Metal detector

By Tomislav Berend

Did you ever want to discover a hidden treasure? One of the first devices that I built as a child was a simple metal detector. Later, I built various different metal detectors from plans published in electronics magazines. Today, the prices for metal detectors vary from a few hundred to a thousand Euro, and therefore I have decided to design one of my own – an improved version of the "pulse induction" metal detector.

Introduction

With technology advancing every day, metal detectors have also improved. All of them are now based on microcontrollers that also handle the analogue circuitry. In this chapter, I will describe a "pulse induction" metal detector that is very sensitive and easy to assemble. However, it does have a drawback: it does not distinguish different metals. Let's look at the history of metal detectors.

History

Long ago, people wanted an instrument that would help them discover precious treasures. The first notes can be found in 1830, with experiments by geologist R.W. Fox. The first detectors detected only the conductivity of the soil and the minerals within.

In the 1879, Prof. D.E. Huges introduced the first "induction balance – IB" metal detector. This detector was used in a London hospital to find metal parts within injured people. This principle is still used by many modern metal detectors.

In the 1881, Alexander Graham Bell used a metal detector to find a bullet that hit President James Garfield. The first portable metal detectors appeared in 1925, invented by Gerhard Fischer, who later founded the A&S Company, which manufactured metal detectors commercially.

The principles of metal detectors have not changed much. Only the data interface has changed, which has improved the sensitivity and accuracy of metal detec-

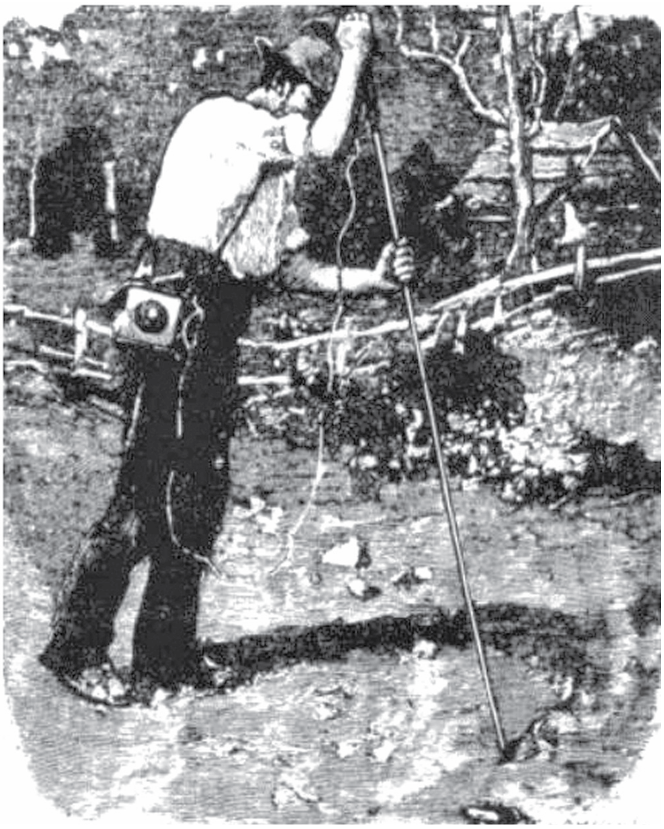

Figure 1: First attempts to use a metal detector

Figure 2: One of the first commercial metal detectors

tors. The principle used is based upon the fact that a coil's inductance changes in the presence of a metal object.

Metal detector Methods

There are a few methods used in metal detectors which I will describe.

Induction Balance (IB)

Figure 3 shows the block diagram of an IB metal detector. This is one of the oldest methods that is still in use today. The detector operates at very low frequencies between15 and 25 kHz. An oscillator produces an electromagnetic field in the search coil. This magnetic field travels through the air to the receiver coil. This signal is amplified, and then rectified by a peak detector. The resulting DC signal is amplified again by a DC amplifier. That DC signal is then chopped at an audio rate, changing it into an audible tone, with a volume proportional to the level of the DC signal itself. After the chopper, an audio amplifier is used to amplify the signal so it can feed a loudspeaker or a headphone.

When a metal object comes near the search coil, it will disrupt the inductive balance between the search coil and the receiver coil, causing a higher voltage to be induced in the receiving coil. The greater the DC output voltage fed to the chopper, the stronger the audio signal will be. Note that the frequency of the audio doesn't change-just the amplitude changes in response to the proximity of metal to the coils. The advantage of this method lies in its better sensitivity, while its drawback is that precise tuning is required during manufacture. Also, the construction and alignment of the search/receiver coils is somewhat critical. It should be noted that this detection method is affected quite markedly by soil conductance (such as the presence of salt-water in the soil).

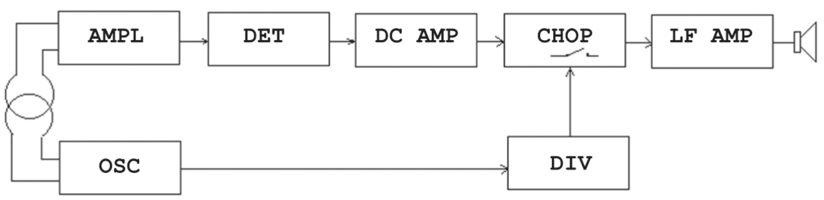

Figure 3: Block diagram of an IB metal detector

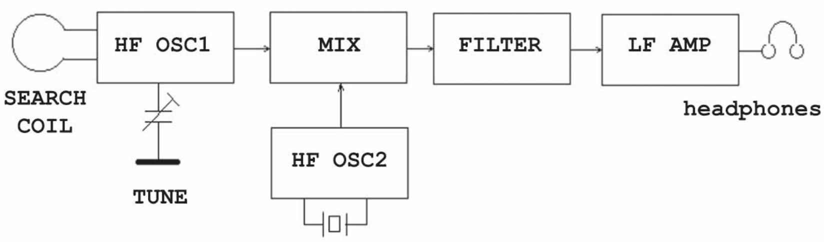

Figure 4: Block diagram of a BFO metal detector

Beat Frequency Oscillator (BFO)

Figure 4 shows the block diagram of a BFO metal detector. This is one of the oldest metal-detection methods. Its operation is quite simple. Oscillator No. 1 contains the search coil as part of its resonant circuit. Its frequency depends upon the search coil's inductance as well as the value of a variable capacitor, which is also a part of that resonant circuit.. Oscillator No. 1 is tuned to a frequency that is virtually the same as the frequency of oscillator No.2. Oscillator No. 2 uses a quartz crystal, which gives it a highly accurate, fixed frequency. When a metal object approaches the search coil, its inductance changes, therefore the oscillator frequency changes as well. Signals from both oscillators are fed to a mixer whose output consists of several frequencies: both input frequencies, their sum, and the difference between the two (as well as some higher harmonic frequencies). Only the difference frequency is within the human hearing range. We amplify that difference frequency, which can be heard as a high pitch tone, that will rise in pitch in proportion to the change in inductance of the search coil, brought about by the presence of a metal object.

Using the variable capacitor connected to oscillator No. 1, we can set a frequency difference which results in a tone within the audible range. If, for example, both oscillators are tuned to 200 kHz and the inductance changes by 0.01 %, then the output frequency changes by 20 Hz. To achieve higher difference frequencies, we need to use oscillators with higher frequencies. Doing this, however, raises an oscillator stability issue, so we have to strike a balance between stability and higher frequency to achieve the best performance.

The advantage of this type of metal detector is simple construction of both the device and the search coil, but a drawback is the high influence of soil conditions to the detector's performance.

Transmit/Receive (T/R)

Figure 5 shows a block diagram of T/R type metal detector. T/R metal detectors are very similar to IB metal detectors. An oscillator signal is sent to a search coil and also sent separately to a limiter (which turns it into a square wave of fixed amplitude). The signal from the receive coil is amplified and sent to another limiter. Both signals will now have the same amplitudes (because of the limiters), but are normally 180 deg. out of phase. These two signals are fed to a phase detector. Under normal conditions, the phase detector output is zero. If a metal object approaches the search coil, the signal's phase will change, giving a DC signal at the output of the phase detector. A drawback of this design involves the difficulty of tuning the coils, as well as the major effect of soil conductivity.

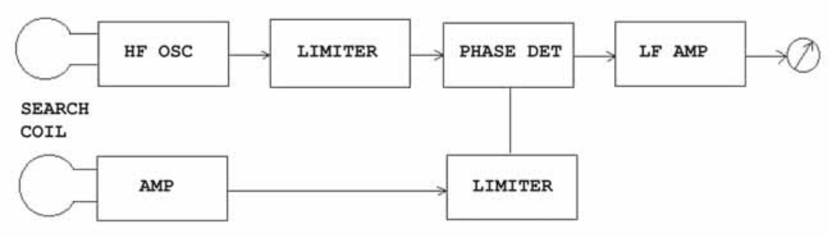

Figure 5: Block diagram of T/R type metal detector

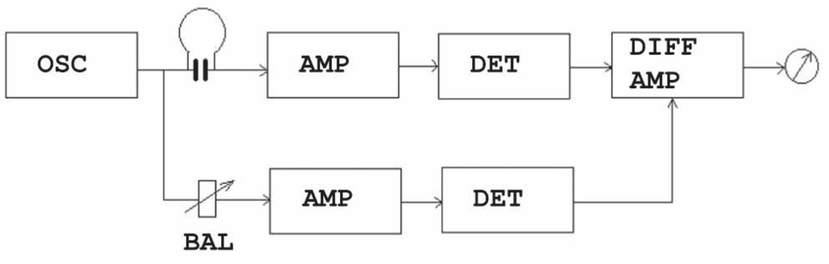

Figure 6: Block diagram of the OR metal detector

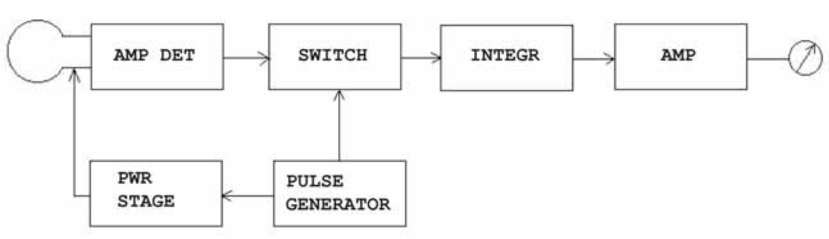

Figure 7: Block diagram of the PI metal detector

Off-resonance (OR)

Figure 6 shows the block diagram of the OR metal detector. With this metal detector, a signal from the oscillator is passed through a stop-band resonant circuit (a "trap") to an amplifier. From the other side of the resonant circuit, a signal is taken through a balance circuit to another amplifier. The stop-band resonant circuit is tuned to the oscillator frequency, which means that it attenuates that signal greatly. Signals from both amplifiers are passed on to detectors and from there to a differential amplifier. When the circuits are in a balanced state, the output signal will be zero. Any metal presence near the search coil will change its inductance, thus changing the oscillator's frequency. This new frequency will pass through the stop-band resonant circuit much more readily, causing a change in the DC signal at the output of the differential amplifier.

Pulse Induction (PI)

Figure 7 shows the block diagram of the PI metal detector PI metal detectors operate on a totally different principle, although they still depend upon the principle of the changing inductance of a search coil when metal is near it. You can see in Figure 7 that a pulse generator creates pulses. The pulses are amplified and connected to an electronic switch. When this pulse is connected to the coil, a magnetic field occurs around it. In Figure 8 you can see the waveform of this pulse.

When the current through the coil is interrupted, the magnetic field around the coil is also interrupted. Due to self-inductance, we will see a strong pulse of reverse-polarity coming from the coil. To prevent self-oscillation, we add a damper resistor to the circuit. When metal comes near the search coil, the reverse-polarity pulse (occurring when the drive current is interrupted), will take longer to decay than normal. This longer pulse, although relatively small, is still large enough to be detected. To boost it, we take many successive measurements, and feed the reverse-polarity decay signals to an integrator. The integrator's voltage output is amplified and fed to an indicator.

The advantage of this type of metal detector is the simple construction of the search coil and the fact that soil conditions do not affect the detector unless there are minerals present in the ground. The drawback of this method is that it does not distinguish amongst different types of metals. Also, the search coil head must not include any metal parts. Another drawback is the higher power consumption and a rather complicated design.

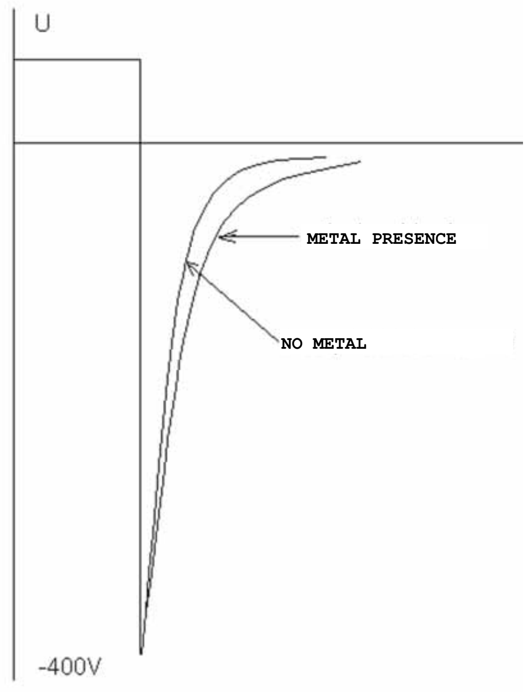

Figure 8: The pulse that is fed to the search coil

Microcontroller - based PI metal detector

If a microcontroller is used for a PI metal detector, it can handle many of the functions. A microcontroller can generate accurate pulses, measure time and time - dependant responses. In place of an integrator, we can use its fast A/D converter to acquire voltages with precise timing.

At the heart of this metal detector, I've chosen an ATmega8, which has all the functions needed. It can operate with a 16 MHz clock, has six A/D converter inputs, enough RAM & Flash memory and enough I/O pins to connect to the peripheral devices. A standard 2x16 LCD was used for the display.

The schematic diagram of a microcontroller-based PI metal detector is shown in Figure 9. The schematic can be divided into a few sections:

- the power supply unit,
- the microcontroller with both a display and configuration switches,
- pulse amplifier,
- search coil,
- detector and amplifier.

Circuit description

Voltage from the battery is fed to the circuit through choke L1 that suppresses interference caused by the search coil pulses. After the choke is a protective diode that shunts out negative spikes arising from self-induction in the search coil. This also protects the circuitry from wrong battery polarity. C2 is a large capacitor (10,000 µF), which is very important: it serves as an energy reservoir during pulse generation. The circuit just described provides the +12V power. A three-terminal 5V regulator provides regulated power for the microcontroller. Since the operational amplifier requires a negative power supply, I've used an ICL7660 charge-pump (U2) to provide -5V (on pin 5).

As mentioned, timing is very important when measuring the voltage from our searching coil. The actual measurement timing depends upon the coil itself and the width of the pulse fed to it. The wider the pulse, the more energy is stored in the coil, and the slower the voltage decay across the coil will be.

To adjust the timing parameters, there are switches to set width+, width-, delay+, delay-.

PortC.0 is configured as an output. The microcontroller generates a short pulse (100 to 450 µsec) on this pin. That pulse is used to create the magnetic field within the search coil. The width of this pulse defines the power of our metal detector. Wider pulses will create a stronger magnetic field thereby increasing the detector's range. The pulse width can be varied in steps of 50 µsec. The microcontroller pulse is fed to a PFET driver U5 (ICL7667).

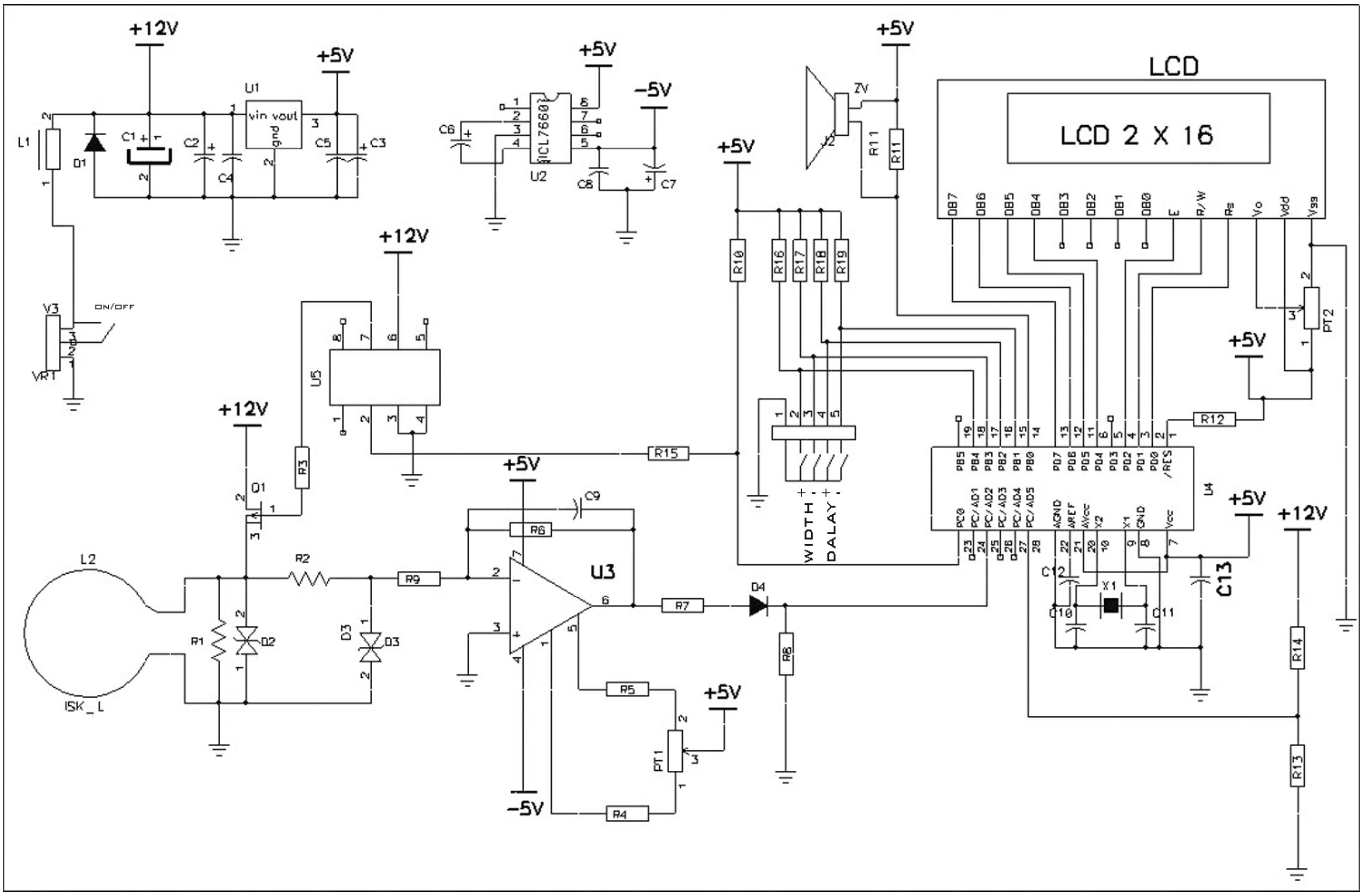

Figure 9: Schematic diagram of a microcontroller-based PI-metal detector

Maybe you will wonder why I have used a PFET here. If we have used NFET instead then our voltage of interest would swing around +/- 12 Volts. That would mean that we would have to adapt power supply for U3 to be +/- 12 Volts too. Maybe you'll wonder why I have used a PFET here. I used a PFET, because the coil decay waveform is best measured with respect to ground, by U3, and a PFET is best suited for this type of switching.

An IRF9630 PFET (Q1) acts as the power stage. It can withstand a maximum voltage of -200 Volts. The MPT2P50E is much better, with maximum voltage rating of -400 Volts, but it is hard to obtain. The PFET **must** be mounted on a heat sink – especially if the search coil is poorly-wound. The search coil is connected to the PFET's source pin, a bi-directional suppressor diode PKE6KE400CA is connected in parallel with the coil. This diode protects the PFET transistor from excessive negative voltage spikes generated by the coil. The pulse waveform is shown in Figure 10.

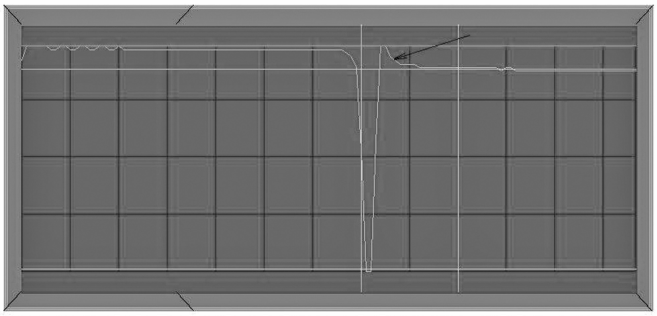

Figure 10: Waveform of the pulse across the search coil (50V/div, 50 µsec/div)

Also connected to the search coil are resistor R2 and diode D3 (a bi-directional suppressor diode PKE6KE-400CA) which limits the signal at the op-Amp negative input pin.

The preamplifier is an LF356 op-amp (the LF357 or LM318 are not quite as good, but still suitable). With PT1, the balance potentiometer connected between pins 1 and 5, we can shift the signal from the positive to the negative power rails. This sets the "zero point" of our detector. The op-amp's output waveform is shown in Figure 11 and Figure 12.

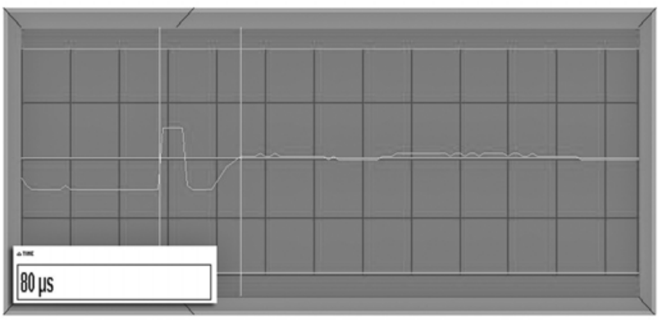

Figure 11: U3 op-amp output signal without metal parts nearby

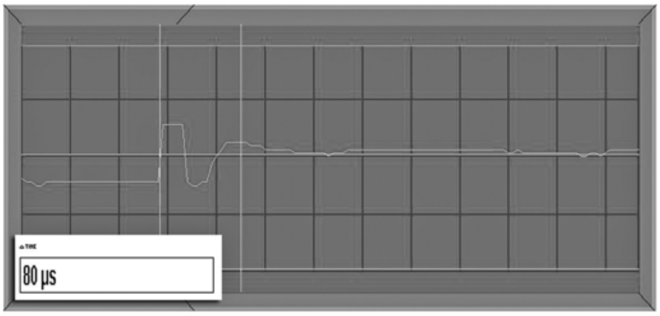

Figure 12: U3 op-amp output signal with metal coin nearby

Because the A/D converter can only handle positive voltages, a protective diode D4 is added in series with the input pin. I recommend that you use a Schottky diode here, for its lower voltage drop.

The signal is fed to the ADC2 pin. I've used 5 Volts as the A/D reference voltage.

The pulse voltage will be measured at a time delay set by the "Zak+" and "Zak-"switches. This delay must be optimized with respect to the coil used and the pulse power fed to the coil. The delay (from the end of the applied power pulse) can be set in 5 µsec steps from 40 to 85 µsec. The detector pulse power can be adjusted with switches "Sir+" and "Sir-" to the following settings: 100, 200, 300, 350, 400 and 450 µsec.

ADC5 monitors the power supply voltage through a voltage divider network. The software checks that voltage every 30 seconds. If the power supply drops lower than 9 Volts, the detector will notify the user that the voltage is too low and the detector will stop working.

The LCD display is connected to PortD in a somewhat unique way. In time-critical programs, Bascom's regular LCD commands are too slow - they take a lot of time just displaying simple information. To avoid that, I have used:

```
$lib "lcd4busy.lib"
Const _lcdport = Portd
Const _lcdddr = Ddrd
Const _lcdin = Pind
Const _lcd_e = 2
Const _lcd_rw = 1
Const _lcd_rs = 0
```

Using this configuration, the LCD display was much quicker (due to the fact that the **lcd4busy** library routines poll the display to see when it has finished a command, instead of just waiting a fixed, *conservative*, time for that command to complete).

The quicker display makes it possible to move the detector over the surface more quickly.

Note that the R/W pin is connected to PortD.1 and not to GND as is usually the case.

The LCD displays all necessary data. The first line shows the power supply voltage, followed by the pulse width and the measurement delay, both in µsec.

On the second line we have bar graph, and a numeric representation of the measured data.

A Piezo speaker is connected to PortB.0. This speaker is very handy, making it un-necessary to watch to display constantly. The speaker generates a frequency which varies according to the presence of metal. In normal operation, we just hear a "click" every second or so.

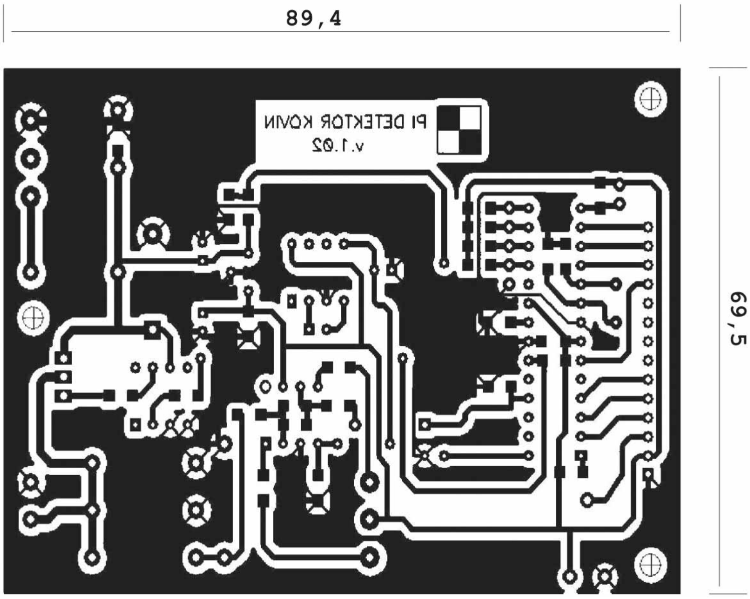

Figure 14: Metal detector PCB layout

The Software

At the start of the program, we configure the microcontroller's Ports. At reset, all AVR ports are in a high-impedance state, which could damage the PFET. Therefore, PortC.0 is immediately configured as an output and set to a low logic state. After this, the program configures the A/D converter, Timer0 (for creating sound) and the LCD display.

Near the beginning of the program the power supply voltage is checked and if it measures less than 9 Volts, the program jumps to a subroutine where a warning is displayed on LCD. Then the program simply loops, disabling the detector from any further operation.

If power supply voltage is OK then the program jumps to the main loop which is repeated 40 times. Within the main loop, a pulse is generated. After that pulse generation, we wait out a fixed (user –specified) time delay, after which time a measurement is performed. All 40 measured results are averaged. This value is displayed on the LCD in the form of "bar graph" as well as its numerical value, which is more precise. At the same time, we vary the tone going to the built-in speaker, according to the measured value. The program also polls the switches periodically, to see if either the "Power" or "Width" settings have been changed. Unless these settings have changed, we do not refresh the display, which saves precious time. The power supply voltage is checked every 30 seconds.

Figure 13: Metal detector LCD display

The Search coil

Making the search coil is not too difficult. The easiest way to make it is to draw a circle 20 cm in diameter on a piece of wood. Divide that circle into sixteen equal parts, and put a nail at each spot (covered with protective heat-shrink tubing). On that template, wind 30 turns of copper "magnet" wire (with a diameter of 0.6 mm).

After the coil is wound, bind it up with string. Then solder a coaxial cable (not longer than 2 meters) to the two coil leads. Connect the other end of the coaxial cable to the detector's input. Finally, the coil should be mounted to a suitable holder.

A smaller coil is better for searching for smaller metal parts, but it will have a shorter range. You can also ex-

ATTENTION

When using this metal detector, you may discover military objects, which may explode and hurt you, if you try to excavate them. The author and publisher do not take any responsibility or liability in case of any injury or damage done while using/building the metal detector. You've been warned!

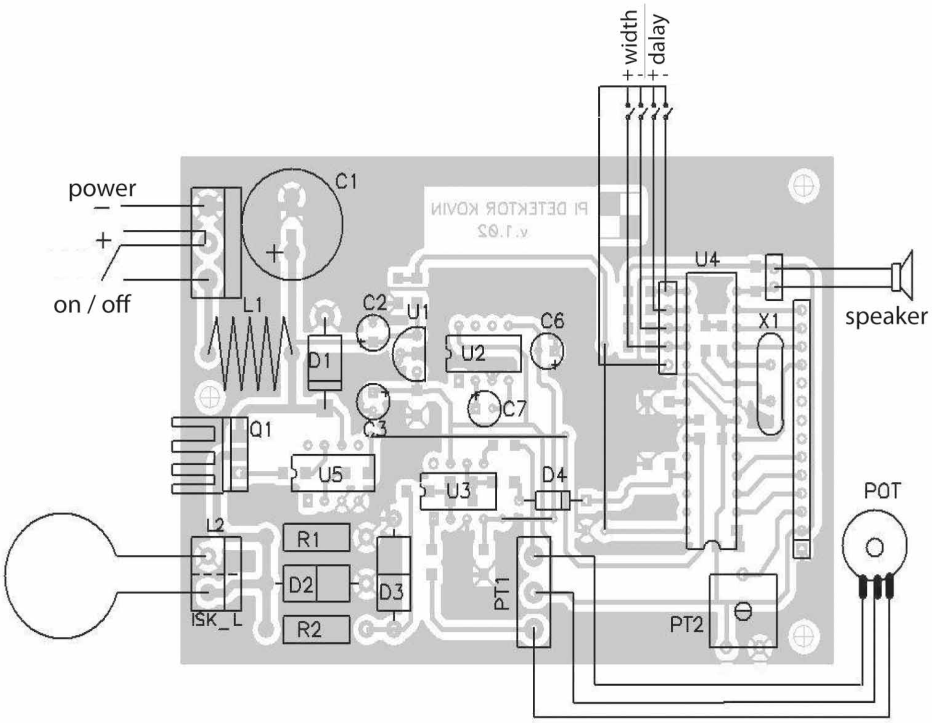

Figure 15: Component layout on the top side of PCB

periment with other coil shapes, but I didn't try this myself. I tested both 20 and 30 cm coils and found that a 20 Cent coin was detected at a distance of 20 cm. It's very important that the coil itself does not contain any metal parts. The coil's inductance should be approximately 400 μH - anything close to this value will be OK. If you decide to experiment with other coils, I suggest that you connect the metal detector to a "bench" supply and measure its current consumption. With this current measurement, you can see if your coil is within the desired range or not. Too few turns will increase both the current and the PFET heating. While experimenting, I suggest you perform your tests with a low pulse power.

Construction details

The Metal detector circuit is contained on a single-sided PCB with dimensions of 89.4 x 69.5 mm. To aid in construction, Figure 15 shows the components on the top of the board and Figure 16 shows the components on the solder side).

Start by mounting the SMD parts, followed by the three PCB jumpers, then mount the IC sockets and other components. The L1 choke can be wound on a small ferrite ring using 10 to 15 turns of magnet wire (0.6 mm diameter). You can also use a choke, salvaged from a cell-phone charger. Capacitor C1 should be mounted parallel to the PCB or else it won't fit into the enclosure. Q1, the PFET transistor should be mounted on a suitable heat-sink. Finally, connect the potentiometers, switches and the LCD display, and you're done.

To power the metal detector, I suggest to use rechargeable batteries because using ordinary alkaline batteries will cost you a fortune.

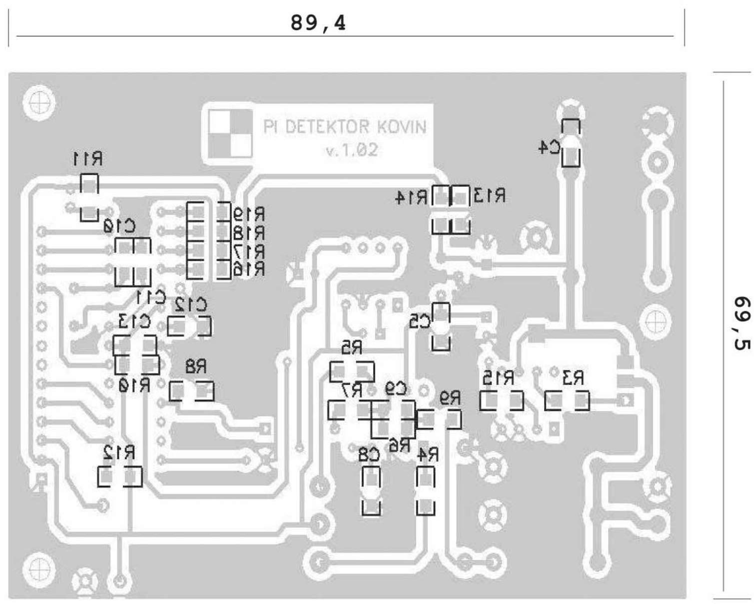

Figure 16: Component layout on the bottom (solder) side of PCB

Tune - up procedure and use

After final assembly, you'll have to check for common mistakes (poor solder joints, shorts etc.) under a magnifying glass. Mounting SMD parts can be tricky for a newbie.

After checkout, you can connect up the power supply **with the search coil disconnected**. The power drain should be in range of 40 to 50 mA, while the LCD display should show the introduction message. If you can't see this, adjust the contrast with PT2.

If that's OK, disconnect the power supply, connect the search coil and power up the detector again. After a few seconds you will hear some sound from the speaker and the LCD will display data as shown in Figure 13. The Search coil should be separated from metal parts by at least 1 meter: then set the frequency of the tone to approx. 1 Hz, using potentiometer P1. If this isn't possible, change the delay time using the delay switches. Then observe the numerical value on the LCD and adjust it to be in range of 5 to 8, using potentiometer P1. Move the search coil near a metal object and you should hear the pitch of the sound changing. You should also see changes on the LCD display as well. At this point, you can change the pulse power and delay to find the optimum detector sensitivity.

Conclusion

In closing, here is one suggestion: Do not test this metal detector near an older style cathode-ray tube PC monitor or TV screen which is powered-up. If you do, the strong electromagnetic signals given off by those devices will disturb the operation of this detector a lot! I found that out during my testing! My work bench is close to a TV set, and I lost a couple of hours troubleshooting the unit, until I discovered this.

Happy treasure hunting!

Example program ID	
Name:	Metal_detector.bas
Microcontroller:	ATmega 8
Testing circuit:	Figure 9
MiniPin compatibility:	/
MegaPin compatibility:	/
Advance program with the possibility to set the time; use lcd4busy.lib	

Designator	Value	Pieces	Note
U1	78L05	1	TO92
U2	ICL7660	1	DIL8
U3	LF356	1	DIL8
U4	ATMega8	1	DIL28
U5	ICL7667	1	DIL8
Q1	IRF9630 ali MPT2P50E	1	TO220
D1	Diode BY399	1	
D2	PKE6KE400CA	1	Can use also P6KE6.8VCA
D3	P6KE5VCA DVOSMERNA	1	
D4	1N4930 Shottky diode	1	
L1	Choke 100uH	1	See text*
C1	10000uF/25V	1	
C2,C3	100uF/25V	2	
C6,C7	47uF/25V	2	
C9	4,7pF	1	SMD 1206
C10,11	22pF	2	SMD 1206
C4,C5,C8,C12,C13	100nF	5	SMD 1206
PT1	potentiometer 22k	1	
PT2	trimmer pot. 10k	1	
R13	1k	1	SMD 1206
R7	2k2	1	SMD 1206
R16,R17,R18,R19	4k7	4	SMD 1206
R10,R11,R12,R14	10k	5	SMD 1206
R3	39 Ohms	1	SMD 1206
R4,R5	47k	2	SMD 1206
R9,R15	100 Ohms	2	SMD 1206
R6	560K	1	SMD 1206
R2	1K /0.5W	1	at least 0.5W
R1	2K /0.5W	1	at least 0.5W
R8	33k	1	SMD 1206
X1	Crystal 16MHz	1	
VR1	2 pole terminal for PCB	1	
VR2	2 pole terminal for PCB	1	
J2	Header 5 pin	1	
ZV	Piezzo speaker	1	
S	Turn ON/OFF switch	1	
LCD	LCD 2X16	1	
Heat sink for Q1		1	
Socket	DIL28	1	
Socket	DIL8	3	
PVC Enclosure	Use at your selection	1	
Button	Use at your selection	1	
Button switch	Use at your selection	4	