DESIGN AND CONSTRUCTION OF A HAND-HELD METAL DETECTOR

SALIHU A. ALI

2000/9916EE

ELECTRICAL AND COMPUTER ENGINEERING DEPARTMENT

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SALIHU A. ALI

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Declaration

I, Salihu Andrew Ali, declare this work was done by me and has never been presented elsewhere for the award of a degree. I hereby relinquish the copyright to the Federal University of Technology, Minna.

SALIHU ALI A.
(Name of Student)

(Signature and Date)

Engr. Dr. Y.A ADEDIRAN
(Name of Supervisor)

(Signature and Date)

Engr M.D ABDULLAHI
(Name of H.O.D)

____
(Signature and Date)

____
(Name of External Examiner)

____
(Signature and Date)

Dedication

This project is dedicated to The One In Whom I Live, In Whom I Move and Have My being without Him I am nothing, and to My Parents Mr. and Mrs. A. Y Salihu. Thank You for always being there.

Abstract

Metal detectors play a pivotal function of facilitating safety and security in any modern society finding applications such as the detection of weapons such as knives and guns, especially at airports, geophysical prospecting, and archaeology. They are also used to detect foreign bodies in food during processing, and in the construction industry to detect steel reinforcing bars in concrete and pipes and wires buried in walls and floors.

Detection is made possible by pulses in a search coil inducing electric currents in a nearby metal which distorts the original magnetic field causing the current. Sensing this feedback or distortion is the key to metal detection.

This project entailed designing a laboratory model beat-frequency hand-held metal detector, characterized by low-cost, fair sensitivity to relatively small objects and very limited depth penetration, by employing the technique of paper analysis and design, implementing the design on a breadboard and testing it before finally soldering the finished circuit unto the Vero board and encasing it.

The project encompassed but was no limited to practically applying the knowledge of electromagnetic induction and beat-frequency oscillators with components sourced from conventional electronics stores taking into cognizance the limitations of access to modern laboratory test and measurement equipment.

Acknowledgements

My deepest appreciation goes to The Head of Department, Engr. Musa Abdullahi, for his earnest efforts to move the department forward. My Heartfelt gratitude goes to my Project Supervisor, Dr. Y.A Adediran, for his fervent admonishing, not forgetting my cherished friends. I couldn't have done this without you, every single one of you. God Bless you.

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CHAPTER 1

INTRODUCTION

1.1 EXPOSITORY INTRODUCTION

Electronic systems refine, extend or supplement human facilities and ability to observe, perceive, communicate, remember, calculate or reason.

The metal detector, an application of an inductive sensor, which is an electronic proximity sensor, detects metallic objects without touching them, is a device that senses the presence of metals.

The applications of Metal detector technology cannot be overstated [1], with a range of uses that spans from Leisure to Work to Safety.

The metal detectors in airports, office buildings, schools, government agencies and prisons help ensure that no one is carrying a weapon onto the premises at entry.

Consumer-oriented metal detectors provide millions of people around the world with an opportunity to discover hidden treasures (along with lots of junk).

Construction companies find applications in detecting and locating metal pipes and cables to avoid the hazard of electrocution by drilling into the electric cables or into the pipes, as is the case while a building is undergoing reconstruction or remodeling.

It finds applications in the Military in detecting the presence of land mines ('de-mining') laid by enemy forces.

In the extractive industries, it is used in Geophysical prospecting.

In order to ensure food safety, metal detectors are often used to detect small metallic particles that may have contaminated food products during food preparation (such as the sawing or cutting of fresh meats).

Metal detectors work with the principle of electromagnetic induction.

There are three types of metal detectors: Beat-frequency Oscillator, Induction Balance, and Pulse induction.

1. In a beat-frequency oscillator detector, a coil is used as an inductor in an oscillator, whose frequency changes when metal causes its inductance to change. Another oscillator produces a close frequency, and audible beats between them signal metal.
2. In an induction balance detector, there are two coils, usually gibbous with about 10% overlap, and a sine wave is transmitted with one coil and received with the other coil. The coils are adjusted so that there is no signal in the receive coil when there is no metal nearby.
3. In a Pulse Induction Detector, a pulse is generated (usually by cutting off an inductor) and is sent through a coil and the detector listens for echoes.

1.2 OBJECTIVE OF THE PROJECT

This project will entail designing a lab model hand-held metal detector to detect small metals. The beat-frequency metal locator is characterized by low-cost, good sensitivity to relatively small objects, and very limited depth penetration. Fig 1.1 shows the generalized block diagram of the unit, while the comprehensive circuit diagram is in Figure 3.5.

1.3 METHODOLOGY

The Methodology employed in this project entailed paper design and analysis first, after which bread boarding the designed circuit to allow for placement adjustments and then actual soldering unto a Vero board.

1.4 SCOPE OF WORK

This project uses a digitized beat frequency technique, such that the changes in the oscillator output is converted to a voltage quantity and then compared with the reference voltage rather than another oscillator of a close frequency. Both voltages are fed in as input to a comparator circuit and the output used to trigger an alarm circuit, which indicates the presence and absence or the metals.

A block diagram of the circuit is given below.

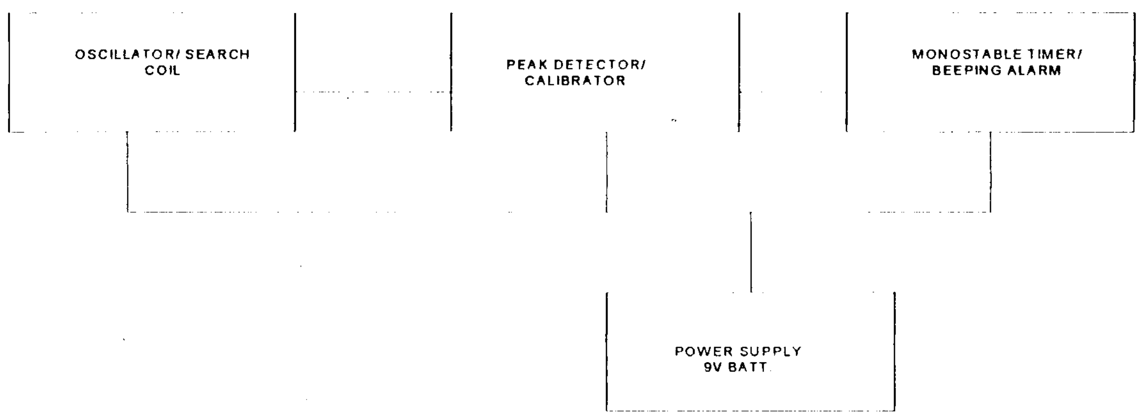

Fig 1.1 Generalized block diagram.

1.5 DESIGN SPECIFICATIONS

Supply voltage: 9VDC from battery.

Detection range: 3-inches max.

Detection type: beat frequency (digitized).

Alarm type: beeping alarm.

CHAPTER 2

LITERATURE REVIEW

2.1 THEORETICAL BACKGROUND

Metal detectors operate via the principle of induction [1]. Induction is the method of coupling two circuits through an alternating magnetic field. The most basic way to detect metal uses a technology called beat-frequency oscillator (BFO). In a BFO system, there are two coils of wire. One large coil is in the search head, and a smaller coil is located inside the control box. Each coil is connected to an oscillator that generates thousands of pulses of current per second. The frequency of these pulses is slightly offset between the two coils. As the pulses travel through each coil, the coil generates radio waves. A tiny receiver within the control box picks up the radio waves and creates an audible series of tones (beats) based on the difference between the frequencies [13].

If the coil in the search head passes over a metal object, the magnetic field caused by the current flowing through the coil creates a magnetic field around the object. The object's magnetic field interferes with the frequency of the radio waves generated by the search-head coil. As the frequency deviates from the frequency of the coil in the control box, the audible beats change in duration and tone [8].

Uses include [7] de-mining (the detection of land mines), the detection of weapons such as knives and guns, especially at airports, geophysical prospecting, archaeology and treasure hunting. Metal detectors are also used to detect foreign bodies in food, and in the construction industry to detect steel reinforcing bars in concrete and pipes and wires buried in walls and floors.

2.2 A BRIEF HISTORICAL BACKGROUND ON METAL DETECTORS

2.2.1 The first detectors

Towards the end of the 19th century, many scientists and engineers used their growing knowledge of electrical theory in an attempt to devise a machine that would pinpoint metal. The German physicist Heinrich Wilhelm Dove invented the induction balance system, which was incorporated into metal detectors a hundred years later. Early machines were crude, used a lot of battery power, and worked only to a very limited degree. Physicist Alexander Graham Bell used such a device to attempt to locate a bullet lodged in the chest of American President James Garfield in 1881; the attempt was unsuccessful because the metal bed Garfield was lying on confused the detector.

Common applications of inductive sensors include metal detectors, traffic lights, car washes, and a host of automated industrial processes. Because the sensor does not require physical contact, it is particularly useful for applications where access presents challenges or where dirt is prevalent. The sensing range is rarely greater than 2 cm, however, and it has no directionality.

2.2.2 Modern developments

The modern development of the metal detector began in the 1930s. Gerhard Fisher had developed a system of radio direction-finding, which was to be used for accurate navigation. The system worked extremely well, but Fisher noticed that there were anomalies in areas where the terrain contained ore-bearing rocks. He reasoned that if a radio beam could be distorted by metal, then it should be possible to design a machine that would detect metal, using a search coil resonating at a radio frequency. In 1937, he applied for, and was granted, the first patent for a metal detector. His designs were soon put to the test in a practical way, as they were used as mine detectors during World War II. They were heavy, ran on vacuum tubes, and needed separate battery packs, but they worked. After the war, there were plenty of surplus mine detectors on the market; relic hunters who used them for fun and profit bought them up. This helped to form metal detecting into a hobby [10].

2.3 REVIEW OF PREVIOUS WORKS OF OTHERS IN METAL DETECTOR TECHNOLOGY

There [9] are three basic methods employed to exploit the above effects:

1. Induction Balance
2. Pulse Induction
3. Beat-Frequency Oscillation

2.3.1 <u>"Induction Balance" (IB) metal detectors</u>: Induction Balance detectors employ two coils. A modulated oscillator drives one. The other is connected to a detector and amplifier. The two coils are carefully positioned with respect to one another such that the receiver coil picks up very little of the energy radiated by the transmitter coil when no metal or mineral material is nearby. When the coils are brought close to a metal object, the field pattern is distorted, greatly increasing the transmitted energy picked up by the receiver coil. The modulated signal is detected and can be indicated by amplifying the recovered modulation to speaker level. Chief advantages are good pinpointing ability and good depth penetration, and they are not sensitive to small ferrous objects.

2.3.2 "Pulse Induction" detectors: these detectors [9] employ coils in the search head that are set up in much the same manner as the IB detector. However, the transmitter is pulsed so that high-energy bursts are transmitted by the search coil. The receiver then compares the phase of portion of the received pulse with the transmit signal. When a ferrous or magnetic object is brought near the search coils the phase of the received signal is advanced with respect to the transmit signal. The opposite occurs when a non-magnetic conductor is brought near the search coils. Thus, this type of detector can effectively 'discriminate' between ferrous and non-ferrous metals as well as exclude ground effects — simply by setting the detection circuitry to exclude signals of the unwanted phase characteristics.

2.3.3 "Beat-Frequency Oscillation" detectors: In a BFO system, there are two coils of wire. One large coil is in the search head, and a smaller coil is located inside the control box. Each coil is connected to an oscillator that generates thousands of pulses of current per second. The frequency of these pulses is slightly offset between the two coils. As the pulses travel through each coil, the coil generates radio waves. A tiny receiver within the control box picks up the radio waves and creates an audible series of tones (beats) based on the difference between the frequencies.

2.3 DIFFICULTIES LIMITING PERFORMANCE

Surprisingly enough the actual inductance doesn't have seem to have much effect on sensitivity, the greater the coil diameter the greater the penetration depth but the less sensitive the metal detector is to small metal objects. The sensing range is rarely greater than 2 cm, however, and it has no directionality.

Another factor limiting performance [8] is that when the search coil is moved around, the capacitance between it and the ground or other objects changes. This changing capacitance 'pulls' the oscillator frequency and can swamp out the small change in inductance required. The coil can be designed to be screened from this capacitance effect by using a Faraday shield around the coil - a ring of tubing (aluminum foil) around the coil but broken at one point so it doesn't make a shorted turn.

CHAPTER 3

DESIGN AND IMPLEMENTATION

3.1 PRINCIPLE OF OPERATION

The metal detector uses the beat frequency technique whereby an inductor is a search coil, which forms part of an LC network circuit. The LC network is part of a Colpitts oscillator stage, which oscillates at a constant frequency. The field strength of the coil reduces as a metal enters the field, which consequently tends to dampen the oscillations and drift the frequency. The output is fed to a peak detector (which senses the d.c level) and comparators with a variable reference for sensitivity adjust. Once a metal enters the field, the output of the comparator goes LOW and triggers a monostable stage for time T, during which a beeping alarm is triggered.

3.2 OSCILLATOR STAGE / SEARCH COIL

The oscillator stage was designed using a Colpitts oscillator where the search coil is the inductor, L. Fig 3.1 shows the oscillator circuit. The oscillator stage generates a varying output when the metal is in the field.

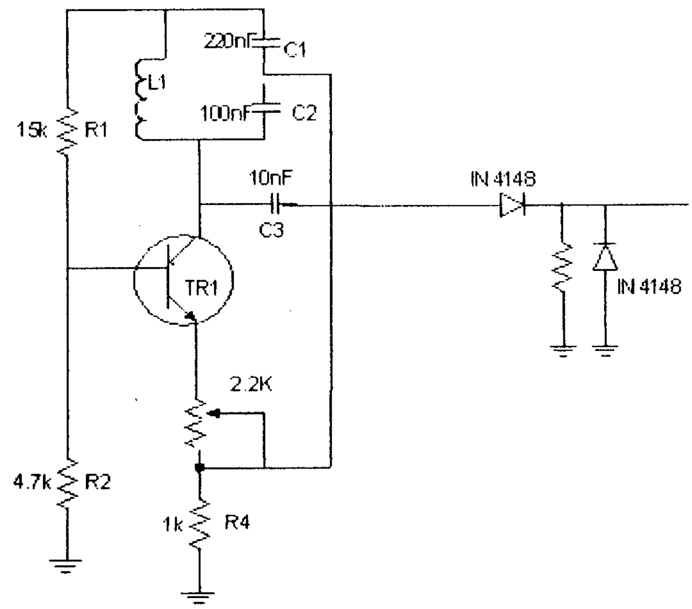

Fig 3.1 Colpitts Oscillator stage

For the Colpitts oscillator stage the frequency of oscillation f_o, is given by,

$f_o = 1 / (2\pi\sqrt{LC})$

Where:

$f_o = 10$ KHz = 10,000 Hz (within the audible range for humans)

$C = [C_1C_2 / (C_1 + C_2)]$

$C_1 = 100nF = 100 \times 10^{-9} F = 1 \times 10^{-7} F$

$C_2 = 220nF = 220 \times 10^{-9} F = 2.2 \times 10^{-7} F$

L =?

$C = [C_1C_2 / (C_1 + C_2)] = [(1 \times 10^{-7}) \times (2.2 \times 10^{-7})] / [(1 \times 10^{-7}) + (2.2 \times 10^{-7})]$

therefore,

$C = 6.875 \times 10^{-8}$ F (or 68.75nF)

Transposing L and substituting for all the values in f_o,

$fo = 1 / (2\pi\sqrt{LC})$

$L = 1 / (2\pi f_o)^2 \times C$

$L = 1 / [(2 \times 3.14 \times 1000)^2 \times 6.875 \times 10^{-8}]$

L = 0.368814519H (or 368.8mH) being inductance (ß).

To get a uniform field, a toroid has to be designed to represent the inductor of inductance

= 368.8mH.

Fig 3.2 below shows the search coil (toroid)

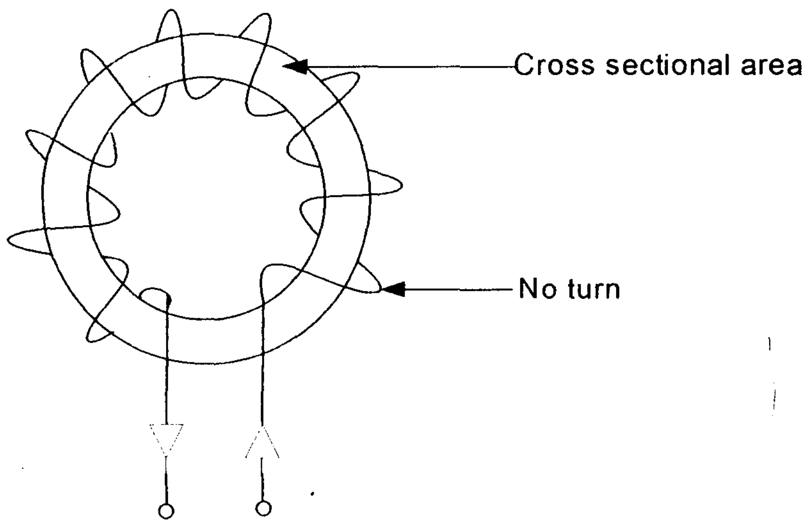

Fig 3.2 search coil (toroid)

Where the inductance (ß) = $[(\mu o AN2) / L_o]$

Therefore, ß = $[(\mu o AN2) / L]$

The number of turns to give the desired inductance would be calculated.

Where: μ_o is permeability of vacuum (Hm^{-1})

A is cross-sectional area (m^2)

N is number of turns of windings

L_o is length of loop

Since $ß = 368.8mH$

and $\mu_o = 4\pi \times 10^{-7} Hm^{-1}$ = a constant

For L_o = 15cm = 0.15m loop length

and $A = \pi r^2$

where d = 1cm = 2r

therefore, r = 0.5cm

Thus $r^2 = (0.5)^2$

$A = \pi \times (0.5)^2$

$A = [(22/7) \times 0.25] = 0.79cm^2$

From the equation,

$ß = [(\mu_o AN_2) / Lo]$

Substituting for all the values,

$0.368814519 = [((4 \pi \times 10^{-7}) \times 0.79 \times N_2) / 0.15]$

Therefore, $N_2 = [(L_o \times ß) / (\mu_o \times A)]$

Therefore, N = 236 turns.

Hence winding 236 turns for the inductor will give the required inductance.

Resistors R_1, R_2 and R_4 are d.c bias resistors for the transistor T_1.

3.3 COMPARATOR/ CALIBRATOR

The peak detector output is fed to the inverting input of the comparator, where it is compared with a reference voltage (akin to a reference oscillator in the analog beat frequency type). When metal enters the field, the voltage at the comparator input drops below the reference to give a LOW output that triggers a 555-timer monostable stage. Fig

3.3 below shows the comparator stage.

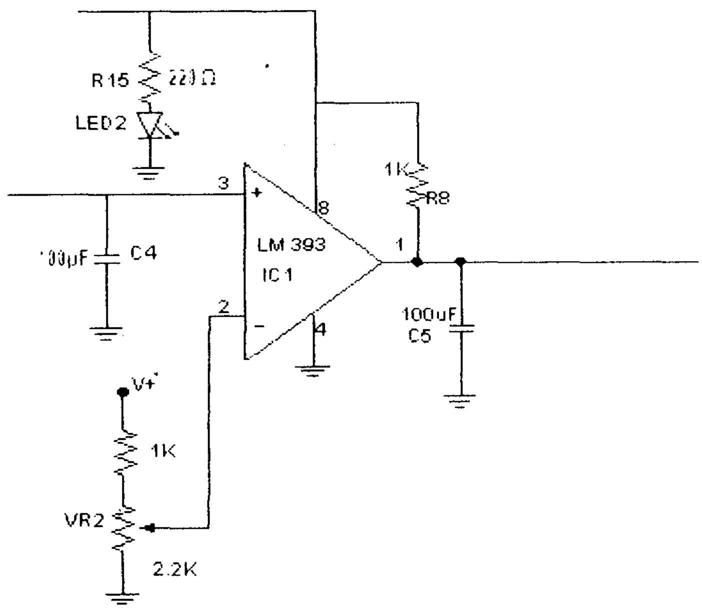

Fig 3.3 Comparator stage.

VR_2 is set at 2.6V (this is because when metal is detected the voltage drops from approximately 4V to 1.5V), any voltage below 2.6V in the inverting input will make the output of the comparator go low, to trigger the monostable stage since,

$V_{out} = A_0 V_{in}$

Where A_0 = open loop voltage gain.

And $V_{in} = V_+ - V_{out}$ will drop to 0V for the slightest negative difference in voltage since A_0 is often very large (in order of 20 000).

3.4 ALARM STAGE

The alarm stage is comprised of a one-shot monostable and astable multivibrator. The monostable is triggered when the metal is detected (to enable timing of the alarm for a specific duration), while the astable generates the beeping tone.

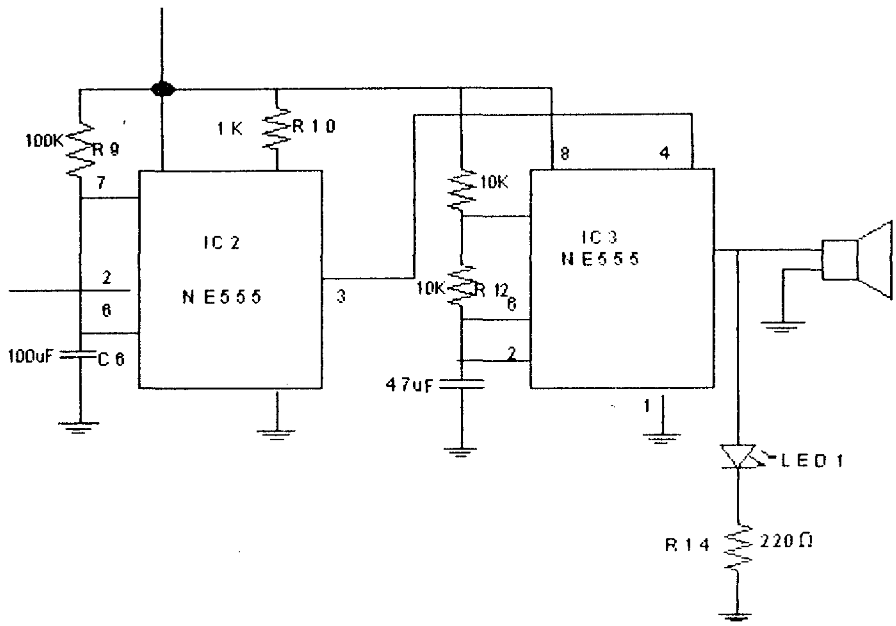

Fig 3.4 Alarm stage

The one-shot monostable stage generates one shot of clock pulse each time the search coil detects a metal. The one-shot monostable is triggered from the output of a comparator, which senses the break beam. The one shot monostable is built around IC2 in Fig 3.4.

Since T = 1.1RC, and the time duration of the monostable is 5s. (To allow for continuous beeping for time T, after metal has been detected).

Letting C = 100µF,

Gives R = 5/ 1.1x100µf

= 9.09K

= 45.5KΩ.

= 47 KΩ.

IC3 in fig 3.3 forms the astable oscillator stage.

For a frequency of 1Hz,

$t_1 = 1.1C (R_1 + R_2)$ seconds (where t_1 = ON time)

$t_2 = 0.693CR_2$ seconds (where t_2 is the OFF time)

Since F = 1/T

& $T = t_1 + t_2$

$F = 1/ \ln 2C (R_1 + 2R_2)$ seconds

$F = 1.44/ (R_1 + 2R_2) C$ .... (1)

Letting R_1 = 10K and C = 47μF

Substituting the values into equation 1

R_2 = 10.3K

=10K (preferred value).

Therefore $R_{11} = R_{12}$ = 10K, & C_7 = 47μF.

3.5 COMPONENTS LIST

100nF Capacitor	x 1	220Ω Resistor	x 2
220nF Capacitor	x 1	4.7kΩ Resistor	x 1
100μF Capacitor	x 3	2.2kΩ Resistor	x 1
47μF Capacitor	x 1	1kΩ Resistor	x 4
15kΩ Resistor	x 1	10kΩ Resistor	x 4
IN4148 Signal diodes	x 2	LM393 OpAmp I.C	x 1
Variable resistors at 2.2kΩ	x 2	NE555-Timer I.C	x 3

3.6 COMPREHENSIVE CIRCUIT DIAGRAM

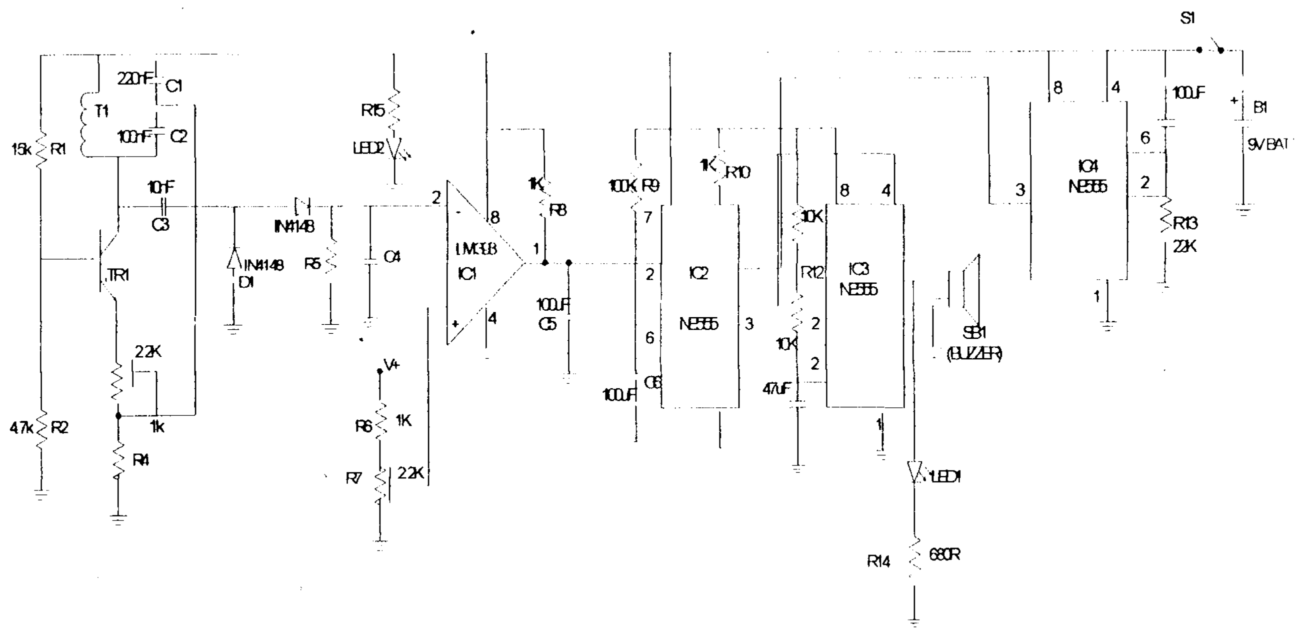

Fig 3.5 Comprehensive circuit diagram

CHAPTER FOUR

TESTS, RESULTS AND DISCUSSION

4.1 TESTING

This is where the fantasy of the whole idea meets reality. After having carried out all the paper design and analysis, the project was implemented and tested to ensure its workability, and was constructed to meet desired specifications. The process of testing and implementation involved the use of some test and measuring equipment stated below.

(i) BENCH POWER SUPPLY: This was used to supply voltage to the various stages of the circuit during the breadboard test before the power supply in the project was soldered. Also during the soldering of the project, the Power Supply was used to power various stages before they were finally soldered board as a single unit unto the Vero board.

(ii) DIGITAL MULTIMETER: The process of implementation of the design on the board required the measurement of parameters like, voltage, continuity, current and resistance values of the components.

4.2 IMPLEMENTATION

The implementation of this project was done on the breadboard. The power supply was first derived from a bench power supply (to confirm the workability of the circuits before the power supply stage was soldered).

Stage by stage testing was done according to the block representation on the breadboard, before soldering of circuit commenced on Vero board. The various circuits and stages were soldered in tandem to meet desired workability of the project.

4.3 CONSTRUCTION

The construction of the project was done in three different stages.

1. Prototyping by connecting the components on a breadboard.

2. The soldering of the circuits to the boards

3. The coupling of the entire project to the plastic casing.

The soldering of the project was done on a Vero board. The Vero board contains the Power Supply, Oscillator/Search Coil, Peak detector/Calibrator and Monostable Timer/Beeping Alarm circuits.

Fig 4.1 below shows the soldering and component arrangement on the Vero boards.

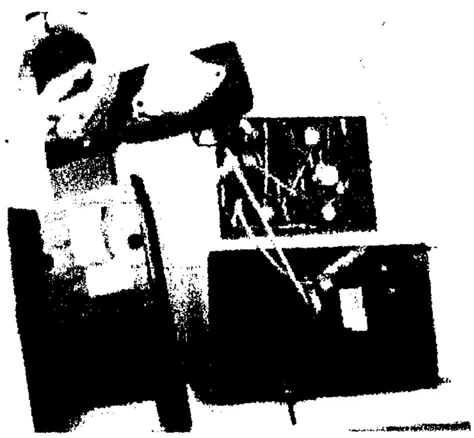

Fig.4.1 Component layout on the Vero board

4.4 CASING AND BOXING

The second phase of the project construction is the casing of the project. This project was coupled to a plastic casing, with special perforations to allow a neat connection of wires from the buzzer to the internal circuit.

Fig. 4.2 Isometric view of the finished project.

4.5 TROUBLESHOOTING

The problems encountered in this project and how they were solved is listed below.

1. Ensuring continuity on the Vero board such that no soldered points bridge unnecessarily. This meant extensive testing and inspection at each instance soldering done.

2. Calculating for the proper amount of Inductance from the number of loops of wire wound into the coil in cognizance of the fact that the greater the coil diameter the greater the penetration depth but the less sensitive it is to small objects.

3. The problem of Microphonics (audible vibration caused by the vibration of some mechanical part) was resolved by securely anchoring the coil to prevent its individual

wires moving.

4.6 OPERATIONAL TESTING

The working laboratory model was put in close proximity to various objects of differing compositions and an audible tone was heard when a metallic material is within range of the search coil.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The project, which is the design and construction of a beat-frequency oscillator based metal detector, was designed in lieu of factors such as economic application, design economy, availability of components and research materials, efficiency, portability and also durability considering its simplicity. The performance of the project after test met design specifications. However, it is pertinent to state that the general operation of the project and performance is dependent on the user who is prone to human error such as manhandling the search coil, which [13] could give rise to "microphonics" and excessive drain on the dry cell battery if the detector is left switched on for prolonged periods while not in use.

In addition, its operation is dependent on how well the soldering is done, and the positioning if the components in on the Vero board. If poor quality soldering lead is used the circuit might form dry joint early and in that case the project might fail. In addition, if logic elements are soldered directly near components that radiate heat, overheating might occur and affect the performance of the entire system.

The construction was done based on a modular design in such that it makes component failure and replacement an easy task and affordable for the user should there be any circuit failure.

I have gained exposure to electronic circuit design, and practical electronics in general. The design of the Metal detector involved research in Electromagnetic Induction, Oscillating Circuits and Operational Amplifiers. Extensive work was done on the Oscillator/Search Coil stage.

5.2 RECOMMENDATIONS

1. I am strongly of the opinion that simple projects should be introduced as group work from the third year of study to familiarize students with electronics design and soldering practices in general.

2. Concerning the project I recommend that research be carried out as regards to determining what factors affect the coil sensitivity and an output that depicts audibly the relative proximity of the metal.

REFERENCES

[1] Robert L. Boylestad & Louis Nashelsky, ELECTRONICS DEVICES AND CIRCUIT THEORY, 8th edition, *PRINCE-HALL*, 2002.

[2] R.J Maddock & D.M Calcutt, ELECTRONICS: A COURSE FOR ENGINEERS (Pages 341-349, IC timers, 249-263 counters, 290-293 decoder drivers), *LONGMAN*, 1994.

[3] Tom Duncan, SUCCESS IN ELECTRONICS (pages 44-75, other passive components), *LONGMAN*, 1983.

[4] Luecke G., J.P Mize AND W.N Carr, SEMICONDUCTOR MEMORY DESIGN AND APPLICATIONS, (chap.3&4, general references), *McGRAW-HILL BOOK COMPANY*, 1973.

[5] EVERYDAY ELECTRONICS JOURNAL, May 1998 Ed (power supplies and multivibrators), *WIMBORNE PUBLISHING*.

[6] Clayton Hallmarkie, COOKBOOK, (Pin configurations of all the IC's), *Mc-GRAW-HILL BOOK COMPANY*, 1986.

[7] Metal Detectors - Microsoft Encarta® 2007, © 1993-2006 Microsoft Corporation

[8] Electronics World Publication, Dec. 1966

*NTE DATA BOOK 12th EDITION (General Data Sheets for the components)

Web Links:

[9] [illegible]

[10] http[illegible]

[11] http[illegible]

[12] http[illegible]

[13] http[illegible]

APPENDIX 1

COMPREHENSIVE CIRCUIT DIAGRAM

USER MANUAL

INSTRUCTIONS

1. Switch the Unit on and wait for the initial beep.
2. With a steady and slow sweeping motion, pass the detector over the probed surface at close range to it.
3. When metal is within its capture range two audible beeping tones are heard. The Unit can then be switched off.

ʼRECAUTIONS

1. This Device radiates an electromagnetic field when in operation and as such should not be brought close to other strong magnetic fields ıch as loud speakers and Cathode Ray tube displays so as not to nage their operation.

Unit should not be held too close to the ear when probing for ls because it emits a high pitched tone which can damage human g at close range.

way from Moisture and extreme heat.