**NCRC to improve linearity and sensitivity for RuO₂ urea biosensor sensing measurement**

Po-Yu Kuo and Ze-Lin Lian

A novel noise-cancelling readout circuit (NCRC) is proposed to improve the linearity and sensitivity of traditional voltage–time (V–T) measurement system for ruthenium dioxide (RuO₂) urea biosensor. To reduce the non-ideal effect related to traditional V–T measurement system that negatively threatened by the impact of power line noise, this NCRC adopts a new power line noise elimination scheme. Moreover, by employing the Twin-T notch filter and the Sallen–Key low-pass filter, the proposed NCRC can increase the linearity by 161% while retaining the sensitivity at an average level than V–T measurement system. A new NCRC for measuring the linearity and sensitivity of RuO₂ urea biosensor is implemented by a real circuit board. The experimental results show that the proposed NCRC can achieve 0.956 linearity and 1.22 mV/(mg/dl) average sensitivity.

**Introduction:** The urea biosensors are well-studied for the past decades. To improve the sensing characteristics, many device structures have been proposed [1–4]. Among them, the latest work was proposed by Chou et al. [4] and his research group fabricated arrayed flexible indium–gallium–zinc oxide/aluminium urea biosensor modified by graphene oxide. This reported urea biosensor has been designed to achieve better sensing characteristics and proved by their measurement results. However, these characteristics of the biosensors were measured using voltage–time (V–T) measurement system based on simple instrumentation amplifiers [4]. This V–T measurement system did not consider the noise generated by the power supply. Practically, the biosensor signal was generally operated under 1 kHz and easily affected by the power line frequency component (60 Hz). Generally, this non-ideal effect cannot be ignored. To analyse the performance impact of power supply noise for the urea biosensor, we applied ruthenium dioxide (RuO₂) thin film to fabricate the urea biosensor. RuO₂ thin film is proved as a stable during the measurement process due to its high electrical conductivity [5–7]. Thus, in this Letter, the RuO₂ thin films were selected as the sensing membranes for the urea biosensors.

In this Letter, the impact of power supply noise for RuO₂ urea biosensor is analysed. The response voltage measured by traditional V–T measurement system [4] is unstable due to the power line noise. Therefore, a novel noise-cancelling readout circuit (NCRC) is proposed to reduce this non-ideal effect. In the new NCRC, a Twin-T notch filter [8] is applied to eliminate the 60 Hz power line noise. Also, a Sallen–Key low-pass filter is used to suppress the signals located at the frequency spectrum that are higher than 1 kHz. The experimental results reveal that the linearity and average sensitivity of a flexible arrayed RuO₂ urea biosensor are improved by using the proposed NCRC. Moreover, the new NCRC is simple, and it is suitable to apply on different biosensors to reduce the non-ideal effect.

**Fabrication of the flexible arrayed RuO₂ urea biosensor:** The RuO₂ thin film is applied to design the flexible arrayed RuO₂ urea biosensor. For the quality assurance, the fabrication process of RuO₂ sensing membrane for this Letter is referenced to Chou’s previous work [4]. The schematic diagram of the completed fabrication processes is shown in Fig. 1a. Firstly, the polyethylene terephthalate (PET) substrate is cleaned by distilled water for 15 min and is cut to a dimension of 30 mm × 40 mm. Secondly, the silver paste is printed on a PET substrate using screen printing technology to form a silver wire (working electrode and reference electrode). Thirdly, we used an RF sputtering machine to sputter the RuO₂ film onto the silver wire/PET substrate. Finally, epoxy resin is used as an insulating layer, printed on a PET substrate, and baked in an oven for 90 min.

In this Letter, the differential reference electrodes are integrated with the flexible arrayed urea biosensor to form the 2 × 3 working electrodes, as shown in Fig. 1b.

**Design of the novel NCRC:** Conventionally, the characteristics of arrayed-type sensors can be measured by the V–T measurement system, as shown in Fig. 2 [7]. The V–T measurement system is composed of the instrumentation amplifier (LT1167), power source, data acquisition card, and a personal computer. In Fig. 2, the output voltage of instrumentation amplifier LT1167 can be expressed as the equation below:

\[
V_{\text{out}} = V_{\text{in}1} - V_{\text{in}2} = (V_{\text{sen}1} - V_{\text{ref}}) - (V_{\text{sen}2} - V_{\text{ref}})
\]

(1)

where the \(V_{\text{ref}}\) is the voltage of the reference electrode; \(V_{\text{sen}1}\) is the voltage of the contrast electrode; \(V_{\text{sen}2}\) is the voltage of the working electrode; \(V_{\text{in}1}\) is the voltage difference between contrast electrode and the reference electrode; and \(V_{\text{in}2}\) is the voltage difference between the working electrode and the reference electrode.

![Fig. 1 Fabrication processes of flexible arrayed RuO₂ urea biosensor](image)

(a) Schematic representation  
(b) Top view of finished biosensor

![Fig. 2 Schematic diagram of traditional V–T measurement system](image)

In the traditional V–T measurement system, the sensing signal is directly sensed by instrumentation amplifier without any noise isolation block. The noise is then coupled into a readout circuit and affects the responding voltage directly. The sensing signal is generally operated under 1 kHz and easily affected by the power line frequency component (60 Hz). In this Letter, a new NCRC is proposed to reduce the effect of power line noise, as shown in Fig. 3a.

![Fig. 3 Proposed novel NCRC](image)

(a) Block diagram  
(b) Circuit schematic representation

The operation of NCRC is as follows. Firstly, a Twin-T notch filter is added to eliminate the power line noise of the sensing signal. The 60 Hz noise generated by power line is suppressed by the notch filter. Besides, a Sallen–Key low-pass filter is added to filter out the signals located at the frequency spectrum that are higher than 1 kHz. The schematic representation of the proposed NCRC is shown in Fig. 3b. In this new NCRC, the Twin-T notch filter was applied to reduce the 60 Hz
power line noise. The notch filter includes two differential amplifiers A1 and A2, four resistors, and three capacitors. The cut-out frequency $f_c$ can be calculated as the equation below [9]:

$$f_c = \frac{1}{2\pi \sqrt{R_C C_1}}$$

From (2), the cut-out frequency can be set at 60 Hz by adjusting the values of resistor $R_1$ and capacitor $C_1$. Therefore, the noise located at 60 Hz, which is generated by the power line can be rejected through the Twin-T notch filter completely.

The sensing signal of urea biosensor is generally operated under 1 kHz. Thus, the frequencies that are higher than 1 kHz can be seen as noises and easily affect the stability of a real sensing signal. In the proposed new NCRC, a Sallen–Key low-pass filter is adopted to suppress the signals that are higher than 1 kHz. The Sallen–Key filter includes one differential amplifier A3, two resistors, and two capacitors. The cut-out frequency $f_c$ can be calculated as the equation below [10]:

$$f_c = \frac{1}{2\pi \sqrt{R_4 R_6 C_3}}$$

From (3), the cut-out frequency can be adjusted by changing the values of resistors $R_4, R_6$ and capacitors $C_3, C_4$. The proposed NCRC is implemented by using some discrete devices such as resistors, capacitors, and amplifiers. The prototype new NCRC is implemented with real circuit board, as shown in Fig. 4.

**Experimental results:** To verify the functions of the proposed NCRC, firstly, the characteristics of a flexible arrayed RuO$_2$ urea biosensor were measured by the traditional V–T measurement system as shown in Fig. 2. After that, the same RuO$_2$ urea biosensor was measured using the proposed NCRC. The RuO$_2$ urea biosensor was immersed in 10, 20, 30, 40, and 50 mg/dl urea concentration solutions, and then the output voltage was measured. Fig. 5 shows the measurement results of linearity and average sensitivity. The linearity and average sensitivity of the flexible arrayed urea biosensor that measured by the traditional V–T measurement system are 0.366 and 1.20 mV/(mg/dl), respectively. By applying the proposed new NCRC, the linearity and average sensitivity are 0.956 and 1.22 mV/(mg/dl), respectively. The performance summary is shown in Table 1. From the results, the proposed NCRC increases the linearity and average sensitivity by 161% and 1.67% compared with that of the traditional V–T measurement system.

**Fig. 4 Implementation of proposed readout circuit**

**Fig. 5 Curves of response voltage in different urea concentrations for flexible arrayed RuO$_2$ urea biosensor using V–T measurement system and proposed readout circuit**

**Conclusion:** In this Letter, the impact of characteristics for a RuO$_2$ urea biosensor affected by power line noise is analysed. The response voltage measured by traditional V–T measurement system is usually unstable due to the power line noise. To solve this issue, a new NCRC is demonstrated in this Letter. By applying the Twin-T notch filter, the power line frequency component at 60 Hz is suppressed. Also, a Sallen–Key low-pass filter is adopted to cancel the noises generated from high frequencies. The proposed new NCRC can increase the linearity by 161% while retaining the sensitivity at an average level than the traditional V–T measurement system. From the experimental results, the linearity and average sensitivity of this new NCRC are 0.956 and 1.22 mV/(mg/dl), respectively. On the basis of our experimental results, the research group suggests that a new potential application regarding integrating this novel readout circuit into different biosensors to reduce the non-ideal effect.

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One or more of the Figures in this Letter are available in colour online.

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**Table 1: Performance summary**

|                | This work (proposed circuit) | This work (V–T measurement system) |
|----------------|-----------------------------|-----------------------------------|
| Year           | 2019                        | 2019                              |
| Sensing membrane| RuO$_2$                    | RuO$_2$                          |
| Linearity      | 0.956                       | 0.366                            |
| Average sensitivity | 1.22 mV/(mg/dl) | 1.20 mV/(mg/dl)                  |

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