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Measurement Resolution in Uncertainty Calculation with the GUM Method Approach: A LabVIEW Application

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ABSTRACT

GUM (Guide to the Expression of Uncertainty in Measurement) is a method used for calculating uncertainty in measurements. The method involves an uncertainty calculation approach which also constitutes a reference for the international ISO/IEC 17025 standard. In the GUM method, all uncertainties are expressed as standard uncertainty. An uncertainty may incorporate various components where impacts from multiple sources are taken into consideration. Resolution errors resulting from the sensitivity of the measurement equipment has a significant impact in the calculation of uncertainty. Sensitivity of an analog measurement device such as a multimeter depends on the resolution of the ADC it contains. Multimeters with 8-bit resolution ADCs are often used as measurement devices for sensor voltage values to be read once or several times. Factors such as high measurement resolution and reading errors by operators lead to an increase in uncertainty. Multiple data from a sensor or many sensors cause a significant increase in uncertainty, which results in a serious loss of time and labor. In order to mitigate said two factors which increase uncertainty in such cases, analog data needs to be converted to digital data at high resolution and transferred into computer medium. In this study, an D7714 analog/digital converter IC with 24-bit resolution has been used to transfer digital data into computer medium via myRIO 1950. A LabVIEW-based software has been developed to perform register settings for the AD7714 IC and to retrieve data at 24-bit resolution.

1. INTRODUCTION (Helvetica 10p Bold)

According to the GUM method, a measurement result is expressed between a measurement value and its uncertainty range. Uncertainty represents the degree of deviation of the measurement result from the estimated actual value and determines the accuracy and reliability of the measurement[1]. According to the GUM method, uncertainty has two components namely Type-A uncertainty and Type-B uncertainty. Type-A uncertainty reflects the repeatability or reproducibility of a measurement and estimated using statistical methods. Type-A uncertainty is based on data obtained through repetition of the same measurement under different conditions [2]. High Type-A uncertainty indicates that the measurement result is less accurate or less reliable [3]. On the other hand, Type-B uncertainty incorporates the effects of factors such as the measurement process itself or the measurement equipment, methods or environment, which usually cannot be directly calculated through the use of statistical methods. Instead, estimations based on information such as expert opinions, past experience, manufacturers' statements, literature data or calibration reports can be used [4].

Differences in results obtained by repeating an experiment multiple times under identical conditions constitute Type-A uncertainty. Such uncertainty is directly related to the repeatability of the measurement, and therefore measurement resolution [5]. For instance, in a voltage measurement device with 8-bit resolution, a one-digit change would result in an under-reading or over-reading of 19.5 mV. On the other hand, a one-digit change at 24-bit resolution corresponds to 298 µV. In summary, the higher the digital resolution is, the lower the Type-A resolution, which plays a major role in total uncertainty, would be. Within such context, if sensor data of wide range is to be collected, it would be appropriate to use delta-sigma ADCs in order to prevent adverse effects of undesired high-frequency components on digitalization and to minimize conversion errors and thereby uncertainty [6]. Further, delta-sigma ADCs are widely used in IoT applications, thanks to their low power consumption, high resolution and favorable performance characteristics [7, 8]. Such ADCs provide high sensitivity and accuracy in the conversion of analog signals into digital signals, thereby enabling more accurate processing of data received from sensors.

Connection of a delta-sigma ADC to a USB interface is generally achieved by the use of a USB data collection board or module. Software such as LabVIEW [9], MATLAB [10], Python [11], Visual Basic and LabWindows/CVI [12] can be utilized to perform register settings for delta-sigma ADCs through aforesaid modules and retrieval, recording and processing of digital data at 50kS/s speed.

In addition, low-pass and high-pass filtering are performed on delta-sigma ADCs in order to minimize noise errors [13]. The register of the low pass filter plays a crucial role in the determination of the sampling frequency of the ADC and the reduction of high-frequency noises. Setting of said register may reduce noise by keeping sampling frequency low, but also impacts the resolution of the ADC. High pass filter register is used for reducing the low-frequency noises in ADCs. Said filter allows measurement of high-frequency components while filtering out low-frequency noise. Setting of said register may affect accuracy of measurement results by determining the frequency response of the ADC. Moreover, the sensitivity of such ADCs may decrease or change in time. Therefore, calibration techniques are utilized in order to ensure that an ADC maintains its accuracy over its lifetime. Self-scale calibration is a widely-used method to measure and improve the accuracy of delta-sigma ADCs. Self-scale calibration is a method where the ADC measures and adjusts itself for the purpose of calibration. In such method, a pre-determined reference voltage is applied to the ADC and the voltage value read by the ADC is checked. Subsequently, the ADC utilizes an internal feedback loop set its parameters in order to equalize the measured value to the correct reference voltage [15].

The benefit of self-scale calibration is that it allows the ADC to automatically calibrate itself. Therefore, allowing the ADC to calibrate itself rather than manually setting the parameters which affect the accuracy of the ADC would lead to more accurate and reliable results.

As such, minimizing Type-A uncertainty and ensuring measurement repeatability by increasing digital resolution in analog measurements have been the primary goal of the study. The study further aims to reduce uncertainty by directly transferring measurements into the computer medium at 50 kS/s speed and thereby eliminating reading errors by operators. An AD7714 Delta-Sigma ADC which performs 24-bit conversion has been used in this study. A LabVIEW-based software has been developed to perform ADC register settings and to retrieve 24-bit data from the ADC output. A myRIO module has been utilized to connect the ADC to a USB interface. The procedures for creating 24-bit digital data for the delta-sigma ADC used in the study and the transfer of the generated digital data to the computer environment via the myRIO module with a developed LabVIEW-based software are discussed in detail, which is also the innovative side of this study. Further, the uncertainty performance of the developed measurement system in repetitive measurements is also analyzed.

2. MATERIAL AND METHOD

The first step of the study has been the establishment of the electronic connection between the AD7714 delta-sigma ADC, myRIO 1950 and the PC. This step involved the determination of myRIO connection points to allow performance of ADC register settings and reading of analog sensor voltage at 24-bit resolution. Pins selected at Connector A for the ADC-to-myRIO connection is exhibited in Figure 1.

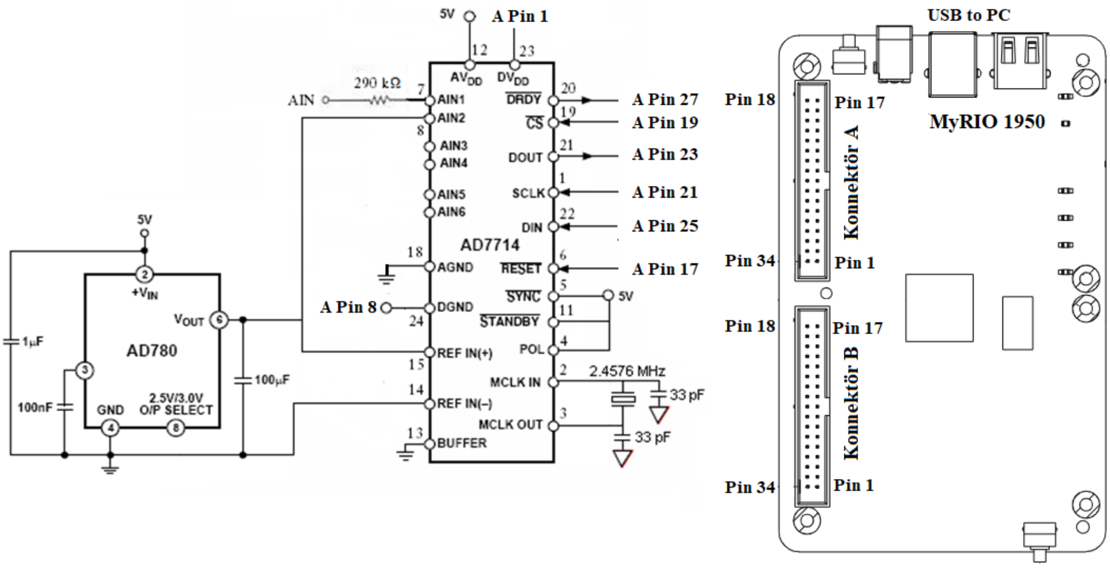


Figure 1. Electronic connection between the ADC, MyRIO 1950 and the PC.

Serial interface of the AD7714 is controlled via pins DIN, $DOUT$, $SCLK$, $\overline{DRDY}$, $\overline{CS}$ of the IC. Pin DIN is used for data transfer to the IC's registers. Pin $DOUT$ provides output for the 24-bit data generated in the data register. Pin $\overline{DRDY}$ is the communication point which indicates whether a 24-bitlik data is generated in the data register of the IC. The pin output is logic 1 if no data exists in the data register, and logic 0 if there is data. Pin $\overline{CS}$ controls IC selection and analog data input. The writing loop of said IC for the registers is provided in figure2.

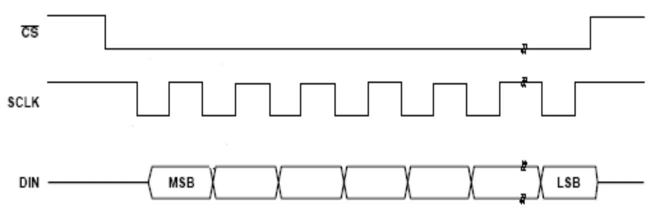


Figure 2. Writing Loop (POL=1)

The reading loop for the IF from the data registers is provided in figure 3.

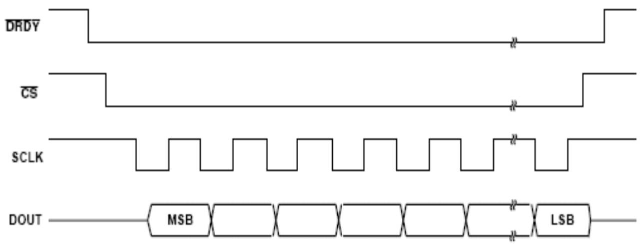


Figure 3. Reading Loop (POL=1)

In this study, programming of the registers of the AD7714 IC to convert analog data into digital data and controlling of the data register have been performed as per the flow chart provided in figure 4.

The AD7714 registers need to be reset before initiating the ADC process. This should be achieved by respectively sending the digital data specified in Table I to the relevant pins of AD7714.

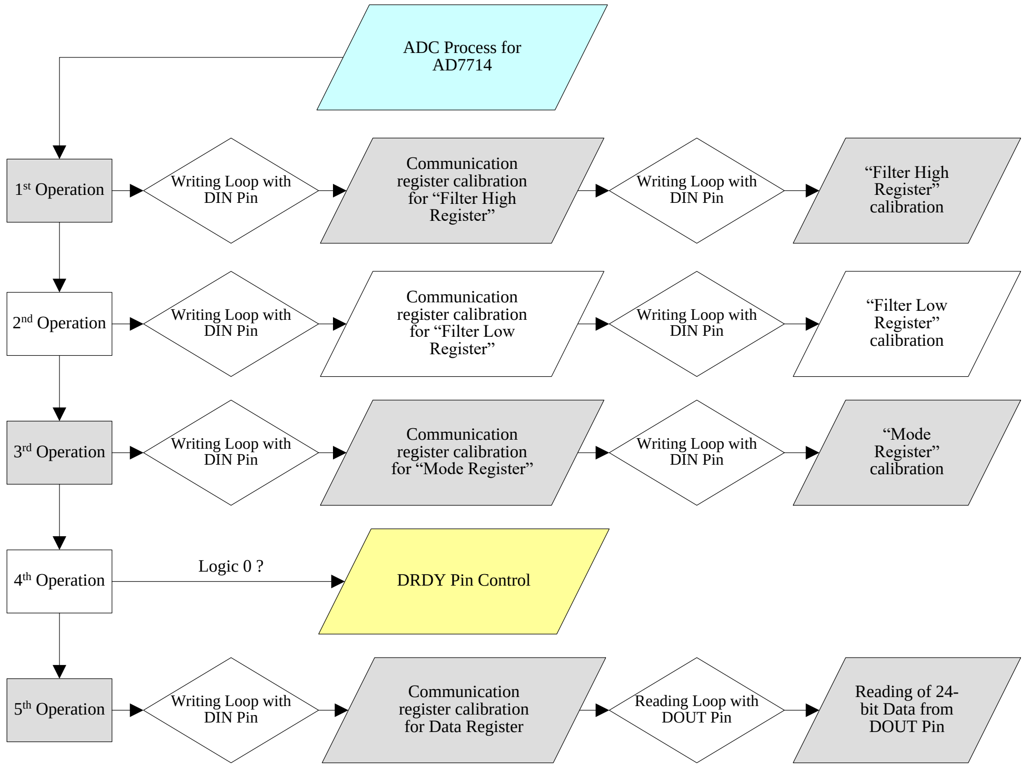


Figure 4. ADC Process for AD7714

TABLE I
RESET PROCESS OF AD7714

Pin	RESET Operations	
$\overline{CS}$	1	1
SCLK	1	1
DIN	0	0
$\overline{RESET}$	0	1

In the 1st operation step, digital data specified for the IC in Table II for communication register calibration for "Filter High Register" and digital data specified in Table III for calibration for "Filter High Register" were sent from the relevant pins of the IC, respectively, using the writing loop.

Logic 0 has been selected for the 8-bit "Filter High Register" communication register calibration of the IC, in order to ensure fastest writing operation. The subsequent 3 bits were used for register selection. The third bit was selected as logic 0 for writing operation, and the remaining 3 bits were set as AIN1/AN2, DC voltage input channels.

TABLE II
COMMUNICATION REGISTER CALIBRATION OF AD7714 FOR "FILTER HIGH REGISTER"

Pin	Communication register calibration for "Filter High Register"																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		DRDY		RS2		RS1		RS0		R/$\overline{W}$		CH2		CH1		CH0		

TABLE III
"FILTER HIGH REGISTER" CALIBRATION OF AD7714

Pin	"Filter High Register" calibration																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	1	1	0	0	0	0	1	1	1	1	1	1	1	1	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		B/U		WL		BST		ZERO		FS11		FS10		FS9		FS8		

During "Filter high register" calibration, the value of the highest bit (bipolar) for DC measurements has been set as logic 0. The value of said bit should be logic 1 for AC voltage or resistance measurements. The 7th bit of the calibration has been set as logic 1 for 24-bit resolution. The bits BST (6th bit) and Zero (5th bit) should always be set as logic 0. Filter selection in said type of ADCs are determined by a total of 12 bits of digital data. The upper 4 bits thereof constitute the lower 4 bits of the 8-bit "Filter high register" calibration. Such calibration aims to reduce low-frequency noise in the AD7714 IC. Said filter allows measurement of high-frequency components while filtering out low-frequency noise. Calibration of said register may affect accuracy of measurement results by determining the frequency response of the ADC.

The 2nd operation step following "Filter High Register" calibration involved communication register calibration for "Filter Low Register" (Table IV) and "Filter Low Register" calibration (Table V), where the relevant digital data were sent from the relevant pins of the IC, respectively, using the writing loop.

TABLE IV
COMMUNICATION REGISTER CALIBRATION FOR "FILTER LOW REGISTER" OF AD7714

Pin	Communication register calibration for "Filter Low Register"																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		DRDY		RS2		RS1		RS0		R/$\overline{W}$		CH2		CH1		CH0		

TABLE V
"FILTER LOW REGISTER" CALIBRATION OF AD7714

Pin	"Filter Low Register" calibration																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		FS7		FS6		FS5		FS4		FS3		FS2		FS1		FS0		

The remaining 8-bit part of the 12-bit filter selection is determined through the "Filter low register" calibration. Filter selection determines the time between the two data consecutively generated at pin $DOUT$ of the AD7714, in other words, the sampling frequency. Said time is also dependent on the frequency and gain selection of the crystal oscillator connected to pin $CLKIN$ of the IC. However, calibration of said register may reduce noise by keeping sampling frequency low, but this would also impact the resolution of the ADC.

The 3rd operation step following "Filter Low Register" calibration involved communication register calibration for "Mode Register" (Table VI) and "Mode Register" calibration

The 3rd operation step following "Filter Low Register" calibration involved communication register calibration for "Mode Register" (Table VI) and "Mode Register" calibration (Table VII), where the relevant digital data were sent from the relevant pins of the IC, respectively, using the writing loop. Channel selection in communication register calibration for "Mode Register" and gain selection in "Mode Register" calibration are determined based on the type of analog data to be measured (AC, DC current or voltage). As the study aims to read DC voltage using pin AIN1 of the IC, digital data 100 was used for channel selection and digital data 000 was used for gain selection during calibration.

TABLE VI.
TABLE VI COMMUNICATION REGISTER CALIBRATION FOR "MODE REGISTER" OF AD7714

Pin	Communication register calibration for "Mode Register"																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		DRDY		RS2		RS1		RS0		R/$\overline{W}$		CH2		CH1		CH0		

On the other hand, bits BO and $FSYNC$ are always set as logic 0 during "Mode register" calibration for calibration mode definition and gain selection. 8 different calibration settings exist for "Mode Register" calibration. However, self-scale calibration is a widely - used method to measure and improve the accuracy of delta-sigma ADCs. In addition, self-scale calibration is a method where the ADC calibrates by measuring and adjusting itself. In such method, a pre-determined reference voltage is applied to the ADC and the voltage value read by the ADC is checked. Subsequently, the ADC utilizes an internal feedback loop set its parameters in order to equalize the measured value to the correct reference voltage.

TABLE VII
"MODE REGISTER" CALIBRATION OF AD7714

Pin	"Mode Register" calibration																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		MD2		MD1		MD0		G2		G1		G0		BO		FSYNC		

The benefit of self-scale calibration is that it allows the ADC to automatically calibrate itself. Therefore, system designers are able to obtain more accurate and reliable results by allowing the ADC to calibrate itself rather than manually setting the parameters which affect the accuracy of the ADC.

The 4th operation step following "Mode register" calibration involved controlling of pin $DRDY$ of the IC, which indicates whether "Data Register" 24-bit digital data is generated. The value at this pin should be logic 0 is data is generated, and logic one if data is not generated. When the value at this pin is Logic 0, the process progressed to the 5th operation step, where communication register calibration for "Data Register" is performed. Digital data determined for said calibration has been respectively sent from the relevant pins of the IC using the writing loop (Table VIII). Subsequently, the 24-bit data generated in the "Data Register" was determined at pin $DOUT$ by the 24 Clock signal sent to pin $SCLK$, starting from the most significant bit (MSB). The decimal equivalent of obtained 24-bit data was determined, its DC voltage equivalent was calculated and recorded into the computer.

TABLE VIII
COMMUNICATION REGISTER CALIBRATION FOR "DATA REGISTER" OF AD7714

Pin	Communication Register Calibration for "Data Register"																	
$\overline{CS}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
SCLK	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	1
DIN	0	0	0	1	1	0	0	1	1	1	1	1	1	0	0	0	0	0
$\overline{RESET}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
		DRDY		RS2		RS1		RS0		R/$\overline{W}$		CH2		CH1		CH0		

TABLE IX
READING OF 24 BIT DATA FROM DOUT PIN

Pin	Reading Process			
$\overline{CS}$	0	0	DOUT check it	DOUT 1 ise $x= x+\underbrace{8388608}_{2^{23}}$
SCLK	1	0		
DIN	0	0		DOUT 0 ise x= x+0
$\overline{RESET}$	1	1		
$\overline{CS}$	0	0	DOUT check it	DOUT 1 ise $x= x+\underbrace{4194304}_{2^{22}}$
SCLK	1	0		
DIN	0	0		DOUT 0 ise x= x+0
$\overline{RESET}$	1	1		
.	.	.	.	.
.	.	.	.	.
$\overline{CS}$	0	0	DOUT check it	DOUT 1 ise $x= x+2^0$
SCLK	1	0		
DIN	0	0		DOUT 0 ise x= x+0
$\overline{RESET}$	1	1		
RESULT	Y= x.5/16777215=……Volt			

The user interface and block diagram of the LabVIEW software developed for programming the registers and retrieval and recording of 24-bit data are exhibited in Figure 5 and Figure 6, respectively.

The Reset and Setup buttons are clicked respectively in the user interface of the developed LabVIEW software. Clicking the Reset button resets the IC, while clicking the Setup button performs calibration for the registers of the IC. Subsequently, when pin $DRDY$ is Logic 0 (when the light on the interface turns off), the 24-bit data is read from pin $DOUT$ of the IC and recorded in the selected file. This operation is repeated until the software is stopped.

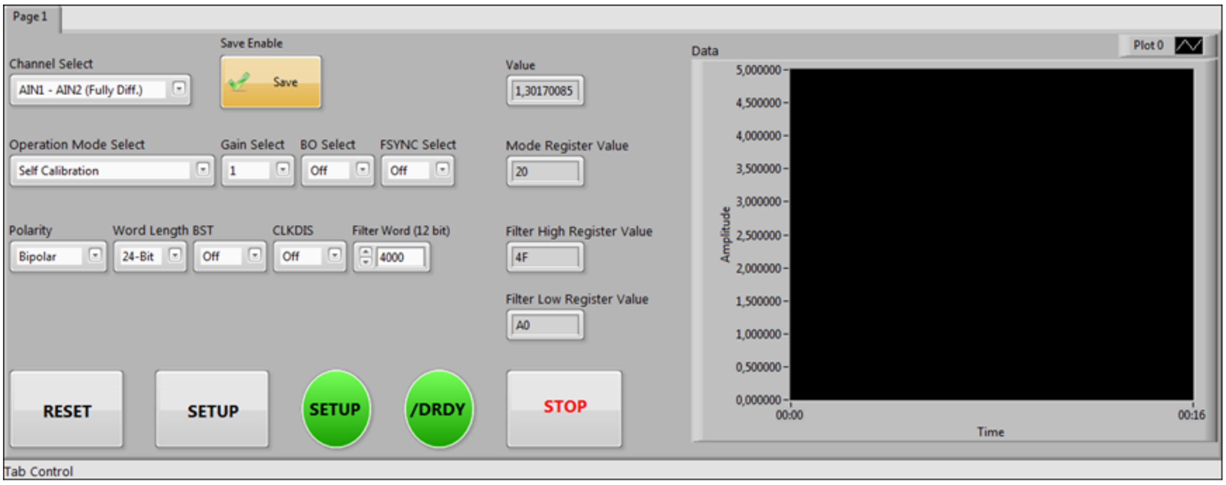


Figure 5. User interface of the developed LabVIEW software

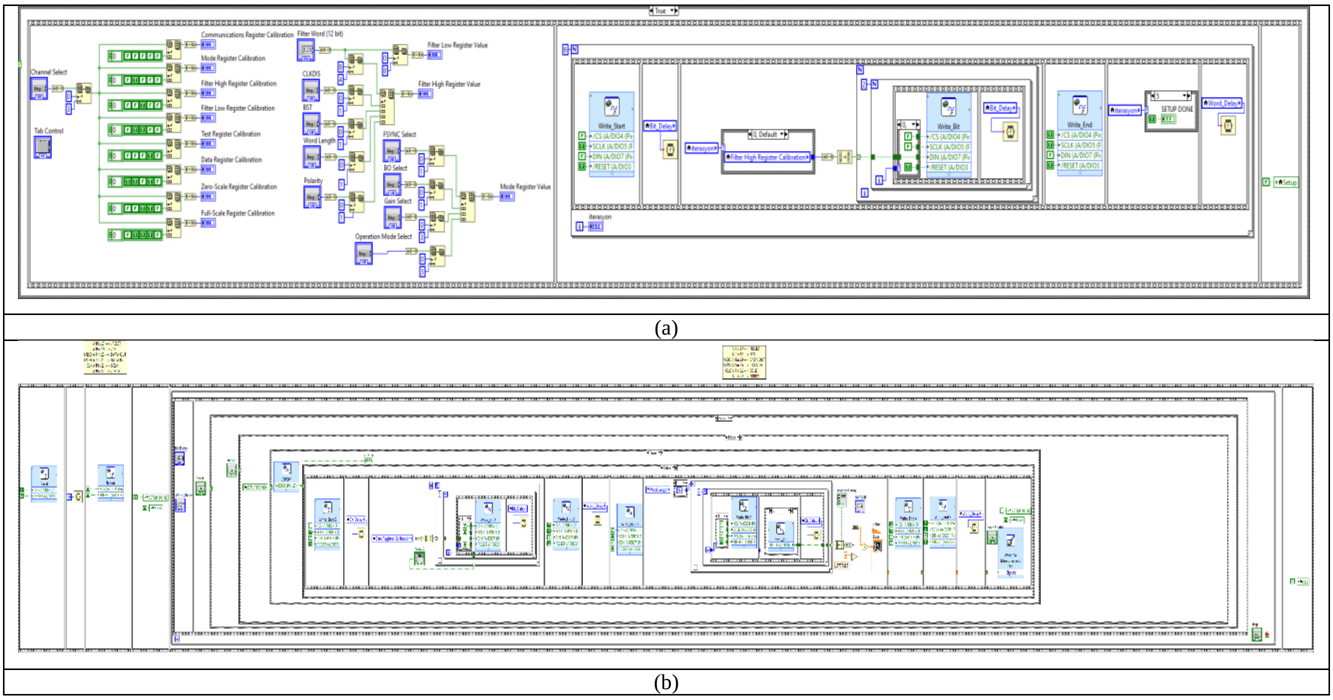
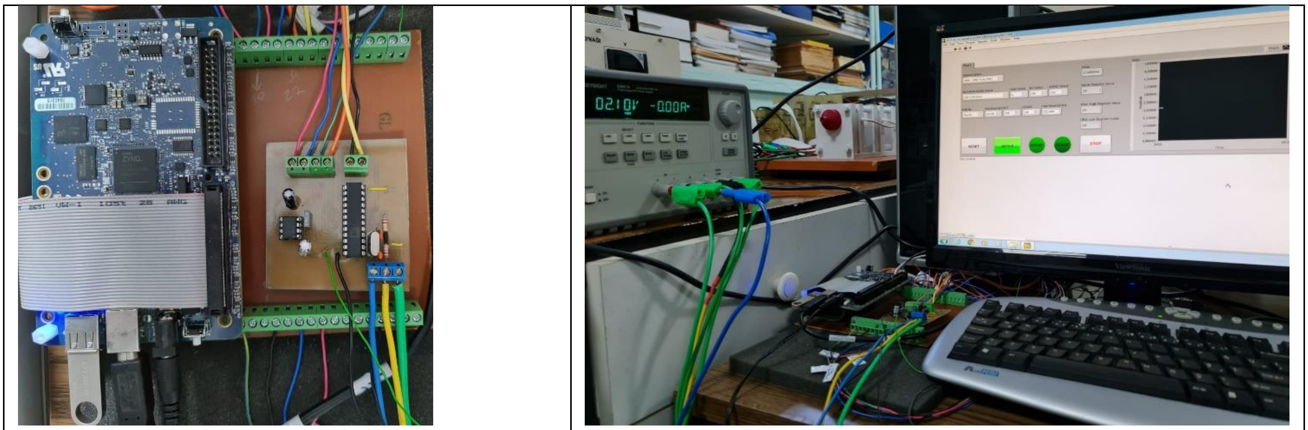


Figure 6. Block diagram of the developed LabVIEW software a) Programming of the Registers, b) Reading of the data in the Data Register

3. TYPE-A UNCERTAINTY OF THE MEASUREMENT SYSTEM: A SAMPLE CASE

A photo of the system developed under the study for DC voltage measurement is exhibited in Figure 7.

The performance of the measurement system developed within the scope of this study to reduce Type-A uncertainty in analog measurements by increasing digital resolution has been analyzed through a sample case. In the sample case, it was attempted to determine the magnetic flux density at a point 10 cm from a magnet by using a TE100 Fluxgate sensor. The analog voltage induced by the magnetic flux density at the sensor was transferred into computer medium and recorded with the use of said system. 8 measurements taken without changing sensor and magnet positions are exhibited in Table X. The same measurements were also conducted using a multimeter. The 8-bit resolution values measured and recorded with a multimeter in the study are given in Table 11.



(a) (b)

Figure 7. a) Electronic connection of myRIO and AD7714, b) A photo of the measurement system.

TABLE X
TE100 FLUXGATE SENSOR VOLTAGE READINGS TAKEN USING THE MEASUREMENT SYSTEM AT 24-BIT RESOLUTION

Test No:	Measured Voltage Value (V)	Average Voltage Value (V)	Deviation from the Mean (V)	Standard deviation σ	Type A Uncertainty $U_A = \frac{\sigma}{\sqrt{n}}$
1	2,0999999105930275	2,099996632337369	0,000003278255658	0,000002447214930	0,000000865221136
2	2,0999987185000609		0,000002086162692		
3	2,0999972283838527		0,000000596046484		
4	2,0999963343141278		0,000000298023241		
5	2,0999945461746779		0,000002086162691		
6	2,0999984204768193		0,000001788139450		
7	2,0999954402444029		0,000001192092966		
8	2,0999924600119865		0,000004172325383		

TABLE XI
TE100 FLUXGATE SENSOR VOLTAGE READINGS TAKEN USING A MULTIMETER AT 8-BIT RESOLUTION

Deney No:	Ölçülen Gerilim Değeri (V)	Ortalama Gerilim Değeri (V)	Ortalamadan Sapma (V)	Standart Sapma σ	A Tipi Belirsizlik $U_A = \frac{\sigma}{\sqrt{n}}$
1	2,0980392	2,08088235	0,01715685	0,01636319	0,00578526
2	2,0784314		0,00245095		
3	2,0588235		0,02205885		
4	2,0784314		0,00245095		
5	2,0980392		0,01715685		
6	2,0784314		0,00245095		
7	2,0588235		0,02205885		
8	2,0980392		0,01715685		

Comparison of Table X and Table XI indicated that Type-A uncertainty calculated according to the GUM model increases by 6687 in repetitive measurements when resolution is decreased. This clearly demonstrates the impact of resolution on Type-A uncertainty. It is also an indication that Type-A uncertainty in a measurement would change by changing the measurement system, even though the sensor and the sensed are the same. Furthermore, in comparison to the use of a multimeter, direct transfer of the measurements into computer medium at 50 kS/s speed during the study helped reduction of total uncertainty, thanks to the elimination of reading errors by operators.

4. CONCLUSION AND DISCUSSION

This study provides a detailed examination of the delta-sigma ADC's procedures for the creation of digital data at 24-bit resolution, as well as the transfer of said generated digital data into computer medium via the myRIO module. A LabVIEW-based software has been developed to perform ADC register settings and to retrieve 24-bit data from the ADC output. In addition, performance of the system developed under this study was tested for repetitive measurements using a sample case, and its effectiveness in reduction of Type-A uncertainty has been proved. Considering the fact that the measurement system eliminates uncertainty reasons such as operator errors at high-speed measurements, total uncertainty to be determined according to the GUM model would also be reduced. Moreover, the developed measurement system is compatible with all sensors which generate analog voltage output based on changing physical characteristics. The system is capable of detecting and recording changes as little as 298μV at the analog output. Today, anomalies in the horizontal component of the earth's magnetic field particularly cause deviations in magnetic sensors at μV levels, which escalates the need for such measurement systems with low uncertainty.

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BIOGRAPHIES

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