback may be added. The generation of the correct combination of clock and Q control signals for the filters rapidly becomes complex. If we consider the example used in the previous section this leads to five independent clock signals and five Q control signals. We have chosen to use a PIC microcontroller to control these functions which is in turn addressed via a USB interface which also handles the data acquisition from the sensor. The PIC generates the serial code required by the digital potentiometers and also addresses the frequency synthesizers used to generate the clock signals. A combination of four synthesizers and six binary dividers allows the fundamental and eight harmonics to be produced simultaneously.
With the centre frequency and Q of each filter under software control it is then a simple matter to program the sensor to respond to a chosen mix of harmonics. Once this has been done we may then scan in frequency, moving all of the harmonics in step and search for signals containing this particular mix of harmonics. This process will further enhance the discrimination between the wanted signal and spurious responses from interference signals.

4. Results
The two most important characteristics of the combined filter and sensor system are; the discrimination between the signal peaks and background; and the ability to achieve adjacent high Q bandpass peaks spaced at harmonic intervals. We present preliminary results for an EPS sensor with two switched capacitor notch filters incorporated into the feedback loop. Figure 2 shows a typical result for such a system. Clearly a multiple bandpass function has been successfully implemented with gain peaks seen at the two chosen frequencies (100 Hz and 400 Hz). In addition we note that for this example the measured discrimination is >50 dB. The centre frequency of each filter is independently adjustable over the range 1 Hz to 100 kHz, with the Q set to ~1000. This data was acquired with the sensor weakly capacitively coupled (~2 pF) to the tracking generator output of a signal analyser.

![Figure 2. Measured response for an EPS with two switched capacitor filters incorporated into the feedback loop.](image)

5. Conclusions
An adaptive sensor capable of responding to a particular mix of harmonics which is tunable over a large range of frequencies is described. This selectivity greatly enhances the effective dynamic range of the sensor and also impacts significantly on the signal to noise ratio. Preliminary results are presented for a simple implementation using two switched capacitor filters. The frequency and Q of the filters, and hence the sensor, are controlled by a PIC microcontroller which in turn is controlled via a USB interface. The system may be scanned in frequency to search for specific signals with specific combinations of harmonics. Ongoing work includes; extending the present system to eight filters which may be programmed with any of the first nine harmonics of a signal; and introducing search and optimisation routines implemented in LabView software to enable the system to act autonomously and acquire specific signals. In addition, we aim to begin trials of the system in an open unshielded environment.
Acknowledgements
The authors would like to thank the Research Councils UK for their generous sponsorship of this work under a Basic Technology Award.

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