High-precision voltage-to-current converters based on single-chip gain-selectable amplifiers

Stefano Salvatori[1] · Maria Cristina Rossi[2] · Marco Girolami[3]

Abstract

A new application of single-chip gain-selectable amplifiers for Howland current pump circuits is here presented and discussed. LT199x integrated circuits, by Linear Technology, were used for the implementation of extremely accurate voltage-to-current conversion. Circuit performance was evaluated for resistive temperature-sensors biasing and signal conditioning. Experimental results highlight the excellent performance of the fabricated prototypes in terms of linearity and sensitivity. In addition, a ratiometric measurement method can be applied, ensuring virtual nulling of errors caused by the limited absolute accuracy of the voltage supply and/or the voltage reference used for the whole acquisition system.

1 Introduction

Howland current pump based on operational amplifiers [1] is a widely used circuit for the implementation of accurate voltage-to-current (V-to-I) converters, mostly used: (1) for circuit biasing and stabilization; (2) as a reference or linearizing system for sensor conditioning; (3) as a current source for setting a test condition, regulating a signal for actuation, or injecting a known current for material characterization in measurement systems [2–5].

Figure 1 shows the schematic of a simple V-to-I converter based on Howland current pump. The load sees the equivalent Norton circuit with an ideal current source $I_{L^-} = (V_2 - V_1)/R_1$, supposing that the well-known balanced bridge condition $R_4/R_3 = R_2/R_1$ is respected, in parallel to a resistor R_O the value of which is given by:

✉ Marco Girolami
  marco.girolami@ism.cnr.it

[1] Faculty of Engineering, Università Niccolò Cusano, Via Don Carlo Gnocchi, 3, 00166 Rome, Italy

[2] Department of Engineering, Università Roma Tre, Via Vito Volterra, 62, 00146 Rome, Italy

[3] CNR-ISM, Consiglio Nazionale delle Ricerche, Istituto di Struttura della Materia, Via Salaria km 29,300, 00015 Monterotondo Stazione, Rome, Italy

$$R_O = \frac{R_2}{R_2/R_1 - R_4/R_3} \tag{1}$$

which, indeed, tends to be ideally infinite if the balancing condition is met. The balanced bridge condition can be obtained by using highly-matched thin film resistors.

It's worth noting that the schematic illustrated in Fig. 1 reflects the topology of a classic *difference amplifier* where, however, both negative and positive feedbacks have to be implemented. In addition, unlike the difference amplifier, in Howland circuit the op-amp non-inverting input represents the output terminal for load connection. Nevertheless, solutions based on difference amplifiers require at least an external high-precision resistor [6] to set the desired V-to-I conversion factor.

In this work, we propose a new solution for Howland current pump-based current sources, exploiting single-chip (LT199x, Linear Technology) selectable-gain-amplifiers, which does not require any additional external component [7]. The designed circuit shows outstanding performance in terms of linearity, output resistance, and temperature dependence, due to the internal thin film resistors excellent matching ratio and the low temperature coefficient, enabling the implementation of high-precision current sources operating in the µA–mA range. In particular, the circuit is here proposed as a current supply and signal conditioning system for resistive temperature sensors, with
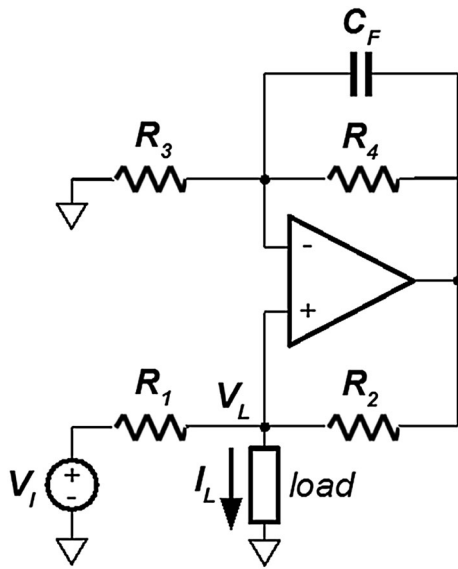
Fig. 1 Howland current pump scheme. $I_L = (V_2 - V_1)/R_1$ if $R_2/R_1 = R_4/R_3$

the possibility of applying a ratiometric method for the implementation of highly accurate resistance measurement stages.

2 Selectable-gain amplifier-based solutions for Howland current pump

As for any other difference amplifier, pins of selectable-gain amplifiers LT199x enable positive feedback, due to the availability of the reference terminal. But, unlike traditional difference amplifiers ICs, current can be sourced with LT199x chips through the available additional internal resistors connected to the op-amp non-inverting input, so that no external component is required for V-to-I conversion.
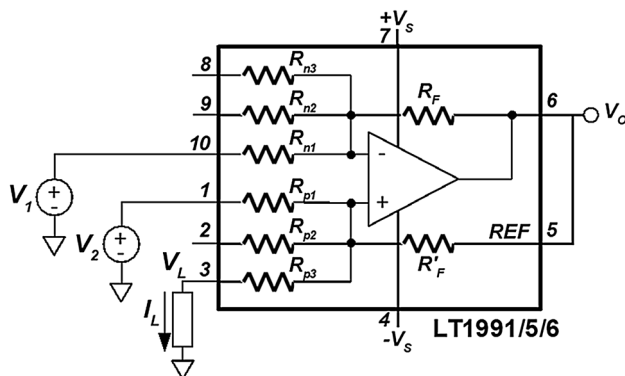

Fig. 2 Connections example for a Howland circuit based on gain-selectable single-chip amplifiers LT1991/5/6

Figure 2 shows the scheme of the proposed circuit using LT1991/5/6 gain-selectable amplifiers. The V-to-I conversion factor can be expressed as:

$$\frac{1}{R_{CONV}} = \frac{I_L}{V_2 - V_1} = \frac{1}{R_{p1}} \left(= \frac{1}{R_{n1}} \right) \tag{2}$$

As can be seen, different conversion factors can be obtained by parallel connections between the resistances R_{px} and R_{nx} used as inputs, whereas parallel connections between the feedback resistors R_F and R_F' allow the system output dynamics to be extended (before op-amp saturation occurs). Also, note that a voltage drop $|\Delta V_L| = I_L R_{p3}$ on the maximum allowable load voltage is introduced by the presence of the R_{p3} resistor in series to the load itself, limiting the V_L voltage compliance; this limitation was not present in the scheme of Fig. 1, which allows for a wider voltage compliance.

Figure 3 reports the measured output current signal I_L as a function of the input voltage difference $V_2 - V_1$, for different values of the conversion factor $1/R_{CONV}$, for LT11991/5/6 based Howland circuits. Note that a very good linearity is obtained in the investigated input voltage range. Non-linearity is indeed lower than $\pm 0.02\%$, approaching $\pm 0.01\%$ for LT1991 and LT1995 ICs, as expected for the resistors high matching ratio declared for the LT199x chips [8]. As expected, the maximum input control voltage amplitude (before op-amp saturation) decreases with decreasing values of R_{CONV}. Moreover, for data shown in Fig. 3, the resistor used for load connection towards the op-amp non-inverting input was the lowest allowed by the chip type (50 kΩ, 1 kΩ, and 5.56 kΩ for LT1991, LT1995, and LT1996, respectively [8]); higher resistance values would have indeed limited the maximum
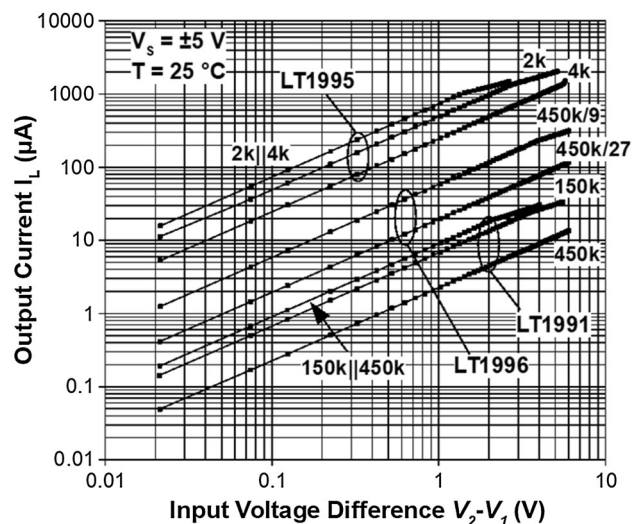

Fig. 3 Output current as a function of the input voltage difference for the circuit of Fig. 2 based on LT1991, LT1995, and LT1996 chips for different values of the conversion factor $1/R_{CONV}$

output current before op-amp saturation. It's worth mentioning here that, in the LT1996 case, the unused resistors were connected in parallel to the feedback ones (R_F and R_F') to avoid op-amp saturation at very low load voltages.

3 Resistive sensor biasing and conditioning

The circuit of Fig. 2 was implemented for Resistive Temperature Devices (RTD) biasing and conditioning. A preliminary characterization was performed to evaluate its feasibility as a precision transducer for a resistive sensor connected as load, by using a fixed reference voltage V_{REF} = 4.096 V obtained by means of a REF3040 followed by an OPA350 acting as a buffer. For this purpose, an LT1995 based circuit, with $R_{CONV} = R_F$ = 4 kΩ, was assembled ($I_L \approx$ 1 mA). A wide range of load resistance values (10^{-2}–10^3 Ω) was used for the test measurements; for obtaining values as low as tens of mΩ, a 0.8 m long, 0.6 mm diameter copper wire was used to obtain five different resistance values, by shifting each time the position of the second terminal to 0.2, 0.4, 0.6, 0.7, and 0.8 m (corresponding to the full length of the wire). Figure 4 shows the measured output voltage change with respect to the output value acquired at a zero load resistance R_L = 0 Ω. It is worth noting the very good linearity obtained over 5-decades of R_L values.

A Pt100 sensor was then connected as load and inserted in a thermostatic bath to regulate the device temperature up to T = 350 °C. A first characterization was performed in the 24–155 °C range. The measured linear temperature slope was $\Delta V_o / \Delta T$ = 0.764 mV/ °C, very close to the nominal one (0.770 mV/ °C) calculated by considering the

Fig. 4 Output voltage change versus load resistance for a Howland current pump based on LT1995 gain-selectable amplifier

temperature coefficient of a Pt100 (0.00385 Ω/Ω/ °C). The evaluated maximum relative error was ± 0.4 °C, mostly attributed to the Pt100 sensor non-linearity. Indeed, best fit of data returned a second order polynomial curve, with a linear coefficient 3.9062×10^{-3} °C^{-1} and a quadratic coefficient $- 6.4141 \times 10^{-7}$ °C^{-2}, in good agreement with those reported in the literature for platinum resistance sensors [9].

The major drawback of the solution depicted in Fig. 2 for RTD biasing and conditioning is the voltage drop $|\Delta V_L| = I_L \, R_{p3}$ at the resistor in series to the load itself, which limits the sensor output dynamics. A Pt100 resistor can indeed span a resistance value from 18.5 Ω (T = − 200 °C) to 390.5 Ω (T = 850 °C), corresponding in our case to an output voltage range V_o = 2.04–2.79 V. To enhance the sensitivity of the overall system, a second prototype was implemented (Fig. 5): note that, in order to reduce the voltage drop across the load, R_{p3} was connected in parallel to R_{p1}, decreasing the overall value from R_{p3} = 1 kΩ to $R_{p3}//R_{p1}$ = 800 Ω. Moreover, the source current was doubled by using R_{CONV} = 2 kΩ, and the LT1995 op-amp inverting-configuration gain was set to 3, increasing the nominal circuit sensitivity to 2.3 mV/ °C. Finally, a LT1991-based second stage was added to limit the maximum output voltage, and a single-pole RC filter was inserted to suppress any high-frequency noise contribution. By considering the full Pt100 temperature range (− 200–850 °C), the output voltage of the circuit of Fig. 5 is V_o = 3.28–1.05 V (output voltage vs. temperature curve has indeed a negative slope), thus exploiting more than 50% of the full-scale range of an A/D converter referenced to the same V_{REF} = 4.096 V voltage.

Figure 6 reports the output voltage V_o of the circuit of Fig. 5 measured as a function of the Pt100 temperature in the extended range 24–350 °C. First of all, note the excellent linearity obtained. A slight non-linearity, due again to the sensor characteristics, was observed only for $T > 300$ °C, underlining the necessity to consider also the quadratic term of the sensor response at high temperatures. However, the maximum relative error, estimated to be in this case as low as ± 0.06%, highlights the possibility to resolve 1 °C in the whole investigated temperature range.

To better highlight the benefits of the proposed solution, which adopts a so-called "ratiometric" measurement method [10], let us consider a n-bit A/D converter, referenced to the same V_{REF} = 4.096 V voltage. If perfectly matched resistors are considered for the LT1995 and LT1991 ICs of the circuit of Fig. 5, the output code related to the R_L value can be simply expressed by:

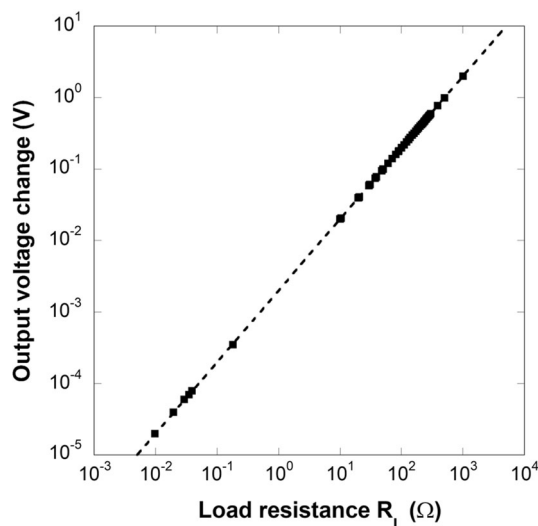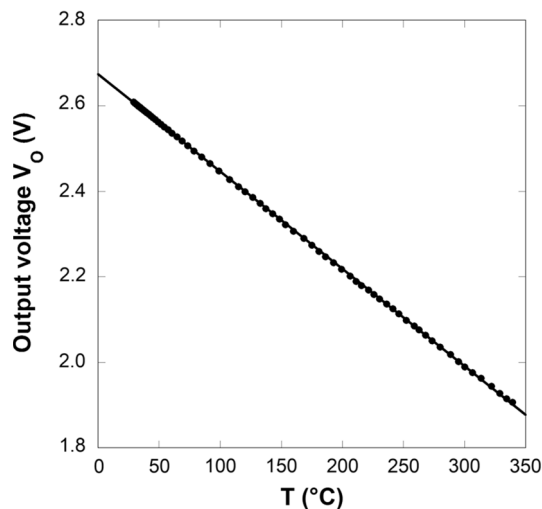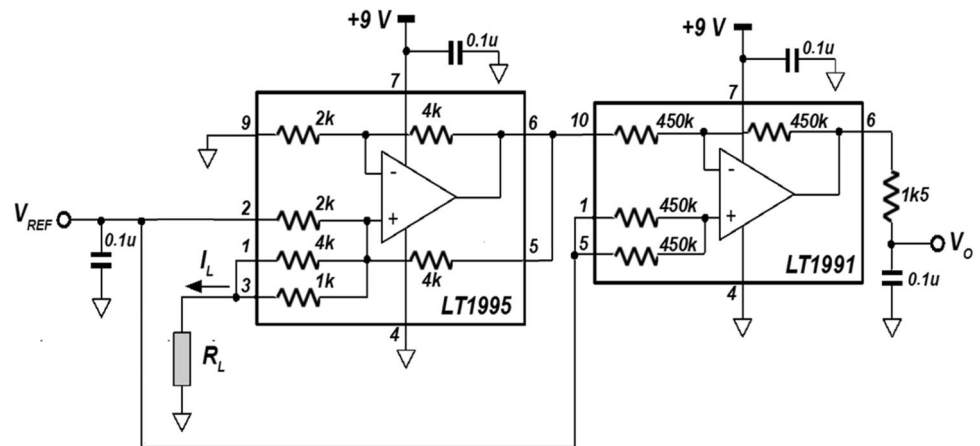$$N = \frac{2^{n+2}}{5} - 3 \times 2^{2n} \frac{R_L}{R_{CONV}}, \tag{3}$$

Fig. 5 Schematic of the prototype implemented to enhance the sensitivity of the system

Fig. 6 Output voltage of the circuit of Fig. 5 in the 24 ÷ 350 °C temperature range for a Pt100 sensor connected as load

excellent performance in the 0.01–1000 Ω range in terms of sensitivity and accuracy. Dedicated prototypes were also designed and implemented for biasing and conditioning of platinum resistor-based temperature sensors, demonstrating their suitability to act as extremely compact and high-precision current sources.

so that the system accuracy is equal, as expected for a ratiometric method, to that of the R_{CONV} factor. In this way, errors caused by a limited absolute accuracy of the voltage reference (and then of the load excitation current), as well as those induced by the excitation drift, are virtually eliminated. Moreover, any noise superimposed to the excitation source is added to reference terminal of the A/D converter, improving significantly the signal-to-noise ratio.

4 Conclusions

A new application of commercially available single-chip selectable-gain amplifiers as low-power Howland current pump circuits, was introduced and discussed. The tested circuits, based on LT1991, LT1995, and LT1996 ICs, were able to generate current signals in the 0.1–10 μA, 1–100 μA, and 10–1000 μA range, respectively, exhibiting a V-to-I non-linearity lower than ± 0.01%, as well as an

References

1. Sheingold, D. H. (1964). Impedance and admittance transformations using operational amplifiers. *Lightning Empiricist, 12*(1), 1–8.
2. Harrison, L. T. (2005). *Current sources & voltage references* (Vol. 11). New York: Newnes, Elsevier.
3. Pelcia, M.M., dos Reis Filho, C.A. (2002). Fully integrated programmable Howland current source for sensors excitation. In *Proceeding of 4th IEEE international caracas conference on devices, circuits and systems* (pp. C028–CI-4) https://doi.org/10.1109/iccdcs.2002.1004016.
4. Poletto, C. J., & Van Doren, C. L. (1999). A high voltage, constant current stimulator for electrocutaneous stimulation through small electrodes. *IEEE Transactions on Biomedical Engineering, 46*(8), 929–936. https://doi.org/10.1109/10.775402.
5. Murnane, M. (2008). *Current sources: Options and circuits*, AN-968, Analog Devices, Inc. Retrieved Jan 21, 2019 from https://www.analog.com/media/en/technical-documentation/application-notes/an-968.pdf.
6. Zhao, N., Malik, R., & Liao, W. (2009). Difference amplifier forms heart of precision current sources. *Analog Dialogue, 43*(3), 22–24.
7. Salvatori, S. (2015). Gain-selectable IC yields voltage-to-current converter. *EDN Europe, 7,* 30–32.
8. LT1991, LT1995, and LT1996. *Gain selectable amplifiers*. Milpitas: Linear Technology. Retrieved Jan 21, 2019 from https://www.analog.com/media/en/technical-documentation/data-sheets/1991fh.pdf, https://www.analog.com/media/en/technical-documentation/data-sheets/1995fb.pdf, https://www.analog.com/media/en/technical-documentation/data-sheets/1996f.pdf.
9. Hagart-Alexander, C. (2010). Chapter 21—Temperature measurement. In W. Boyes (Ed.), *Instrumentation reference book* (4th ed., pp. 287–288). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-7506-8308-1.00021-8.

10. Deval, Y., Ducouret, S. G., & Dom, J. P. (1993). Ratiometric temperature stable current reference. *Electronics Letters, 29*(14), 1284–1285. https://doi.org/10.1049/el:19930857.

Stefano Salvatori (M'00) received the Ph.D. in Electronic Engineering from Università degli Studi Roma Tre, Rome, Italy. He is Associate Professor of Electronics with the Faculty of Engineering at the Università degli Studi "Niccolò Cusano", Rome, Italy. His research activity is mainly focused on diamond-based sensors for UV, X-ray, and particle detection, including processing and characterization of thin-film opto-electronic devices. He is primarily involved in the development of low-noise single- and multi-channel front-end electronics for low-level signal sensors.

Maria Cristina Rossi was born in Rome, Italy, in 1962. She received the Ph.D. in Electronic Engineering from Università degli Studi Roma "La Sapienza" in 1993. In 1994 she became a Research Associate at Università degli Studi Roma Tre, Rome, then becoming Associate Professor in 2006, at the same university. Her research interests include but are not limited to transport properties in nanostructured semiconductors and related electronic devices.

Marco Girolami received the Ph.D. in Electronic Engineering from Università degli Studi Roma Tre, Rome, Italy, in 2011. Since 2012, he has been a researcher with Consiglio Nazionale delle Ricerche, Istituto di Struttura della Materia, Rome, Italy. His research interests include low-noise current-input electronics for diamond-based ionizing radiation detectors, solar energy conversion modules based on thermionic emission, and laser-induced microstructuring of semiconductors for applications in energy and photonics.