

Design, Construction and Implementation of Digital Dual-Scale Measuring Machine Using Microcontroller

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ABSTRACT

A digital dual-scale measuring machine was constructed consisting of two identical ring magnets coupled in repulsive configuration and a microcontroller. The two magnets in repulsive mode behaves as an elastic spring obeying Hooke's magnetic law provided the elastic limit of the magnets is not exceeded. The dual-scale machine with upper scale limits of mass 1.2 kg and extension 1.5 cm was used to measure assorted masses of objects and their corresponding extensions. Using the linear relation between mass and extension, the following magnetic quantities were determined: magnetic force constant 8244.3 N/m, push strength of the magnet 44.15 N, pole strength 588.22 Am, magnetic dipole moment 23.53 Am², magnetization 138762.70 A/m, and remanence 0.1744 T. In addition, the product moment correlation coefficient between the actual mass and measured mass is 0.9926 and the cumulative power consumption of the constructed machine is 4.25 watts.

Keywords: Dual-scale measuring machine, Hooke's magnetic law, microcontroller, elastic limit of magnet, magnetic quantities, cumulative power

INTRODUCTION

Measurement methods have been of huge significance ever since the beginning of human civilization as soon as measurements were first required to control the movement of goods in barter trade to make sure that exchanges of items were equitable. The manufacturing revolution during the nineteenth century led to a rapid growth of new instruments and measurement methods to meet up the demands of industrialized production methods (Alan, 2001). Consequently, this needed a parallel growth in new instruments and measurement methods (Alan, 2001; Fritz and Hanzarian, 1999; Dahikar and Patle, 2013; Petruso, 1981; Rossi *et al.*, 2009; Ialongo *et al.*, 2021). Today, the desire for digital measuring machine is growing rapidly in most business enterprises since measurement using digital measuring machine is safe and clean with variety of different applications (Sartish and Vanaraj, 2012). Therefore, the tendencies to employ digital measuring machine as a substitute of classical measuring system is adopted mostly in the world and so the need increases to design variety of advanced digital measuring machine at competitive level (Sartish and Vanaraj, 2012; Fagbemi *et al.*, 2014).

Demands of digital measuring machines are on the increase for businesses that deal on measurands because it gives the precise and exact measurements quantities. The digital measuring machine gives a high accuracy and efficiency in measuring items and this brings about satisfaction to the producer/seller and the buyer. For example, sensing devices such as transducer load cells are

employed in analogue weight scales. These weight scales do not utilize digital processors and they are read in an analogue manner. These analogue weight scales utilize a rotating pointer which rotates. There are disadvantages to the analogue weighing indicator which are high power consumption because the actuators are electro-mechanical in nature. The actuator works with high current, low resolution which is caused by the fact that there are little differences in the weight of various objects which are not easily detected and the efficiency of the analogue weight scale is low due to the rotating pointer which always shakes or moves (Ayoola *et al.*, 2018).

A fundamental aspect of science is measurement and a key challenge to scientists is to minimize associated errors in cost-effective ways. As instruments increase in sensitivity and hence cost, this balance becomes harder to achieve. Nevertheless, it is a balance that must be made. A key part of measurement is the process of calibration. This involves checking the reading of an instrument against known values that span an anticipated range or comparing an instrument's readings with those of a gold-standard equivalent and should not be confused with graduation; this is simply the marks on an instrument's dial that allow a measurement to be recorded. Calibration should occur immediately before an instrument is used (Winter, 2012).

Calibrations must be performed properly. Thus, the calibration results can be compared to the respective maximum permissible errors established for measuring instruments. This requires that laboratories establish the Calibration and Measurement Capacity (CMC) consistently and referenced in valid and updated normative documents, when available. This paper provides a critical review on CMC made available by accredited laboratories and makes considerations for appropriate selection of the calibration service provider. The calibration activities are part of the routine of industrial organizations, being a prerequisite to evaluate the adequacy to the equipment's use in the measurement tasks. Calibration is defined as the operation that, under specified conditions, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties. The International Metrology Vocabulary - IMV itself notifies that calibration should not be confused with adjustment or verification. This note comes because of several organizations considering that calibration means leaving the instrument with no errors or deviations less than the maximum permissible errors (MPE) set out in normative documents, manufacturer's manuals or even by the organization itself (Becker, 2018).

Quite a number of digital measuring scale designs with unique features have been reported in many literatures. For example, Jorge (2012a) presented three different projects with different scales. First, he started with the Fagor BB-90 scale, a cheap and simple scale with LCD screen. The aim of his project was to store the data on an SD card and further add more advanced features to the scale. He achieved so by replacing the original LCD screen and hence added his own LCD screen and a microcontroller (LPC2103) which he could easily control. The microcontroller obtained data from the SD card and performed multiple calculations before transferring it on the LCD screen. The new features were time and date, increase or decrease in weight, and multi-user support. He further improved the scale to give it Bluetooth connectivity. The scale communicated with his android phone via a Bluetooth link. He used the android application smart weight chart to show the data as a graph. Second, his work was similar to the first one but with a different scale. Third, he manipulated the Beurer BG 16 scale which measures weight, percentage of fat, percentage of water, and percentage of muscle (Jorge, 2012b) in which he made the same modifications as with the other scales. Although the scale was very sophisticated, it was however expensive and unaffordable by most people.

In another context, measurement is important in the health sector. For example, the demand for a person to monitor his weight cannot be overemphasized because the number of patients with obesity is increasing at an overwhelming rate, posing the danger of heart attack and stroke problems are also on the increase. Fat and obese people are vulnerable to increased risk for many diseases and health status, including high blood pressure, cholesterol and low HDL, cholesterol, diabetes, plaque in arteries of heart, gall bladder infection, breast cancer, degenerative joint disease, respiratory problems, high LDL, and heart stroke. It is worth noting that these diseases are weight related, bathroom scales become essential as those who do not have bathroom scales at home often do not care to monitor their weight and this can be dangerous to their health.

The most common and available measuring machines are the analogue types. Although, analogue measuring machines are relatively cheap and do not need power supply, they are associated with the problems of zero error, calibration, inaccurate result, to mention a few. Therefore, the limited digital measuring balance available in the market (Ialongo *et al*, 2021) are very costly and out of reach of many people. Consequently, the demand for digital measuring machine is increasing day by day in most business enterprises (Lund *et al.*, 2008; Sartish and Vanaraj, 2012). Hence, the need for designing and constructing a digital-dual measuring scales for measuring mass and extension is user friendly with variety of different uses.

METHODOLOGY

Design

The main materials used to design and construct the digital weighing balance is categorized into two parts: the electrical part (Lund *et al.*, 2008; Aguilar *et al.*, 2022; Amos and James, 2013; Mowad *et al.*, 2014; Mulla and Mulla, 2013; Rajagukguk and Sari, 2018; Sugriwan and Soesanto, 2017; Swathi *et al.*, 2016) and the mechanical part (Nakajima *et al.*, 2013; Lewis and Jimenez, 2013; Gandzha *et al.*, 2018). The mechanical part essentially converts the mechanical compression of the two magnets in repulsive mode into corresponding electrical quantity whereas the electrical part deals with the digitalization of the resultant analogue voltage and extension. Fig. 1 depicts the block diagram of the digital weighing machine.

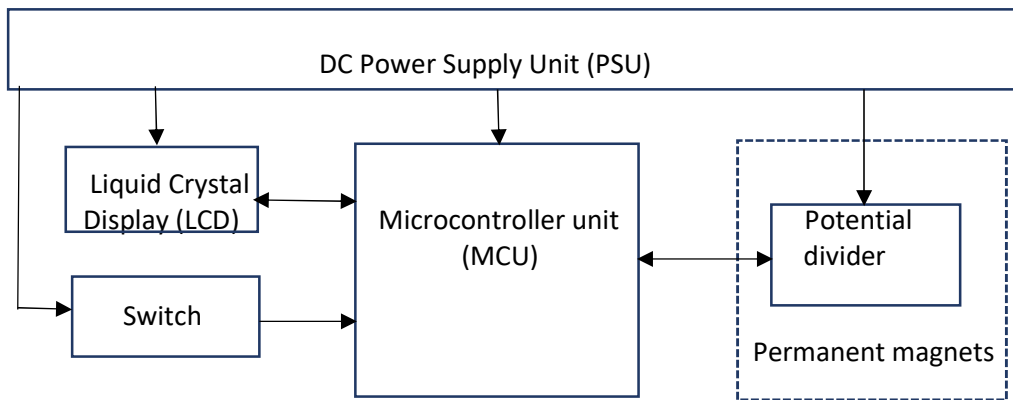


Fig.1 Block diagram of digital weighing machine

A transducer made up of a potentiometer and voltage source was used to convert the mechanical energy due to the suspended magnet into electrical signal. An ADC fixed in a microcontroller was programmed to produce a digital signal equivalence of the standard quantity. The microcontroller was programmed to generate the measured mass on one hand and the extension on the other. Both the mass and the extension are then displaced side by side on an LCD (Fig. 2). For the circuit to operate a power supply is provided and connected to all the parts requiring it.

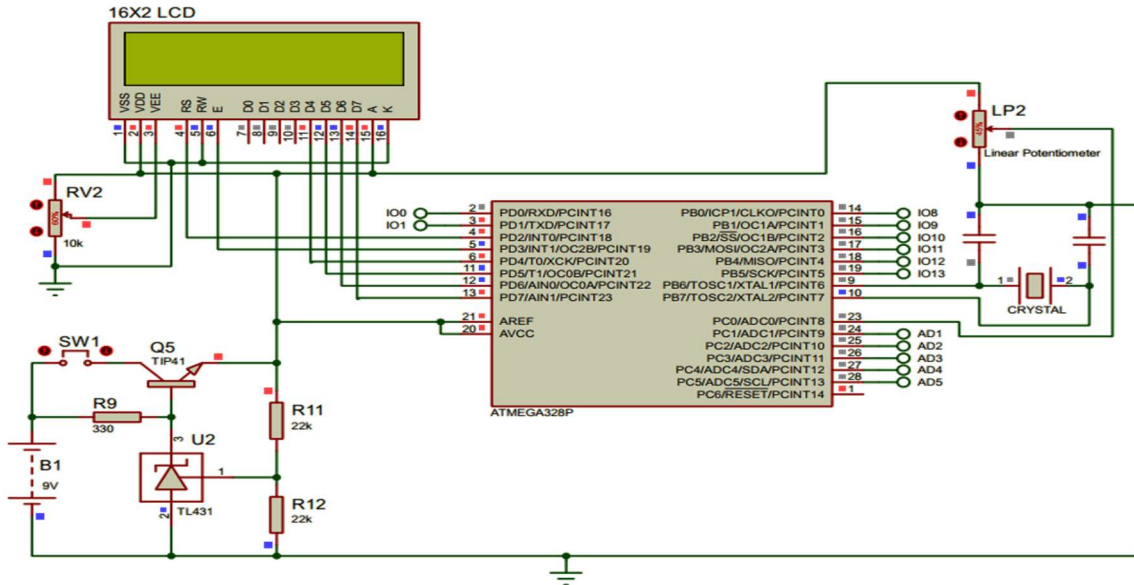


Fig. 2 The circuit diagram of the system

- **The Scale Modification**

In Fig. 3, magnet C is fixed at the bottom of the cylinder while magnet A is suspended freely to move up and down inside the cylinder. The two ring magnets in the cylinder are arranged in repulsive configuration, that is, like poles are closer to each other such that the magnets repel each other as they come closer. Magnet A is suspended at the origin of the graduated scale on the cylinder so that when a mass M is placed on top of it, it moves down through a distance z to a new position B (Fig. 3). When the mass is removed, magnet A returns to its original position due to the repulsive force exerted on it by magnet C. This arrangement is equivalent to a mass suspended on an elastic spring system which produces an equivalent extension z and the magnetic repulsive force is the restoring force, F . Thus, according to Hooke's law (Assi and Assi, 1999; Amos and James, 2013; Guiliodori *et al.*, 2009; Lee *et al.*, 2013), F is proportional to z provided the elastic limit of the magnet is not exceeded and the constant of proportionality is called the magnetic force constant.

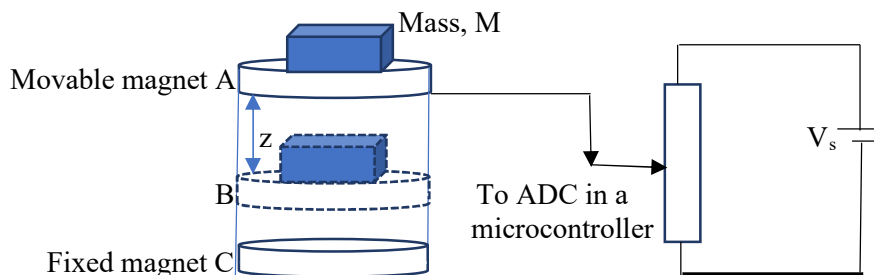


Fig. 3 Schematic diagram of the digital weighing scale

The magnetic part of the digital weighing scale (Fig. 3) which acts as a spring is attached to the moving arm of the potentiometer. A mass placed on top of the moving magnet causes the magnet to move downward through a distance z proportional to the mass. This movement is used to appropriately reduce the airgap between the two magnets. Consequently, the measured mass is converted to electrical quantity using the potentiometer which is a transducer. The output voltage of the potentiometer (Fig. 3) is then fed to the ADC terminal of the microcontroller for conversion into digital equivalent.

- **Analogue Signal Unit**

Fig. 4 depicts the analogue signal unit made up of a variable resistor with one of its ends pulled up to V_{cc} and the other end to ground. The third end which is the center terminal is connected to the ADC channel of the microcontroller that corresponds to port 40 of the microcontroller. The center tap forms a voltage divider network. According to the voltage divider law, the voltage V across the center arm and ground is given by

$$V = \frac{V_s R_2}{R_1 + R_2}$$

where V_s is the voltage across the two ends of the potentiometer, R_1 is the resistance of the upper arm of the potentiometer, R_2 is the resistance between the center arm and the ground.

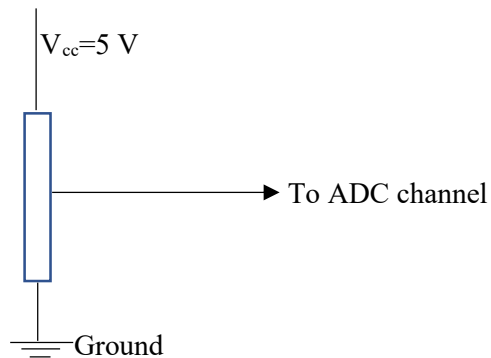


Fig. 4 Conversion of extension to electrical quantity using potentiometer

The variable resistor used in this work is of the value $50\text{ k}\Omega$. Now if current is kept constant, V will be directly proportional to R i.e. when resistance is reduced, voltage will decrease and vice versa.

- **ADC Design**

The output of the potential divider or potentiometer transducer was connected to pin-40 of the microcontroller. By means of converters, the precision is fundamentally controlled by the number of bits in the digital output usually referred to as resolution. In this paper, an 8-bit converter generated $2^8=256$ possible digital values over a range 0-5 V. Thus, an interval of one bit in the output correspond to a change of $(5\text{ V})/256$ which is approximately 19.5 mV in its input. This is known as the least significant bit (LSB)

which is another way of defining resolution. The ADC itself has a resolution of 8 bits and the system has a resolution of LSB of 19.5 mV.

The internal ADC of the microcontroller is 8-channel with the connections at pins 33 to pin 40. These terminals apart from serving as port A₀ with bits A to A₇ also serves as the ADC terminal, from ADC₀ to ADC₇ where the lowest bit is 40 and the highest bit is bit AP₇ (pin 33). In this paper, only one sensor (output of the potentiometer) is connected to the least significant bit of the port A (pin 40). The microcontroller ADC uses 10 bits for successive approximation of analogue to digital conversion. The inputs are multiplexed internally and converted to digital signals as configured. Internally the signal is amplified by a programmable amplifier before conversion. Before conversion a sample and hold circuit is internally used to hold the data while it is being converted. This ensures that the converted voltage remains constant during the conversion process (Ismaila and Momoh, 2011).

- **Power Supply Unit**

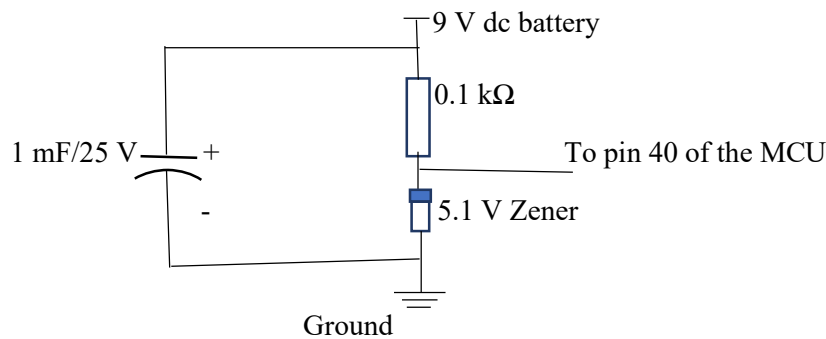


Fig. 5 Power supply circuit

Fig. 5 is the power supply circuit made up of a 9 V dc battery, capacitor (1mF/25 V), a 0.1 kΩ resistor and a 5.1 V dc Zener diode. The basic requirement of an electronic circuit is a power supply unit which must be properly rated to ensure the proper working conditions of the circuit. In this paper, the parts requiring voltage sources are the microcontroller, transducer, and LCD circuits. The voltage specification of the microcontroller and that of the LCD in their data sheets is 5 V. For this reason, a voltage source of 5 V was adopted for the transducer to reduce circuit complexity. For portability and to ensure stable voltage, a 9 V battery was used as supply which was stabilized to 5 V using a Zener diode. With this arrangement the 5 V supply is ensured for a longer duration.

The dc voltage is supplied through the 0.1 kΩ resistor connected in series with the cathode of the Zener diode giving rise to a resistive diode voltage divider network. The output voltage 5 V dc is in turn supplied to the microcontroller as its required operating voltage. For the purpose of safeguarding the life span of the battery a control switch is provided at the front of the panel so that power can be switched off when not in use (Aguilar *et al.*, 2022).

- **The LCD Unit Design**

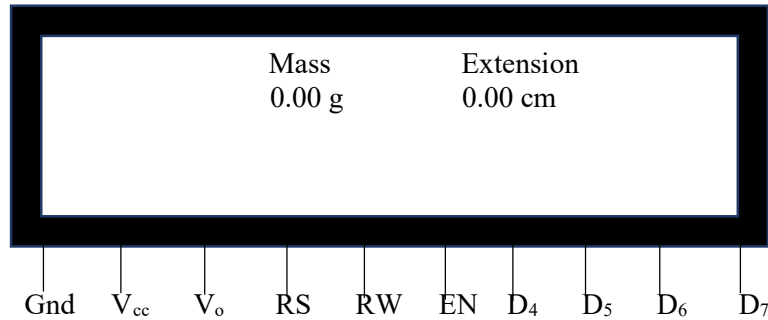


Fig. 6 The LCD package with its pins' configuration

The microcontroller was applied to interface the output of the ADC with an LCD unit. Fig. 6 shows the LCD and its pin configuration. The design unit consists of a 16 character by two rows LCD (liquid crystal display). The ground terminal is connected to the ground of 5 V supply while V_{cc} is connected to its positive terminal. Also, V_o is connected through a 2 k Ω for setting the contrast while the corresponding RS, RW, EN, D₄, D₅, D₆, and D₇ were connected to port 2 of the microcontroller. The 8-bit output of the ADC is sent to the LCD by dividing it into two halves of lower and upper units. The method allows 8-bit data to be sent via a four-wire bus thereby reducing the number of required connecting wires.

- **Software Development**

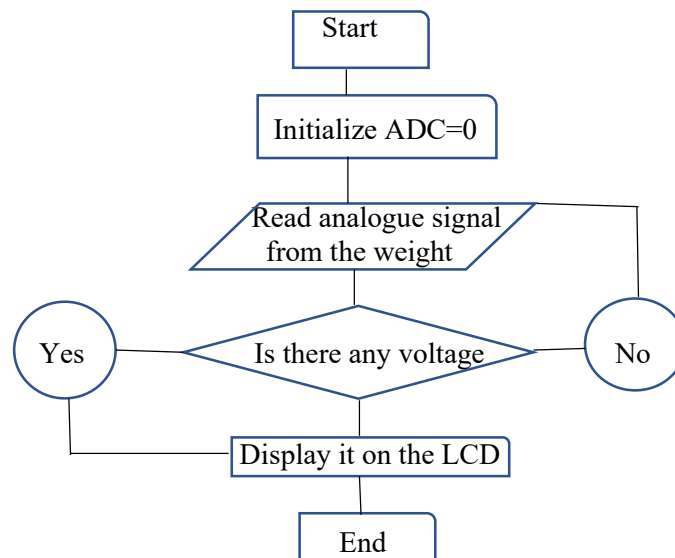


Fig. 7 The system flow chart

The computer program was written, compiled and loaded into the microcontroller using STC90RC51 programmer. The flow chart in Fig. 7 gives brief description of the software application. The programming language used is the C language which incorporates a number of functionalities that makes it very versatile.

The use of a wide range of header files for various microcontrollers makes C language up to standard for programming embedded control systems. One of the advantages of C language is that it allows the embedding of assembly of language within it. Delay routines in C language are by and large written in assembly language, embedded within the C language thereby making it possible to still use it to handle applications depending on real-time speed. Fig. 7 shows the conversion flow chart. At the start, when the device is switched on; the microcontroller initializes its internal ADC to zero to avoid error. The value of the voltage from the potentiometer is read by the microcontroller. The value is converted to digital form by the ADC converter. This value is used to compare the initial value on the ADC. If there is difference, the value is displayed on the LCD, otherwise the microcontroller goes back to monitor if there is change in the value of the potentiometer. Changes in the potentiometer output is as a result of load placed on the weighing machine.

CONSTRUCTION

First, each component of the system was tested to ensure their working conditions. Second, the circuit was set in advance temporarily on a bread board and then permanently soldered on a Vero board. A 40-pin socket was first soldered to the Vero board then the microcontroller IC was fitted in order to complete the electrical circuit. This arrangement allows for easy maintenance as the components could easily be replaced. Furthermore, the IC circuit ascertains that the microcontroller which is the costliest is not damaged during soldering. The LCD was moved to the front panel. The analogue display unit was carefully removed and replaced by the digital LCD. A default potentiometer was also provided to set the constructed weighing machine value to zero before use.



Fig. 8 The constructed digital weighing balance

TESTING

- **Range Test**

The mass and extension scales were tested to determine the range of values for which the scales can be used. The lower limits of mass and extension ($m=0$, $z=0$) of the scale were determined by taking the scale reading on no load while the upper limits ($m=m_{max}$, $z=z_{max}$) of the scale were determined by gradually

loading the scale using assorted masses until the two magnets just come into contact. The readings $m=m_{\max}$ and $z=z_{\max}$ were recorded as the upper limits. A plot of mass against extension should be done to check whether the elastic limit of the magnets in repulsive configuration is obeyed or not. The linear region is the portion where Hooke's law is obeyed and the elastic limit of the magnet is not exceeded. If the elastic limit is not exceeded, the upper limits remain but if otherwise the upper limits should be determined from the linear portion of the graph.

- **Accuracy Test**

For the accuracy test, a standard weighing machine was obtained and its readings were used to compare that of the digitalized scale. The two scales were placed side by side and used to take the masses of assorted objects available in Physics laboratory at Modibbo Adama University Yola, Nigeria. At each instance, the mass of each object was measured with the standard scale and then with the digital scale. The results of the measurements were then tabulated. The difference between the standard scale measurement (M_s) and that of the digital type (M_d) was also calculated. The mean difference (M_m) was evaluated using equation (1)

$$M_m = \sum \frac{(M_s - M_d)}{N} \quad 1$$

where N is the number of measurements taken.

Also, the standard deviation σ is defined by equation (2)

$$\sigma = \sqrt{\frac{\sum(M_s - M_d)^2}{N}} \quad 2$$

A simple product moment correlation coefficient was used to establish the relationship between the two readings. The product moment correlation coefficient was calculated using equation (3)

$$r = \frac{Y_{DD}}{\sqrt{Y_{DS}Y_{SS}}} \quad 3$$

where D is the readings obtained from the constructed digital weighing scale, S is the readings obtained from the standard weighing scale, $Y_{DS} = \sum DS - n\bar{D}\bar{S}$, $Y_{DD} = \sum D^2 - n\bar{D}^2$, $Y_{SS} = \sum S^2 - n\bar{S}^2$, and n is the number of values.

RESULTS AND DISCUSSION

Table 1 contains the list of the quantities and their values that form the magnetic parts of the weighing machine measured by a meter rule or a standard weighing scale or otherwise calculated.

Table 1 Quantity and value

Quantity	Symbol	Value
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Mass of ring magnet	M_{rm}	820 g
Inner radius of ring magnet	R_i	3.0 cm
Outer radius of ring magnet	R_o	6.0 cm
Thickness of ring magnet	t_{rm}	2.0 cm
Length of cylindrical case	L_{cc}	8.0 cm
Thickness of cylindrical case	t_{cc}	0.4 cm
Inner radius of cylinder case	r_i	6.25 cm
Outer radius of cylinder case	r_o	6.65 cm
Airgap between free and fixed magnets	z	2.8 cm
Minimum load to bring the magnets in contact	M_{min}	4500 g
Mass upper limit adopted	M_{ul}	1200 g
Extension upper limit adopted	Z_{ul}	1.5 cm
Push strength of the magnet	F_{push}	44.15 N
Volume of ring magnet	V_{rm}	169.56 cm ³
Magnetic force constant	k_m	8244.3 N/m
Pole strength	p	588.22 Am
Magnetic dipole moment	m	23.53 Am ²
Magnetization	M	138762.70 A/m
Magnetic remenance	B_r	0.1744 T

Table 2 contains known masses of various objects and their corresponding extensions measured using the magnetic part of the weighing machine which has two identical ring magnets with one suspended in repulsion mode inside a graduated vertical cylinder. Also, Tables 1 and 2 show the value of the minimum mass (4500 g) required to bring the magnets in contact and the corresponding extension 2.8 cm. The weight of the minimum mass required to bring the magnets in contact is referred to as the push strength of the magnet and its calculated value is included in Table 1.

Table 2 Mass of object and extension

SN	Actual mass of object (g)	Extension (cm)
1	0.00	0.00
2	200	0.35
3	400	0.60
4	600	0.90
5	800	1.10
6	1000	1.30
7	1200	1.50
8	1400	1.70

9	1600	1.80
10	1800	2.00
11	2000	2.15
12	2200	2.20
13	2500	2.30
14	2800	2.40
15	3100	2.50
16	3400	2.60
17	4000	2.70
18	4500	2.80

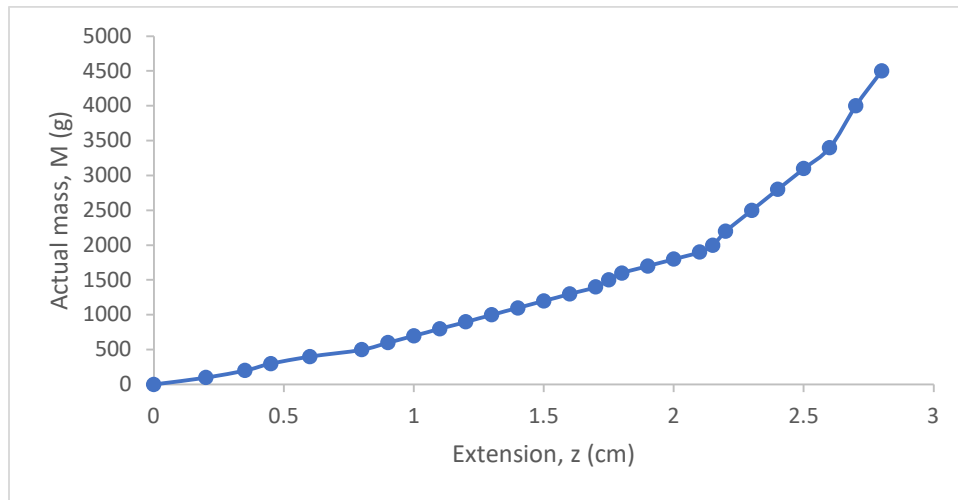


Fig. 2 Actual mass against extension

Fig.2 depicts that the graph of mass against extension does not obey Hooke's law for $z > 2$ cm. This means that the repulsive force due to a magnet is equivalent to the restoring force due to a spring in the region $z < 2$ cm. Hence the spring in weighing machine can be replaced by a pair of magnets arranged in repulsive mode. Therefore, to construct a weighing machine, the upper and lower limits of the mass- and extension-scales can be determined from the linear portion of the graph of mass against extension. In this case, Fig. 2 shows that the linear region of the graph lies in the range mass ≤ 1800 g and $z \leq 2$ cm, which indicates that the choice of the scales must be within these limits so that the elastic limit of the pair of magnets is not exceeded. In this work, for convenience and to ensure the elastic limit is not exceeded the maximum scales of the constructed digital weighing machine were chosen as $z=1.5$ cm and $M=1200$ g. Therefore, the linear graph of mass against extension (Fig. 3) in the region $z \leq 1.5$ cm or $M \leq 1200$ g yields the regression equation $M=840.4-106.4$ in g. The slope of the regression line is 840.4 g/cm or 8244.3 N/m representing the magnetic force constant (Table 1) using the value of the average of acceleration due to gravity equal to 9.81 m/s².

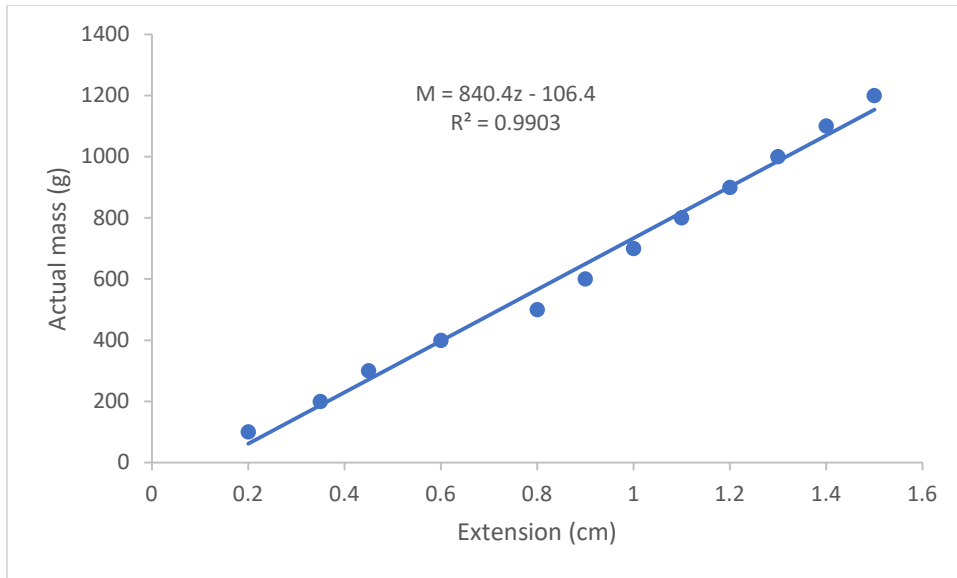


Fig. 3 Actual mass versus extension

The constructed digital weighing machine and a standard weighing balance were used to measure the masses of twelve objects. The readings obtained using the two scales are included in Table 3.

Table 3 Actual and measured masses of objects

Actual mass (g)	Actual extension (cm)	Measured mass (g)	Measured extension (cm)
100	0.2	104.9	0.22
200	0.35	201.1	0.35
300	0.45	302.3	0.46
400	0.6	404.6	0.63
500	0.8	504.2	0.81
600	0.9	604.6	0.92
700	1.0	701.3	1.01
800	1.1	802.7	1.12
900	1.2	903.6	1.21
1000	1.3	1001.2	1.32
1100	1.4	1105.1	1.43
1200	1.5	1203.3	1.52

The difference between actual and measured masses lies in the range $-5.1 \leq \Delta m \leq -1.1$ g and mean value - 3.09 g. Similarly, the difference between actual and measured extensions lies in the range $-0.05 \leq \Delta z \leq 0.02$ cm and mean value -0.01 cm. This means to get the actual mass and extension of the digital dual-scale measuring machine 3.09 g and 0.01 cm should be subtracted from its mass and extension readings respectively.

Also, using equation (2) the standard deviations of mass and extension are ± 3.5 g and ± 0.019 cm which are the measures of how far each reading lies from the mean mass (653.4 g) and mean extension (0.91 cm) respectively. In addition, using equation (3) the product moment correlation coefficients r for mass is 0.9926.

Similarly, the difference between actual and measured extension lies in the range $-0.5 \leq \Delta x \leq 0.2$ cm and mean value -0.1 cm. This means to get the actual extension of the digitalized weighing machine 0.1 cm should be subtracted from its readings. Also, using equation (2) the standard deviation was found to be ± 0.02 cm which is the measure of how far each reading lies from the mean extension 0.91 cm. In addition, the product moment correlation coefficient was neglected because same extension-scale was used to measure extension for both the standard and constructed measuring machines.

Table 4 shows how the current varies across each device in the electrical circuit. And the microcontroller and the LCD need a constant voltage of 5 V to work. Thus the total power across the circuit was found to be 4.25 watts.

Table 4 Cumulative power consumption.

Components	Max current (mA)	Max voltage (Volt)	Total power (watt)
Microcontroller ATmega 328p	200	5	1
LCD 16×2	650	5	3.25
Potential divider	1×10^{-4}	5	5×10^{-7}
Total	850	5	4.25

CONCLUSION

In this paper, the major steps taken in the design, construction and testing of the digital weighing machine are outlined as follows:

- Replace the spring in conventional weighing scale by a pair of freely suspended ring magnets in repulsive mode and vertical position
- Assume the repulsion between the two like poles of the magnets is equivalent to the restoring force due to an elastic spring provided the elastic limit of the spring is not exceeded
- At equilibrium, the weight of the suspended magnet balances the repulsion it experiences due to the fixed magnet
- Apply the equilibrium condition to obtain a relation between mass and extension to determine some magnetic/electrical quantities such as magnetic force constant, magnetic pole strength, pull/push strength, magnetic dipole moment, magnetization, and remanence

- Determine the cumulative or total power of the circuit
- Use standards instruments to perform the range test to determine the upper limits of the quantity (mass/extension) scales
- Perform the accuracy test by determining the mean differences between the actual and measured quantities and the product moment correlation coefficient for mass-scale

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