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Assessment of a low-cost angle-meter based on resistance measurements

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***Abstract* – In this work, an accurate, low-cost electronic angle-meter is designed, manufactured and metrologically characterized. The idea at the basis of the proposed electronic goniometer is to transduce the mechanical rotation into the variation of an electrical quantity, namely a resistance. Then, such a variation can be easily measured through a low-cost multimeter used as an ohmmeter.**
The metrological characterization of the prototype demonstrated that the proposed system can achieve an uncertainty as low as 1° with costs of an order of magnitude lower than devices currently available on the market.
In practical applications, this device can be used for the metrological characterization of heading instrumentation thanks to an isolated rotating plate on which several devices can be placed.
***Keyword* - Low-cost instrumentation, electronic goniometer, metrological characterization, heading.**

I. INTRODUCTION

Angle measurements are required in many applications, such as inertial and measurements unit calibration [1], diffractometer measurements [2], posturology medical studies [3, 4], etc. Several rotation measurements systems are currently available on the market.
A broad classification includes two types of devices: *electrogoniometers* and *rotation stages*. The former are especially used in two fields, namely the study of human posturology [5] and small angles detecting systems (e.g., the pitch of naval models in tanks). One of the downsides of electrogoniometers is that, in spite of their accuracy, they are not designed to withstand external loads.
As for the rotation stages, they are mostly used in the optical field for the alignment of optical systems (e.g., laser beams or lenses in laser applications). Generally, rotation stages are mechanical systems, able to carry heavy objects [6, 7, 8].

The problem with these commercial devices is related to their high cost [9]; in particular, rotation stages are considerably expensive. On the other hand, less-expensive solutions limit the weight of the object that must rotate with the structure. In the literature, several works have addressed the characterization of such devices; however, none of them has considered the costs that are typically associated with this type of instrumentation.

Starting from these considerations, in this work, a low-cost angle-meter based on resistance measurements is presented. The idea at the basis of the proposed electronic goniometer is to transduce the mechanical rotation into the variation of an electrical quantity, namely a resistance variation. The proposed system was practically implemented and characterized metrologically. As detailed in the following, the obtained results demonstrate that the proposed system allows to achieve accuracy specifications comparable to those of similar products on the market, but with much lower costs (tens of euros against hundreds of euros).

The present work is organized as follows. In Section II, the design of the proposed prototype is described in detail. The section also addresses the fabrication of the angle meter and the methods for calibration and use. Section III reports the results of the metrological characterization of the device. Finally, in Section IV, conclusions are drawn.

II. MATERIALS AND METHODS

A. *Design of the angle meter*

The proposed system consists of two major components: the mechanical and the electrical one. The mechanical part includes the rotation plate and the stopper mechanism. The electrical parts include the linear rotative precision potentiometer. The conceptual architecture of the system is shown in Fig. 1. A screw rigidly blocks the plate on the potentiometer shaft and a mechanical support rigidly houses the potentiometer. The weight of the object mounted on the plate is unloaded on the mechanical support. In this way, the plate can rotate freely and along with the potentiometer shaft. The aim of the mechanical stopper is to fix the rotative plate into a known position and angle.

An angle plate rotation corresponds exactly to a θ potentiometer rotation (1:1 coupling ratio). Using an inverse calibration method, the measured resistance depends linearly

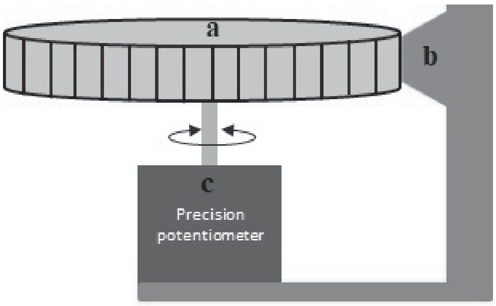

Fig. 1. The low-cost heading-meter principle schematization. The rotative plate (a), the rotation mechanic stopper (b), and the precision potentiometer (c).

(a) Plate

(b) Cylinder

Fig. 2. Mechanical manufacturing of cylinder and plate

on rotation. Hence, the mechanical rotation is directly related to the resistance variation. These variations can be measured through commercial, low-cost multimeters used as ohmmeter.

B. *Manufacturing of the cylinder and plate*

A plate and a hollow cylinder were made of Teflon (to ensure light weight) with a lathe machining before and a milling cutter after. Fig. 2a and Fig. 2b show the manufacturing of plate and of the cylinder, respectively. Cuts with a 5° steps were made on the plate (Fig. 2a); the cuts serve the purpose of blocking the plate into a fixed known position. If necessary (for example, for mounting a heavy object), Teflon can be replaced with a more resistant material.

The center of the plate was keyed to the shaft of the linear rotative potentiometer, by three small steel screws. The potentiometer was housed in the teflon cylinder and fixed in it. This allows to make the system mechanically stable and to limit the effect of possible angular torsions.
In the assembly, particular care was taken to verify that the shaft center coincided with the center of the plate. The plate joint with the potentiometer shaft could rotate by an angle at user's will. In this way, only the plate (and therefore the potentiometer's shaft) could rotate by an estimated angle during the measurements.

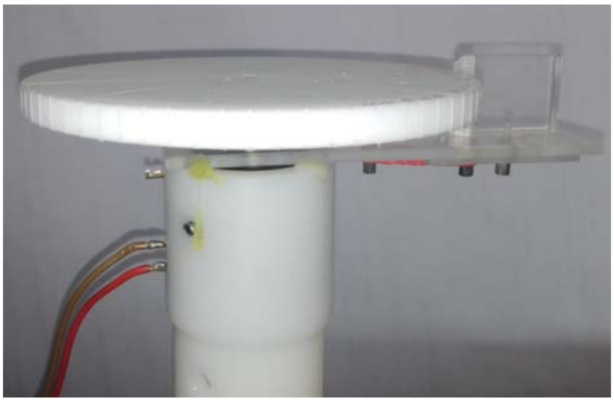

Fig. 3. Picture of the fabricated electronic goniometer prototype. The plate can be rotated clockwise and anticlockwise. Arbitrary heading angle can be chosen for the measurements.

Fig. 3 shows a picture of the prototype. The potentiometer is a ten-turn linear precision potentiometer of $2\ \text{k}\Omega \pm 5\ \%$ resistance, and with a $0.23\ \%$ linearity (Bourns 3590S-2-202L [10]). The cost is approximately 10 euros.

C. *Methods*

To calibrate the angle meter, a two-step, inverse calibration procedure was carried out.

The first step of the procedure consists in the initial calibration and is used to evaluate the two coefficients (offset α and gain β) of the linear model, as shown in Fig. 4. This first step involves a complete rotation of the plate between 0° and 360°.

This rotation corresponds to the change in resistance of the potentiometer in a range [min, max] Ω which is measured through the ohmmeter. By exploiting the linearity of the potentiometer, the coefficients that relate the resistance variation to the angle variation are obtained. This procedure can be carried out just once, and it must be repeated only if the plate or potentiometer are replaced.

In the second step, the inverse calibration model is exploited. For any (unknown) angle rotation, the corresponding resistance is measured and used to evaluate the angle rotation, as shown in Fig. 5.

In practice, once the object is positioned on the plate,

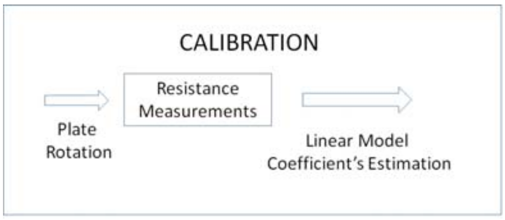

Fig. 4. First step of the inverse calibration.

Fig. 5. Second step of the inverse calibration.

the desired rotation is performed. Through the coefficients calculated in the first step of the procedure, the measured resistance value can be used to infer the angle measurement.

III. EXPERIMENTAL RESULTS

The first step of the experimental characterization was the evaluation of the coefficients of the inverse calibration model.
In the developed prototype, the mechanical angle measurements system was characterized using an automatic test equipment based on the multimeter Agilent 34401A used as ohmmeter. Fig. 6 shows a picture of the Automatic Test Equipment used for the measurements. A LabView® software was developed to control the ohmmeter via IEEE 488 interface. For each 5° step-rotation of the plate, 32 resistance measurements were carried out.

The χ^2 test for gaussianity verification was applied. The gaussianity test resulted positive for all measured points. Fig. 7 shows the results for the [-30,+30]° range.
Starting from these measurements, a type A evaluation of uncertainty was carried out. Additionally, using the accuracy specifications provided by the ohmmeter's manufacturer [11], a type B evaluation was carried out. Expanded combined uncertainty with a coverage factor $k = 2$ [12] was chosen and the procedure was repeated 72 times to resolve the entire circumference. Successively, the mean, the standard deviation, and the variance were used to check the linearity of the estimated model thanks to the Fisher-Snedecor test, which was positive.

The β and α coefficients thus evaluated are used to obtain the measurement of any rotation angle from a single resistance measurement.

Fig. 6. Picture of the measurement station.

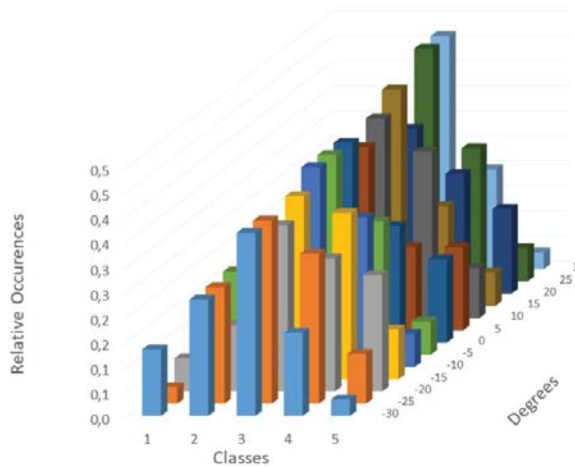

Fig. 7. Relative Occurrence Histogram in the [-30,+30]° range

The positioning error on the plate circumference is $\delta_p = (1.0 \pm 0.1)$ [mm]. The positioning error and its uncertainty affect the plate angle error and the uncertainty of system. The angle error depends on the diameter of the plate (d) and positioning uncertainty. The value of d, measured by means of a caliper, is (162.5 ± 0.1) [mm]. The angular error can be easily evaluated through the following equation:

$$\epsilon_{angle} = 2 \arcsin\left(\frac{\delta_p}{d}\right) \quad (1)$$

Applying the law of propagations of uncertainty in indirect measurements (worst case approach), the angle error is $\epsilon_{angle} = (0.70 \pm 0.06)$ [°], with a 5° resolution. As aforementioned, the evaluated gain (β) and offset (α) coefficients, were used to obtain the measurement of any rotation angle from a single resistance measurement. Using the linear regression model the measured angle can be obtained from the resistance measurements through the following equation:

$$\phi = \frac{R - \alpha}{\beta} \quad (2)$$

where ϕ is the angle's estimation;α is the offset; β the gain; and R is the measured resistance.

The resistance values (corresponding to angle values) were first measured through a benchtop multimeter (HP 34401A) and the calibration curve was obtained.
To verify the robustness of the proposed system, the measurement procedure was carried out also through two inexpensive, commercial multimeters: the VC9205N and the DT830D.

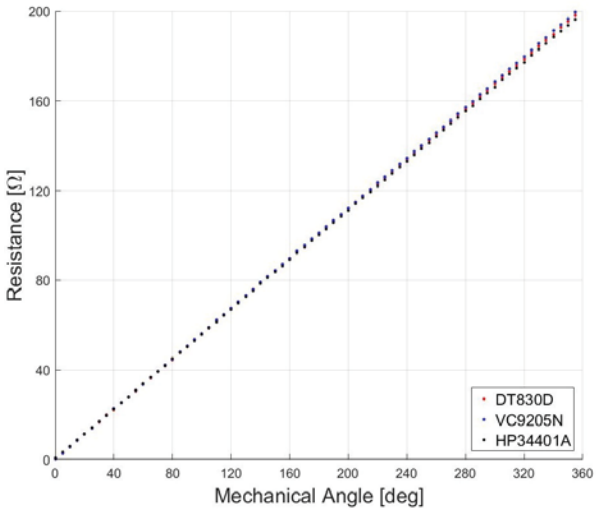

Fig. 8. Comparison of the linearity obtained using low-cost multimeters (DT830D and VC9205N) and a benchtop HP34401A multimeter.

Fig. 8 shows the results of the measurements of resistance obtained through the three multimeters with their uncertainty intervals. It can be seen that the results from the multimeters are compatible.
In Fig. 9, the measurements of angle, with their uncertainty, are reported. The evaluation of uncertainty for the commercial tester DT830D and VC9205N is based on the resolution of the multimeters (0.1 Ω) for this full-scale range.

As shown in Table 1, the uncertainty depends more on the position of plate's cursor, rather than on the measurements of resistance made through the low-cost multimeters. It depends on the metrological characteristics of the low-cost linear potentiometer used.

To asses the behavior of the prototype in presence of loads positioned on the plate, two weights in steel and brass for a total of (0.66 ± 0.01) [kg] were added, as shown in Fig. 10.

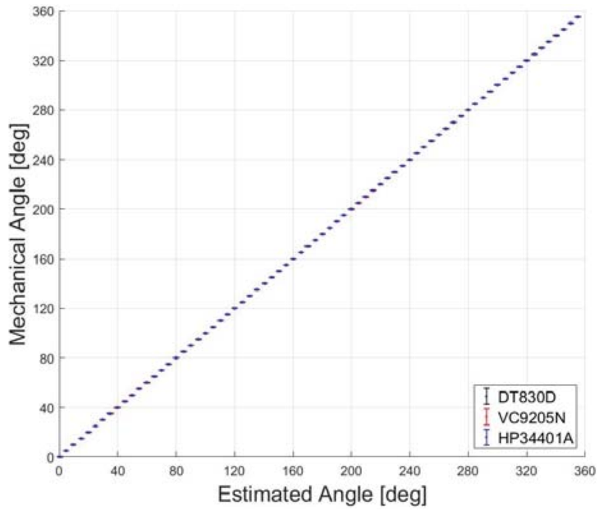

Fig. 9. Angle measurements comparison.

Table 1. Values of α and β coefficient and of the angle uncertainty for the three considered multimeters

	DT830D	VC9205N	HP34401A
α = offset [Ω]	0.648	0.268	0.125
β = gain $\left[\frac{\Omega}{degrees}\right]$	0.552	0.557	0.561
Uncertainty [deg]	0.2	0.2	0.001

When adding the weight, it is important to pay close attention to the positioning of the load on the plate's center, to avoid misalignments and bends of the shaft. This effect called in literature, "swash effect" (as described in [13]) occurs when the plate is mounted concentrically with the potentiometer shaft, but has its geometric axis inclined with respect to the axis of rotation (see Fig. 11).

Fig. 10. The device with a weight of 0.66 kg.

This effect imparts a once per-revolution sinusoidal axial motion to the periphery of the shaft potentiometer causing an error in the nominal linearity of the potentiometer.

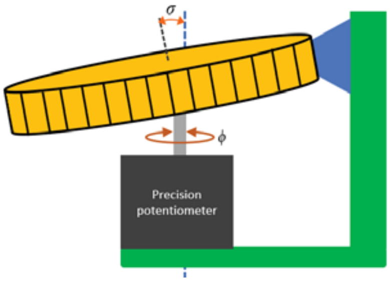

Fig. 11. Swash effect.

This error can be considered negligible if the rotation is limited within a single turn angle.

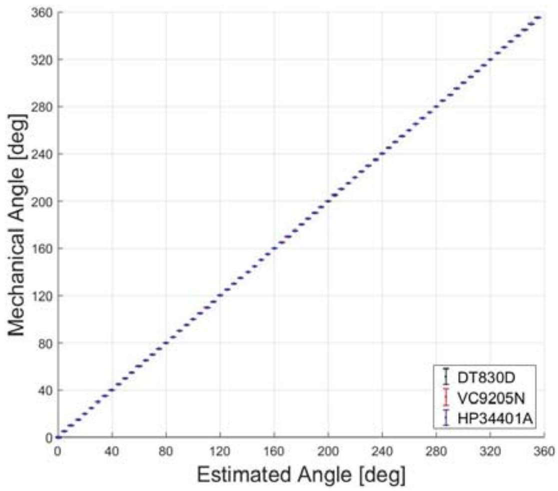

Fig. 12. Angle measurements comparison with a weight of 0.66 kg.

To demonstrate this, a new measurement campaign was carried out, this time placing a load of 0.66 kg on the plate and the results are shown in Fig.12

To verify that the behavior of the instruments was similar, the Bland-Altman test were performed, using the HP34401A as a "gold reference" as shown in Figures 13 and 14.

IV. CONCLUSIONS

A low-cost device for measuring angles was designed, manufactured and metrologically characterized. The device is based on transducing the mechanical rotation into a variation of electrical resistance. The resistance values (corresponding to different angle values) were first measured through a benchtop multimeter and the calibration curve was obtained. To verify the robustness of the proposed system, resistance measurements were carried out also through two inexpensive multimeters. The results obtained, thanks also to comparative tests (such as the Bland-Altman test) show that the proposed device guarantees an

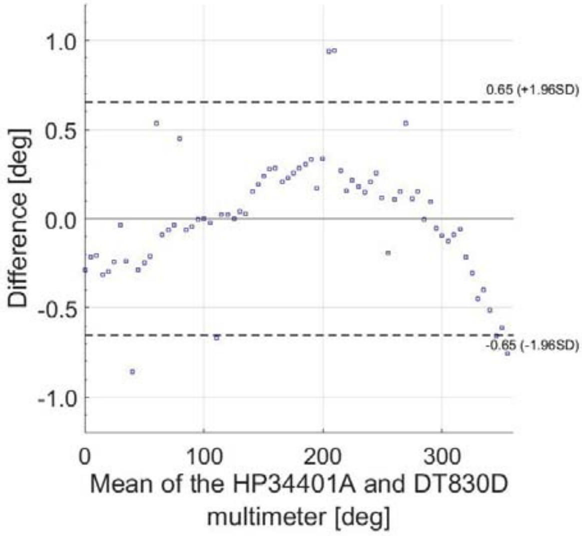

Fig. 13. DT830D-HP34401A Bland Altman test.

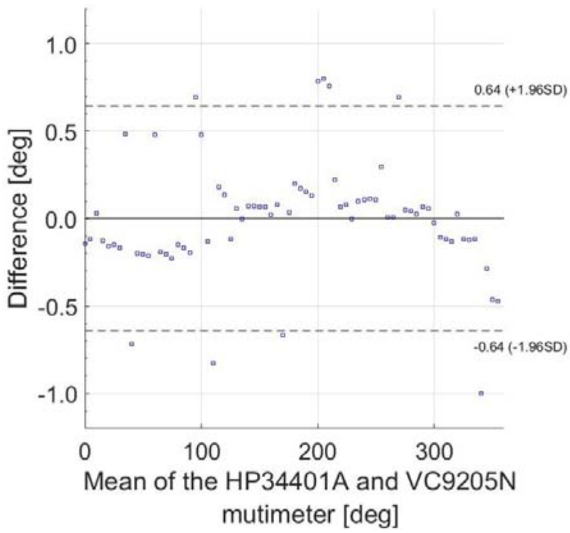

Fig. 14. VC9205N-HP34401A Bland Altman test.

accuracy performance comparable with other, more-costly commercial devices.

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