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An open-source and low-cost data acquisition system for surface water monitoring: analysis of measurement uncertainty

Um sistema de aquisição de dados de código aberto e baixo custo para monitoramento de águas superficiais: análise da incerteza de medição

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Abstract

Agricultural activities are strongly dependent on the availability of water resources, despite this, little is known about local water availability. This is due to the high acquisition cost and difficult sensors handling. This article aims to assess low-cost equipment (sensor and datalogger) capable of monitoring the water level in dams and rivers based on the Arduino platform. For this purpose, the following were used: Ultrasonic sensors HC-SR04 and DHT11 for humidity and temperature. The data was stored on a micro SD card integrated into the Arduino nano. The total cost was $17.98 (dollars). The equipment was calibrated from 0.1 to 4.0 m in length and considering surface inclinations of 0, 5, 10 and 15° in relation to the horizontal. The results show that there was a tendency to underestimate the data in relation to the distribution of errors and an acceptable error of less than 0.04 m can still be considered for all slopes and distances evaluated. The ultrasonic sensor must be installed perpendicular to the target surface, as using a single calibration for various inclinations results in overestimated measurements. The equipment proved to be viable and low-cost for monitoring water levels in dams and rivers.

Keywords: *arduino; datalogger; ultrasonic sensor.*

Resumo

As atividades agropecuárias são fortemente dependentes da disponibilidade dos recursos hídricos, apesar disso, pouco se sabe sobre a disponibilidade hídrica local. Isso ocorre devido ao alto custo de aquisição e difícil manuseio de sensores. O presente artigo objetiva avaliar um equipamento de baixo custo (sensor e datalogger) capaz de monitorar o nível de água em açudes e rios baseado na plataforma arduino. Para isso foram empregados os sensores: ultrassônico HC-SR04 e DHT11 de umidade e temperatura. Os dados foram armazenados em um micro SD card integrado ao Arduino nano. O custo total foi de U$ 17,98 (dólares). A calibração do equipamento foi realizada de 0,1 a 4,0 m de comprimento e considerando inclinações de superfície de 0, 5, 10 e 15° em relação a horizontal. Os resultados mostram que houve uma tendência à subestimativa dos dados em relação a distribuição dos erros e ainda pode-se considerar um erro admissível menor que 0,04 m para todas as inclinações e distâncias avaliadas. O sensor ultrassônico deve ser instalado perpendicular à superfície alvo, pois o emprego de uma única calibração para diversas inclinações resulta em medições superestimadas. O equipamento mostrou-se viável e de baixo custo para o monitoramento do nível da água em açudes e rios.

Palavras chave: arduíno; sistema de registro de dados; sensor ultrasônico.

INTRODUCTION

Brazil has continental dimensions and is made up of 12 major hydrographic regions from which 61.46 trillion liters are retained each year. Irrigation consumes 53.7% of this volume, urban human consumption 22.6%, industry 8.8%, animal consumption around 7.6%

and thermoelectric plants, mining and rural human consumption together around 7.3% (ANA, 2022).

The National Water Resources Policy, Law No. 9.433 of 1997, establishes the granting of water use as an instrument of this policy in the country and states that the consumption of water resources must guarantee multiple use. In this way, the monitoring of river flows and the volume of water in reservoirs must be carried out by the licensee or public body. This legislation also establishes the Water Resources Information System (SIRH) to provide data on the flow and storage of water in the main watercourses. However, the fluviometric network (total of 2024 river flow observation points) and the water monitoring stations in reservoirs (total of 713) are insufficient for most farmers who need to monitor water availability throughout the hydrological cycles, whether for irrigation or animal watering.

In this context, continuous environmental monitoring of water resources can take place by measuring the water level in river channel. The product of the cross-sectional area of the flow and the average speed of the watercourse is a good estimate of the flow (Gunjalli et al., 2018). Similarly, in lakes and reservoirs, it is possible to estimate the stored volume by the height of the water table at a point, knowing the topography of the reservoir.

Time-of-Flight (ToF) sensors coupled to dataloggers have been widely used to monitor the water depth (Azevedo et al., 2023; Bello et al., 2018; Hanan et al., 2019; Komarizadehasl et al., 2022). ToF's consider the travel time that a given signal takes to reach a target and return to the source of emission. Knowing the transit speed and time, it is possible to estimate the distance from the sensor to the water table and the difference in the height of the water table or the water level of a natural reservoir.

Despite being simple, this instrumental arrangement has a high cost for both monitoring and acquiring sensors, making its use unfeasible for small and medium-sized farmers. The cost of purchasing a datalogger and a high-resolution ToF sensor varies depending on the model chosen. For example, Melo et al. (2021), before March 2021, recorded an average price for a CR1000 datalogger of 1,354.32 USD (eBays offers). On the same website, an SR50 ultrasonic sensor compatible with the aforementioned datalogger can be found for 199.71 USD (average offer, shipping not included). Therefore, a set for continuous environmental monitoring of water resources capable of storing information is more than

1,554.03 USD. In this context, it should be noted that this estimate is for used equipment and does not take into account the costs associated with the software.

In this context, Ismailov et al. (2022) and Cressey (2017) point out that the Arduino microcomputer has been widely disseminated due to its low cost, easy acquisition, easy learning and because it is easily programmed (Puig et al., 2022), Furthermore, it’s programming can be produced with assistance of artificial intelligence. Kaswan et al. (2020), reinforce that the large community active on forums and social media make it possible to idealize any project at a very low cost.

Not only in society, but also in the scientific community, Arduino has been cited more and more every year. Komarizadehasl et al. (2022) and Cressey (2017), evaluating citations on the Scopus database, note that the growth in citations associated with Arduino and similar platforms has received special attention from researchers from all over the world and from various areas of science. However, the main disadvantage of these platforms when associated with low-cost sensors is the lack of precise information on the estimation error of the quantities monitored. This can make it impossible to use them for scientific or even professional applications.

The aim of this article is to evaluate a low-cost electronic data acquisition and storage system based on the Arduino board coupled with the HC-SR04 ultrasonic distance sensor for environmental monitoring of the height of water levels in canals, rivers, artificial reservoirs, lakes and reservoirs.

MATERIAL AND METHODS

Ultrasonic sensor HC SR04: working principle

The HC-SR04TMT sensor is widely found on digital sales websites and inexpensive to purchase (Abreu et al., 2021; Komarizadehasl et al., 2022). It measures distance by estimating the time it takes sound pulses on the ultrasonic scale (> 20 kHz) to travel the distance from the emitter to a receiver.

This is possible knowing that the speed of sound propagation in air is approximately 340 m.s^{-1}. Knowing the time taken and the speed of propagation, it is possible to estimate the distance traveled by the pulse (equation 1).

$$d_E = \frac{V_s \times T}{2} \quad [1]$$

Where dE is the estimated distance (meters), VS is the speed of sound (m. s^{-1}) and T is the time taken between the emission and reception of the sound signal (seconds). "T" is also known as "TOF" time-of-flight. Equation 1 shows an overestimate of the distance due to the spacing between the Trigger (transmitter) and the Echo (receiver), namely 2.6 cm (d_{TE}). Using basic trigonometry (Abreu et al., 2021; Buachoom et al., 2019), equation 1 can be rectified in order to obtain the corrected estimated distance, Equation 2.

$$d_{E_C} = \sqrt{(d_E)^2 - \left(\frac{d_{TE}}{2}\right)^2} \quad [2]$$

Ultrasonic pulses are not influenced by the color or brightness of environments or target surfaces. However, they are influenced by humidity and air temperature. Various models have been used to correct for this influence. Aliew (2022), for example, considered the effect of humidity to be negligible in the context of distance measurements in an industrial environment. It should be noted that for environmental and agricultural applications of ultrasonic sensors, both effects must be considered. Equation 3 expresses the speed of sound considering the influence of temperature and humidity (Hoodmod & Al-Chalabi, 2017; Komorizadehasl et al., 2022):

$$V_S = 331.4 + (0.606 \times T_E) + (0.0124 \times H) \quad [3]$$

Where Vs is the speed of sound (m.s-1), TE is the ambient temperature in ºC and H is the relative humidity in percent. Therefore, substituting equations 1 and 3 into equation 2 gives the corrected estimated distance, equation 4:

$$d_{E_C} = \sqrt{\left(\frac{331.4 + (0.606 \times T_E) + (0.0124 \times H) \times T}{2}\right)^2 - \left(\frac{d_{TE}}{2}\right)^2} \quad [4]$$

Air temperature and humidity were measured by the DHT11 portable sensor for purpose of correct the distance estimated by the HC SR04 sensor. The main technical characteristics of the HC-SR04 sensor are shown in Table 1.

Table 1 - Technical characteristics of the ultrasonic sensor models HC SR04.

Technical characteristics	**Sensor**	
	HC-SR04	DHT11
Power supply DC	3.3-5 V	3.3-5 V
Current sulply	15 mA	0.5 – 2.5 mA
Working frequency	40 kHz	-
Range (Min – Max)	2 – 400 cm	RH 20-90 %; T 0-50°C
Angle of measure	0-15 degrees	-
Trigger signal TTL pulse	10 µS TTLa	-
Usual application	Roboticsb	Environmental monitoring

Transistor-transistor logica; Komarizadehasl et al., 2022b

The HC SR04 sensor was coupled to the Arduino nano, which is an open-source electronic signal processing and analysis platform (C++ language) that allows the creation of various projects that permeate different areas of knowledge. In order to store the data, a MicroSD Card Adapter was also incorporated into the Arduino, which allows data to be communicated with and stored on external media (figure 1A). The pulses were emitted for 10 µS (trigger) and interspersed with an echo reception time of 4 µS, as shown in the diagram in Figure 1B:

Equation 4 was used to estimate the distance between the sensor and a solid surface in a laboratory environment under different contact distances and angles. The total of components costs are presented in Table 2.

The ease of acquiring sensors and electronic equipment via websites, the large community using the Arduino board (video tutorials and free manuals) allow projects for environmental monitoring to be disseminated quickly.

Figure 1 - A) Schematic diagram showing the connections between the HC-SR04 ultrasonic sensor, Arduino Nano, and MicroSD card adapter; B) Diagrams illustrating: the temporal behavior of sound pulse emission and reception by the HC-SR04 sensor (top); and the ultrasonic wave propagation for estimating the estimated distance (d_E), corrected estimated distance (d_{EC}), and actual distance (d_R) (bottom).

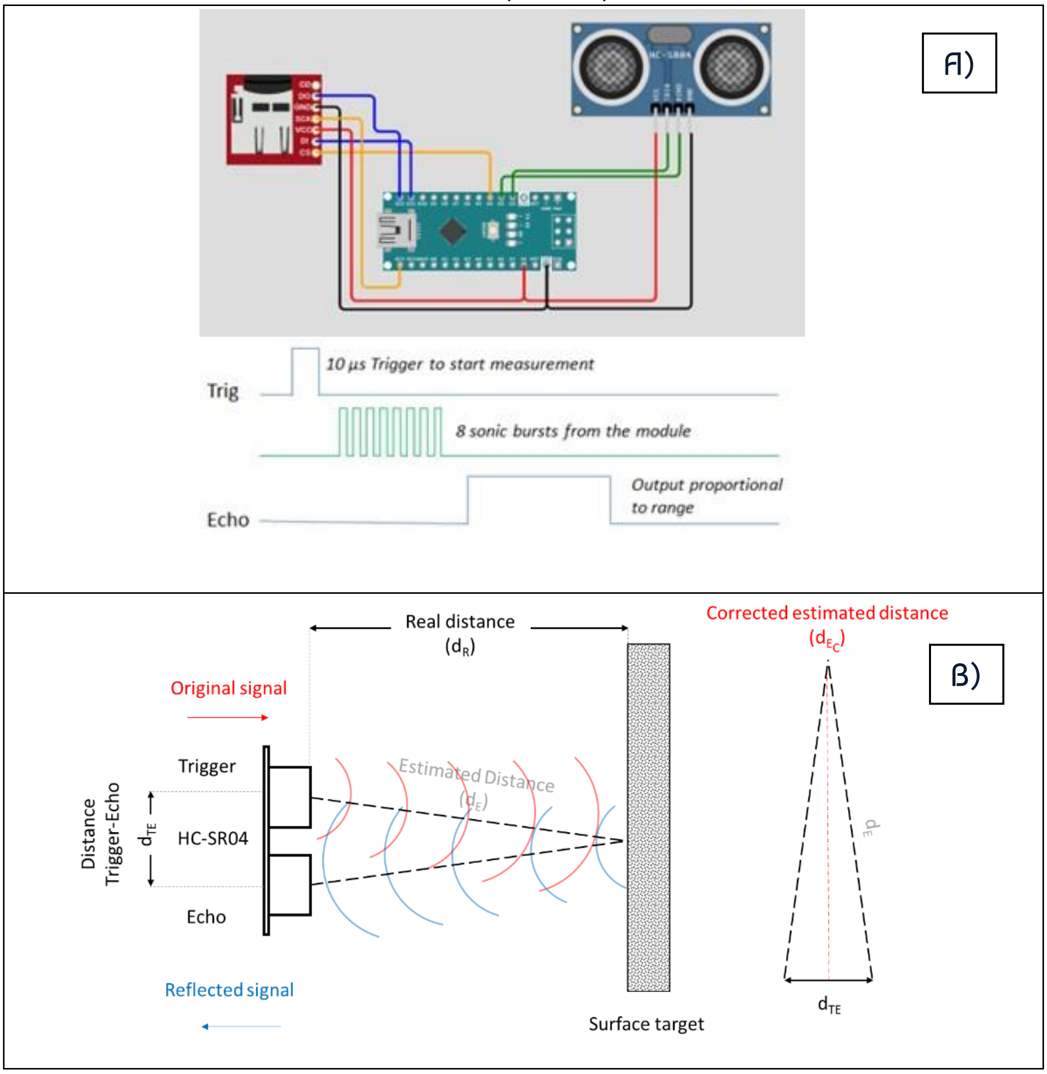

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Table 2 - List of equipment's items and values.

Item	Unit	Cost (USS)
Arduino Nano (ATM ON BORD)	1	8.30
HC-SR04 (TMTTM)	1	3.15
MicroSD Card Adapter	1	1.42
DHT11	1	3.11
Cables and onboard supporta	-	2.00
	Total	17.98

[a]Estimated values of connections, solders, boards, storage box commonly used in electronics projects.

Experimental setup

The experiment was conducted in a laboratory with the rigid surface of the wall as the target surface. The sensor was positioned horizontally 1.5 meters from the ground. The vertical distance from the bench to the laboratory ceiling was 2 meters. The angular variation was caused by the inclination of the sensor with the horizontal plane.

The actual horizontal distance (dREAL) considered to be the reference distance was measured using a 4 m rigid tape measure with a resolution of 1x10-5 m (Vuolo, 1996). Distance measurements were taken at the following intervals: 0.10, 0.20, 0,50, 1.00, 1.50, 2.00, 2.50, 3.00, 3.50 and 4.00 cm of horizontal distance. 30 readings were taken to estimate the distance corrected by the sensor at 10-second intervals. The reading procedure was carried out at different sensor inclinations in relation to the target surface: 0, 5, 10 and 15 cranes of inclination. The sensor was kept at a height of 100 cm from the horizontal and at 200 cm from the sensor to the laboratory ceiling.

A calibration equation of the type Y=A.X was considered to adjust the measured and estimated values for the sensor inclination at 0 degrees. Parameter A is an angular correction between the linear correlation of the estimated and measured values. This adjustment was considered for all other inclinations since the HC SR04 is used for measurements from 0 to 15 degrees. Considering this correlation, the estimation error was obtained from equation 5.

$$Error = d_{REAL} - \frac{d_{E_C}}{A} \quad [5]$$

Where the error is the distance in m. It is positive when there are underestimates and negative when there are overestimates of the real distance. The regression was carried out using the Levenberg-Marquardt proposition and the coefficient of determination was obtained using STATISTIC 7.0 software.

The error values were tested for adherence to the Gaussian distribution using the Kolmogorov-Smirnov test. The mean value of the error associated with the slopes and the corresponding sample standard deviation were obtained. The error values were tested in groups considering the slope as the divisor between groups. Median box plots were used to better visualize the errors per actual distance measured.

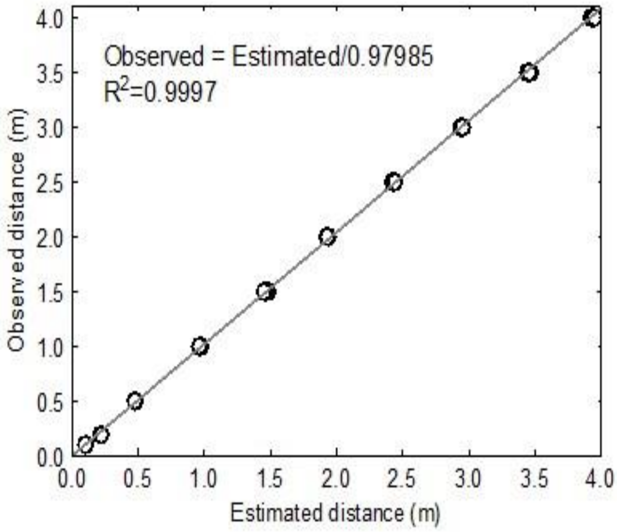
The value corresponding to twice the sample standard deviation was taken as the confidence interval for the uncertainties. This represented 95.45% of sampling errors.

RESULTS AND DISCUSSION

Figure 2 shows the linear fit between the measured and estimated distance values using the Levenberg-Marquardt regression method. The coefficient of determination close to 1 indicates a high fit between the measured and estimated data. The angular coefficient indicates that on average the ultrasonic sensor underestimates the measurements by around 2%. Similar coefficient of determination results for calibrating ultrasonic distance sensors are presented by Sudarmato et al. (2023) who used linear regression (non-affine line) for distance estimates considering inclinations of 0 to 18 degrees with the surface.

Notably, the aforementioned adjustment does not provide an in-depth study of the error and its distribution over the course of the measurements. The lack of a more in-depth approach to the study of instrumental error can hinder the monitoring of physical quantities. In this context, Abreu et al. (2021) highlighted the importance of studying error in depth when they observed variations of 10% around the mean due to temperature variations using the HC SR04 sensor.

Figure 2 Linear calibration regression for adjusting the distance measurements estimated by the HB-SR04 ultrasonic sensor with a 0 degree inclination to the horizontal.

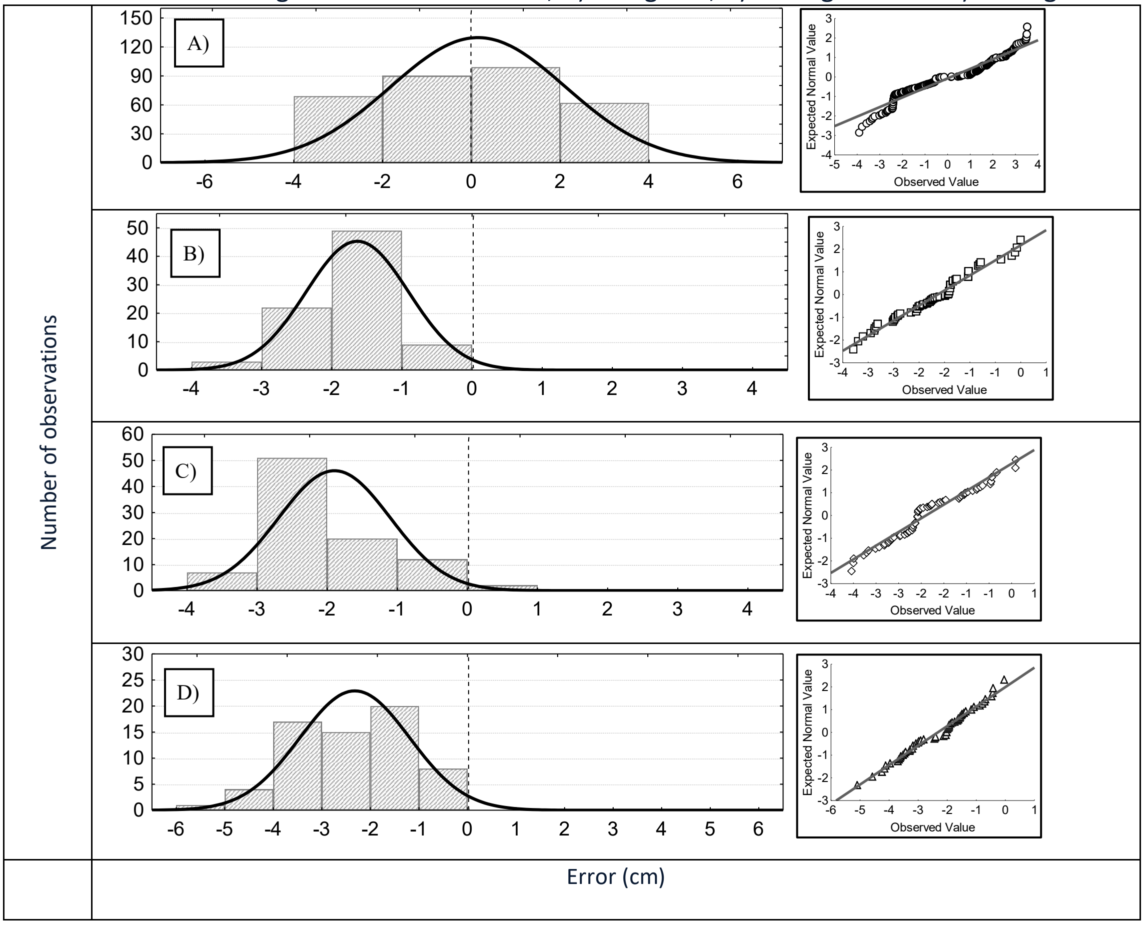


According to error theory (Vuolo, 1996), an experimental physical quantity is determined by a measurement and the result is always an approximation of the true value of the quantity. The Laplace-Gauss distribution, also known as the normal distribution, is widely used to quantify the uncertainties associated with instrumental measurements. Considering that the linear fit is valid for the inclinations applied in this study, Figure 3 shows the Kolmogorov-Smirnov adherence test for the fits of the Laplace-Gauss distribution to the error values of the distance measurements.

The adherence tests showed that all the error values were well adjusted to the normal distribution, with "d" values greater than 0.05 in all cases, namely: 0.12676, 0.11648, 0.19193, 0.15098, respectively, for 0, 5, 10 and 15 degrees of inclination from horizontal. The instrumental error associated with the sensor's positioning error (inclination) did not cause a tendency to underestimate or overestimate the average error. In other words, the errors were consistently close to an average value.

Abreu et al. (2021) observed the same behavior of the errors associated with distance measurements using the HC SR04. However, in a more in-depth analysis, these authors observed that the most appropriate adherence distribution was the bicaldal distribution, which indicates two modal values for a distance of 1.00 m. On the other hand, Komarizadehasl et al. (2022), evaluating the same sensor from 0.29 to 1.17 cm, observed not only that the average error was close to zero, but also that it fitted well with the Gauss distribution.

Figure 3. Adherence of the error data to the normal distribution: A) Error values obtained with the sensor at 0 degrees to the horizontal; B) 5 degrees; C) 10 degrees and D) 15 degrees.



Another interesting aspect is that the average value of the errors differed for the inclinations of the ultrasonic pulses with the contact surface (see Table 3).

This is a clear indication that the linear adjustment used for the slope at 0 degrees to the horizontal is not appropriate for different slopes, since, despite good adherence to the normal distribution, the average error values for the other slopes are significantly offset from zero. A plausible solution to mitigate this error is to perform a linear adjustment of the type y=ax+c for each slope. This would correct the average error to values closer to zero. Certainly because of this, Sudarmanto et al. (2023) studying the performance of the HC SR04 ultrasonic sensor in detecting slopes in buildings used a non-affine straight-line model, obtaining an excellent fit (R^2=0.9992). Similarly, Hoodmod & Al-Chalabi, 2017, recorded an error due to overestimation as the contact angle increased from 0 to 20 degrees with the surface, which reinforces the need for an additional methodology for using the sensor on slopes greater than 0 degrees.

Table 3. Average error and sample standard deviation of distance measurements in relation to the different installation inclinations of the HCSR-04 ultrasonic sensor.

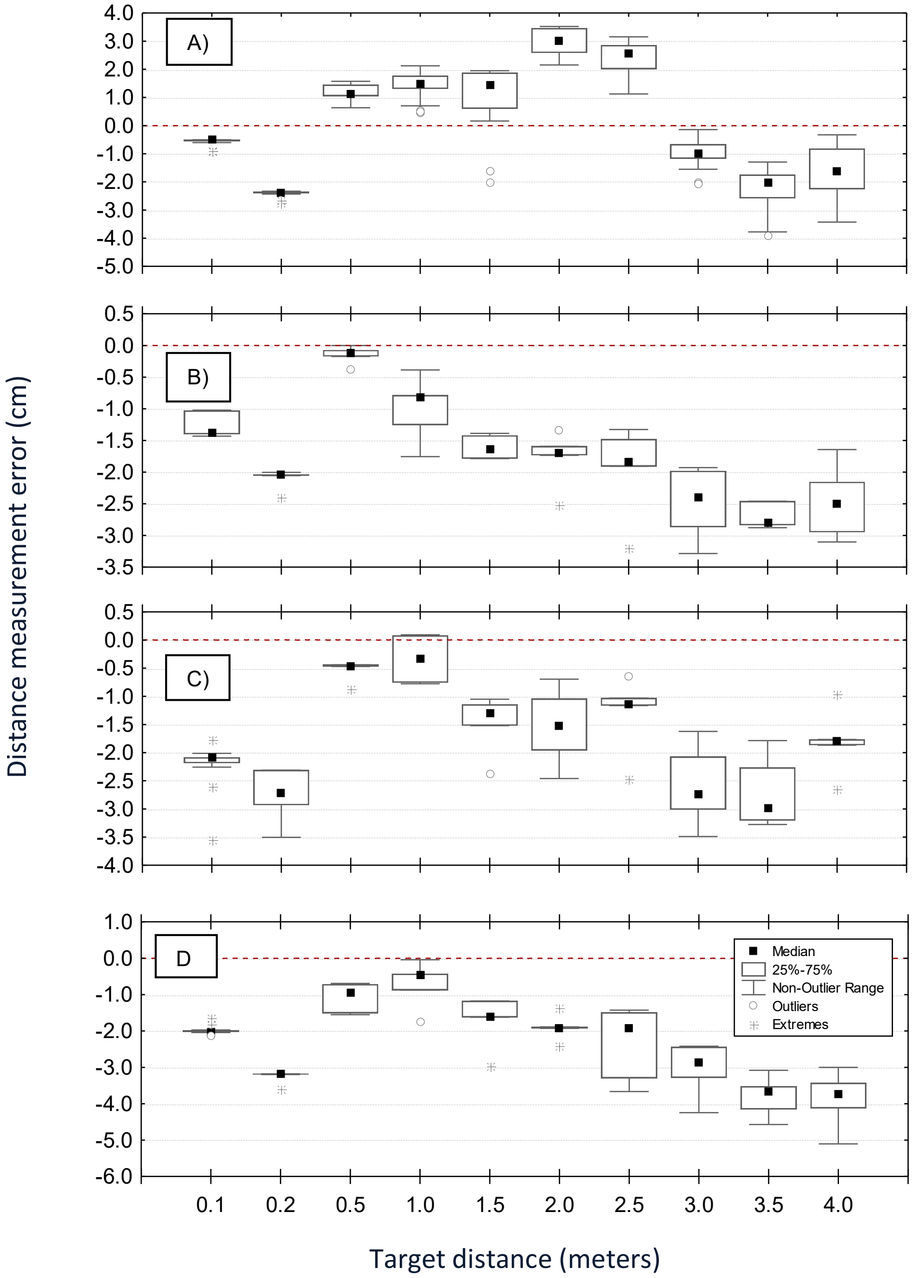
Inclination	Error (cm)	
	Sample Average	Sample standard deviation
0º	0.1478	1.9698
5º	-1.6360	0.7312
10º	-1.8962	0.7970
15º	-2.3216	1.1318

The data dispersion, represented by blocks of median box-plots, also shows a peculiar pattern for distance estimates when considering the dispersion of errors over the measured distances, Figure 4. in relation to the median, there is a slight (up to 0.04 m) tendency for the sensor to overestimate distance, even after preliminary calibration. This can be seen between 0 and 0.20 m and between 3 and 4 m. However, between 0.5 and 3 m there is a tendency to underestimate distances.

The HC-SR04 sensor manual, which is widely published on the internet and highlighted by Scianna et al. (2022), states that the resolution can reach 0.3 cm, but the document implies that this resolution is associated with the operating range of 2 to 400 cm. Aliew (2022) obtained an average error of 0.1 cm when measuring distances of around 25 cm.

Komarizadehasl et al. (2022), used 25 HC SR04 sensors to estimate distance and found an error of between 0.0 and 0.31 cm. Using just one sensor, these authors recorded an error of up to 6.7%, which for the study above represents an error of 0.0 to 7.839 cm. It is important to note that the study carried out by Scianna et al. (2022) and Hoodmod & Al-Chalabi (2017), indicates that the HC-SR04 sensor must have a minimum contact area of 0.5 square meters, so the error mentioned in these discussions corresponds only to instrumental errors and any errors associated with the electronic devices present in the sensor and the microprocessor.

Figure 4. Box-Plot of the distance measurement errors of the HC-SR04 ultrasonic distance sensor. A) Positioning the sensor at 0 degrees inclination from horizontal; B) Positioning the sensor at 5 degrees inclination to the horizontal; C) Positioning the sensor at 10 degrees inclination to the horizontal; and D) Positioning the sensor at 15 degrees inclination to the horizontal.



The study of the uncertainties applied to the calibration of the HC-SR04 ultrasonic sensor, installed at 0 degrees to the horizontal, indicates that 95.45 % confidence that the data will be between +2σ and -2σ, which corresponds to +3.9396 and -3.9396 cm of error around the distance estimate. A similar approach to treating instrumental error was also used by Pérez et al. (2023), Abreu et al. (2021), Koval et al. (2016) and Ponciano et al. (2016).

Gabriel et al. (2020) used this sensor and obtained an average error of 1% in the calibration considering a distance of 0.20 to 3.09 m, which corresponds to an absolute error of 0.0001 to 0.005 m. Azevedo et al. (2023) recorded a resolution of 0.03 m for the same sensor in similar conditions. Koval et al. (2016), under similar instrumentation conditions obtained errors of around 0.01 m of underestimation for distances greater than 3 meters. This demonstrates the need for local calibration with the electronic array used (sensor set and data acquisition platform).

Pérez et al. (2023) and Droujko et al. (2023), also suggest that the application of electronic equipment should present boundary conditions and calibration should take place in an environment similar to that of its application.

FINAL CONSIDERATIONS

The main features and limitations of the system are listed below. The HC-SR04 sensor applied to distance measurements between 10 and 400 cm shows excellent performance when installed perpendicular to the target surface and calibrated using simple linear regression of an affine line with a distance measurement confidence interval between +3.9396 and -3.9396 cm (95.45% confidence). The test of adherence to the normal distribution and the mean error close to 0 ratify the good calibration for application in the agricultural sciences, at low cost, whether for monitoring the flow of canals or the level of natural and artificial reservoirs, etc.

The installation of the ultrasonic sensor with slopes of 5, 10 and 15 degrees, despite good adherence to the normal distribution, should not be used under the same calibration conditions with the sensor perpendicular to the target surface, as there is a shift in the average errors which causes an overestimation of the measurements. Our study indicated that the application of low-cost electronic equipment should present boundary conditions and calibration should take place in an environment similar to that of its application.

In inclined conditions, a specific calibration should be carried out on a surface with the sensor's installation inclination and with the adjustment of a non-affine line to standardize the central measure of the measurements.

Finally, the sensor's installation inclination in relation to the contact surface must always be perpendicular, otherwise the average error values will tend to overestimate the distance values.

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