Universal Low Cost Electronic Edge Finder for use in a Machine Shop, v4.2

By R. G. Sparber

Copyleft protects this document.[1]

Background

Using the flow of electrical current to establish a reference surface is nothing new in machining. But all of the existing commercial instruments require either a special probe or a special touchdown surface. They also tend to cost more than I am willing to pay.

Overview

The **E**lectronic **E**dge **F**inder (EEF) presented here works with any metal cutter if you want to set a Z reference on a mill. To set X or Y it is best[2] to change to a polished metal rod of known diameter.

You just drop the magnetic clip on the spindle and feed until you see a large drop in the displayed number. For example, you might see 3.80 before touchdown and 0.04 at touchdown.
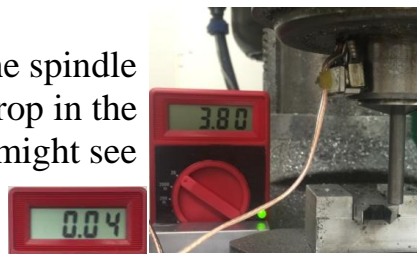
On my Z axis, a change of 0.0001 inches is easily detected.

Attaching the magnetic clip powers up the EEF. Removing the clip turns power off.

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[1] You are free to distribute this article but not to change it.
[2] It can be done with a cutter but getting the flutes to line up right is tricky.

The cost of the electronic components is under $3 plus shipping and tax. The meter is commonly on sale for $6 but is sometimes a loss leader and given away at no additional cost when you buy something else from Harbor Freight.

How accurate is the EEF? Touchdown is detected when the circuit sees a change from no current to current flow. The voltage applied across the contacts is less than 1 volt. This is not enough voltage to cause arcing. At some distance far smaller than useful in machining, there will be a gap and therefore no current flowing. When this gap goes to zero, current flows. So talking about the accuracy of just the EEF doesn't make sense. What defines overall accuracy is how precisely the position indication instrument tracks actual movement. If a Digital Read Out (DRO) tied to an axis tells me position to ±0.001 inches, then that is the accuracy by which I can set touchdown. If the DRO is only good to ±0.01 inches, then that is the accuracy. On my RF-30 mill/drill, my overall accuracy of setting touchdown is better than ±0.0001 inches. However, other factors associated with machining make it pointless to be more accurate than ±0.001 inches.
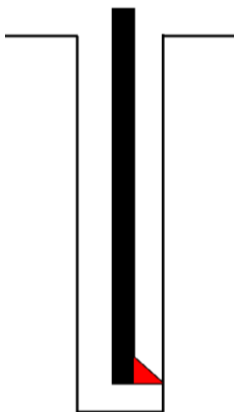
See these YouTube videos for how the EEF can be used on a mill:

https://www.youtube.com/watch?v=od8k3BBB3-E&feature=youtu.be

and

https://www.youtube.com/watch?v=6ZYyS9jCD2o

This EEF will also work on a lathe. Here is a video of a previous design. The procedure is the same as with my newest design:

https://www.youtube.com/watch?v=r4CLX7tR8Vk

One particularly interesting application involves touching down with a boring bar at the bottom of a deep hole. You do not have to see touchdown for the EEF to detect it.
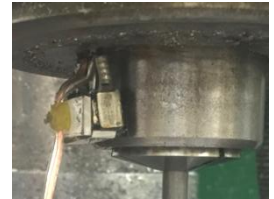
Contents

Operation

Initial Setup

The EEF has two connections to the machine. One is via a lug that is bolted to any part of the machine except the spindle. On my mill, it is clamped to the apron. On my lathe it connects to one of the legs.

The other connection is via a magnetic clip that contains two wires.

When this clip is not touching a conductive surface, the EEF is off. The display on the meter is blank and the power indicatior is dark.

One time only, connect the magnetic clip to the table of the mill or ways of the lathe. Select the meter scale that displays a number rather than "1 " which means overload. Remember this number which may be positive or negative. It is your *minimum reading*.

If turned full counterclockwise, the dial can be set to an invalid setting. This will not cause damage but will display a 1 with 3 blanks to the right.

Normal Use

1. Be sure the spindle, all contact surfaces, and the magnetic clip are free of swarf.

2. Place the clip onto the spindle being sure both conductive pads make contact.

   a. If the display reads the *minimum reading*, the spindle needs to be hand rotated a few degrees until the display reads a much larger number or "1 " (overload).

   b. If the green power LED does not come on, either the battery is dead or one of the pads is not making contact. Reposition the magnetic clip.

   c. If the display reads close to the minimum reading, one of the pads on the magnetic clip is not making contact. Reposition the magnetic clip.

*The display should have a number substantially larger than the **minimum reading** or read overload.*

3. Move along the desired axis towards the reference surface. At touchdown, the display will jump down to near the *minimum reading*.

4. Remove the magnetic clip from the spindle[3].

Low Battery Indications

If the meter shows low battery and the green LED is dim, replace the circuit's battery.

If the green LED is bright but the meter's low battery icon is displayed, replace the meter's battery.

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[3] I store my magnetic clip on my sheet metal belt guard. A piece of tape insulates the clip from the metal.

What is going on?
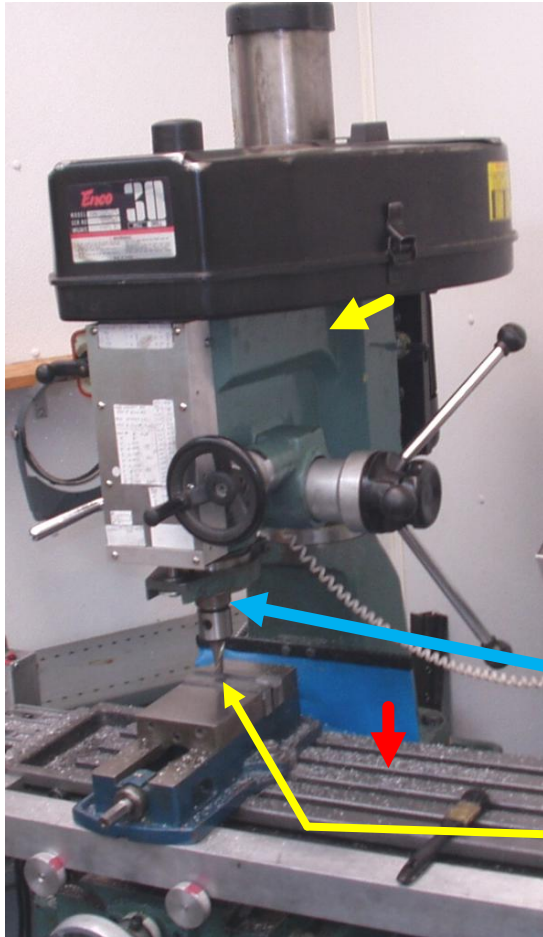
A typical milling machine is made from massive pieces of metal. The pieces are either bolted together or permitted to slide along limited paths at low speeds. This arrangement causes the electrical resistance between these pieces to be a few thousandths of an ohms.

My milling machine consists of a table (red arrow) that can slide left and right plus forward and backward. It also has a head (yellow arrow) that can be raised/lowered but is clamped in place during machining.

Inside the head is the spindle. It rotates at a high speed and is supported by bearings. These bearings have a much larger *electrical* resistance than the rest of the machine.

Cutting tools are typically mounted to the spindle.
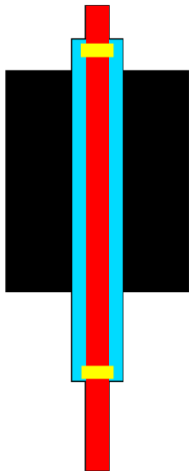
Here is a simplified X-ray view of the head (black), quill (blue), spindle (red), and spindle bearings (yellow). While the spindle is turning, it rides inside the quill which is able to slides up and down. A cutter attached to the end of the quill will spin and can also be driven down in order to cut.

The quill slides inside the head on a large bearing surface. They are in intimate contact so the electrical resistance between quill and head is very small. On my machine it is about 0.01 ohms.

Taken all together, the electrical resistance from table to quill is very close to zero ohms.

The spindle bearings (yellow) are coated with lubricant. The electrical resistance measured between quill (blue) and spindle (red) can vary between a few milliohms and, on my mill, about 2 ohms. When nothing is moving, the resistance will be fairly constant. A small twist of the spindle can swing the resistance between these extremes.

Here I have secured an end mill to the bottom of the spindle. Below it is a piece of metal to be machined that is secured to the table. The electrical resistance between this piece of metal and the table is near zero ohms.

As I feed the quill and therefore the spindle down, the end of the end mill will eventually contact the piece of metal. Making contact is called "touchdown". At the instant of touchdown, the spindle electrically shorts out to the metal. By zeroing the measuring device that indicates quill movement, we have precisely defined the surface of the piece of metal as a height of zero.

There will be a position where the end of the end mill is, say, a millionth of an inch above the surface of the table[4]. The electrical resistance measured between end mill and the piece of metal is essentially equal to the electrical resistance across the spindle bearings[5].

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[4] This assumes that the only motion is the quill moving down. On my CNC converted RF-30 mill I can increment 0.0001 inches and easily see the touchdown event.
[5] The test voltage is far too small to cause arcing even at this distance. Search for "Paschen's law".

Upon moving that last millionth of an inch, we short out the spindle resistance. The resistance between end mill and that piece of metal went from some relatively large number down to less than 0.1 ohms.
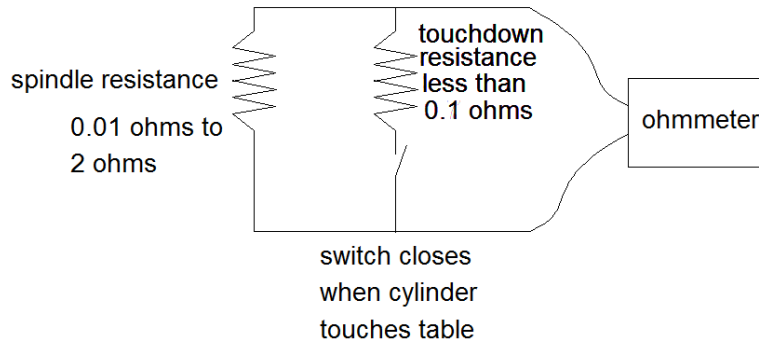
Viewed as an electrical circuit, we have a spindle resistance shunted by the touchdown resistance which is in series with a switch. One switch contact is the end of the end mill and the other contact is the surface of the piece of metal.

We cannot detect touchdown with the ohmmeter if the spindle resistance is too small. Fortunately, a slight twist of the spindle will cause this resistance to jump from near 0 up to a large number. Then it is easy to see the sudden drop in total resistance at touchdown.

You could buy a commercially[6] made milliohm meter to detect touchdown but be prepared to spent well over $100. We really do not need to know the exact resistance, just the change in value. This greatly simplifies the problem. So instead of a milliohm meter, we just need an Electronic Edge Finder!

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[6] A low cost option does exist but you will have to built it yourself: http://rick.sparber.org/electronics/ramp.pdf

The Electonic Edge Finder Electronics

My EEF is based on a low cost Harbor Freight Multimeter. Sometimes they are given away as a loss-leader. Otherwise, expect to pay around $6 when it is on sale.
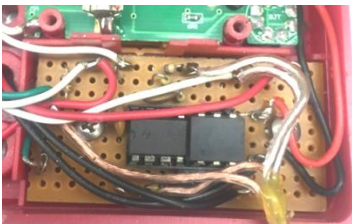
The circuit that feeds the meter is small enough to fit inside the meter's case. It occupies the space previously filled by the battery. The components cost under $3 plus S/H at Mouser's.
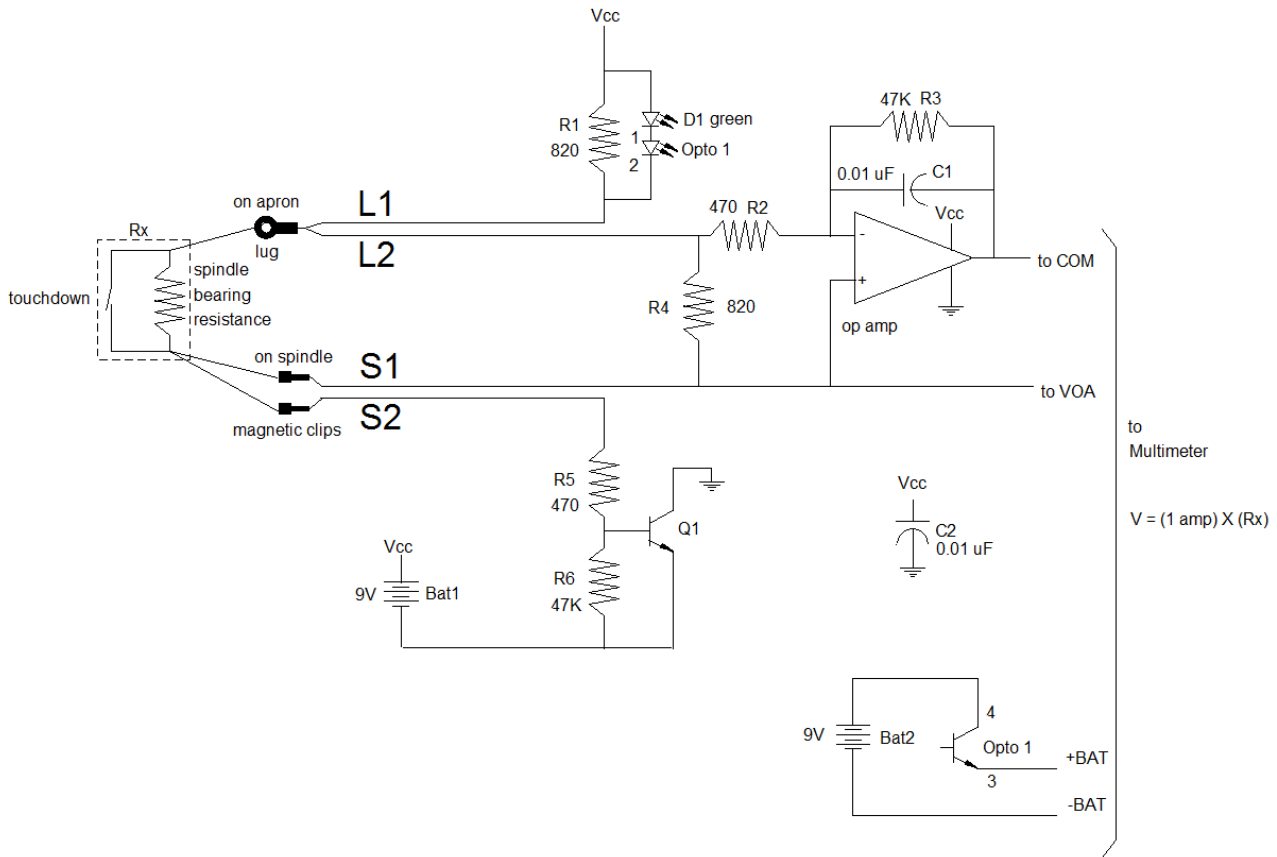
Using a black permanent marker, I blocked out all text and symbols except the three voltage options.

I mounted both the meter and circuit batteries outside of the case. More on the battery enclosure later.

The General Circuit

Vcc

R1 820 — D1 green — Opto 1 — 1, 2

on apron — L1

Rx — lug — L2

touchdown — spindle bearing resistance

on spindle — S1

magnetic clips — S2

470 R2

R4 820

47K R3

0.01 uF C1

Vcc

op amp

to COM

to VOA

to Multimeter

V = (1 amp) X (Rx)

R5 470

Q1

R6 47K

9V Bat1

Vcc

C2 0.01 uF

9V Bat2

Opto 1 — 4, 3

+BAT

-BAT

Part	Value	Mouser[7] part number	Price, $
R1, R4	820Ω	MOS1/2CT52R821J	0.20
R2, R5, R7	470 Ω	660-MF1/4LCT52R471J	0.30
R3, R6	47K	71-CCF0747K0JKE36	0.20
C1, C2	0.01 μF	581-SR155C103KAATR1	0.20
D1	Green LED	696-SLX-LX5093GD	0.07
Q1	2N3904	821-BC550B-A1	0.13
dual op amp	LM358	512-LM358AN	0.42
Opto 1	LTV-817	859-LTV-817	0.18
	(2) battery clips	123-5118-GR	0.88

R7 is not shown in this schematic. I am using the op amp in an unconventional way. It lets me get the lowest possible reading on the display when at touchdown. For now, I show only one op amp with no pin numbers. Details later.

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[7] http://www.mouser.com/

Just about any op amp can be used here although low input offset voltage is important. The opto is assumed to have a minimum current transfer ratio of 0.20 so just about any one will do. Avoid Darlington output optos as they will cause the meter's low battery indicator to come on prematurely.

All resistors are at least 0.1 watt with a tolerance of ±5%. Capacitors are low voltage bypass. Total without tax as of June 2016 is $2.58 + $4.99 S/H.

No parts are critical. You can substitute for the capacitors, LED, NPN transistor, and opto. Do verify that the op amp input offset voltage is less than 7 mV.

The specified opto is in a 4 pin package. I have a bunch on order but they have not come in yet. So I resorted to an old 6 pin packaged device.

The battery clip that comes inside the meter is marginal. I cut it off and used a better quality one. A second battery clip is used for the circuit.

You can access a shopping cart with the parts in it via:

http://www.mouser.com/ProjectManager/ProjectDetail.aspx?AccessID=f69b21d660

Op Amp Evaluation

Before we can select which EEF circuit to use, the two op amps inside the LM358 must be measured for *input offset voltage*.
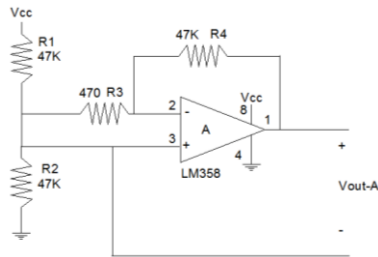
Temporarily build this circuit which will let you measure this voltage for op amp "A". You can just tack solder the resistors to the pins of the IC socket. If you have more than one LM358, run them all through this test and record their values.
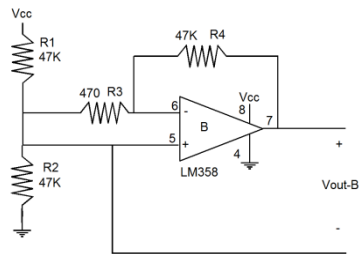
Then build this circuit for op amp "B" and repeat the test.

See the detailed circuit description for what I found.

For each dual op amp, look at V_{out-A}, V_{out-B}, V_{out-A} minus V_{out-B}, and V_{out-A} plus V_{out-B}. Ignoring the sign of each number, select the one that is smallest.

For details on why this works, see the detailed circuit description.

Specific Circuits

Based on your testing of one or more dual op amps, you will have identified the configuration with the smallest total offset.

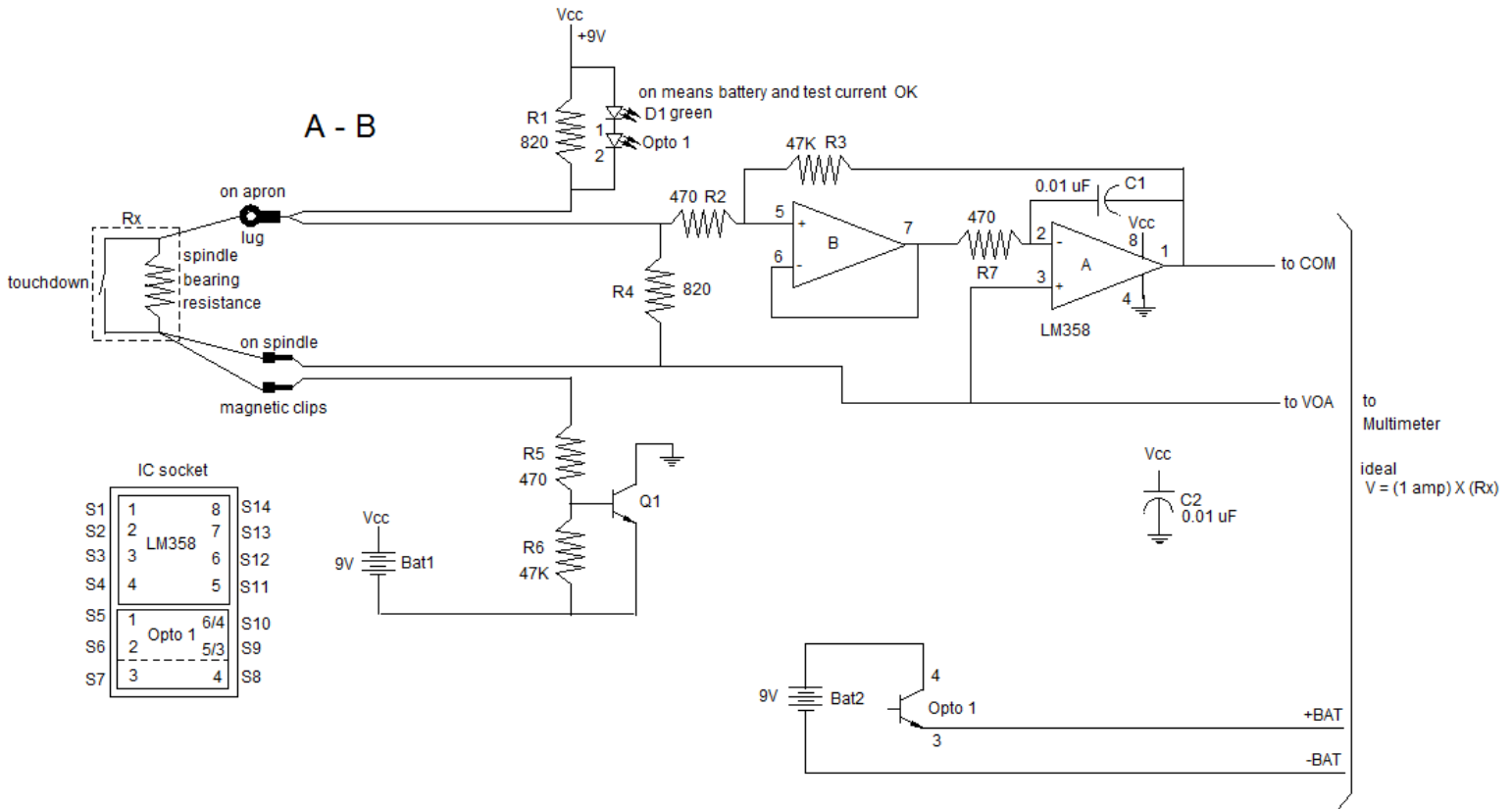If V_{out-A} has the smallest magnitude, the circuit is
Optionally, you can use a 14 pin IC socket to hold both the LM358 dual op amp and the opto coupler. The opto called out in the parts list has 4 pins but the one I used in my prototype uses 6 pins. Both options are shown here.
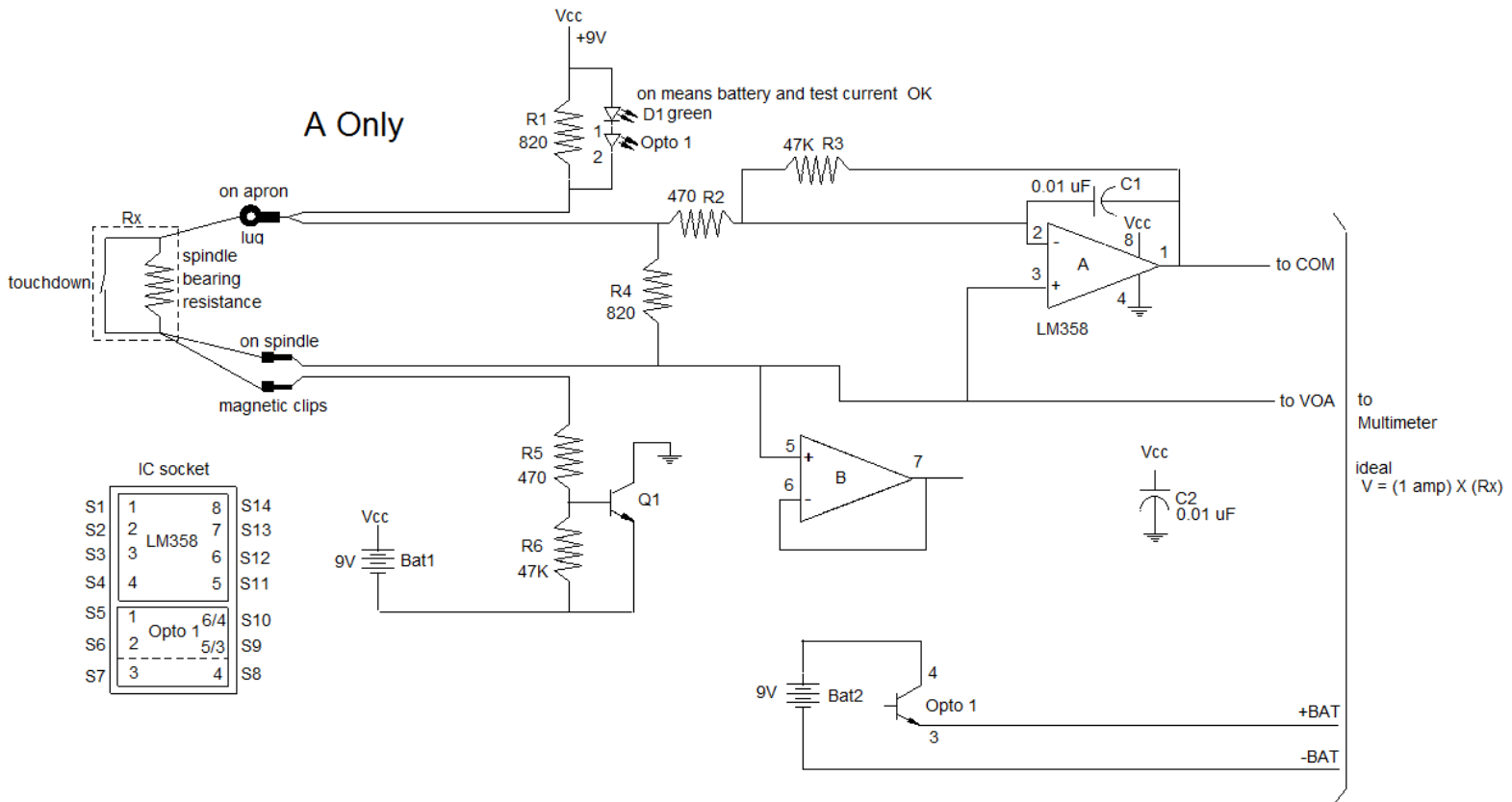
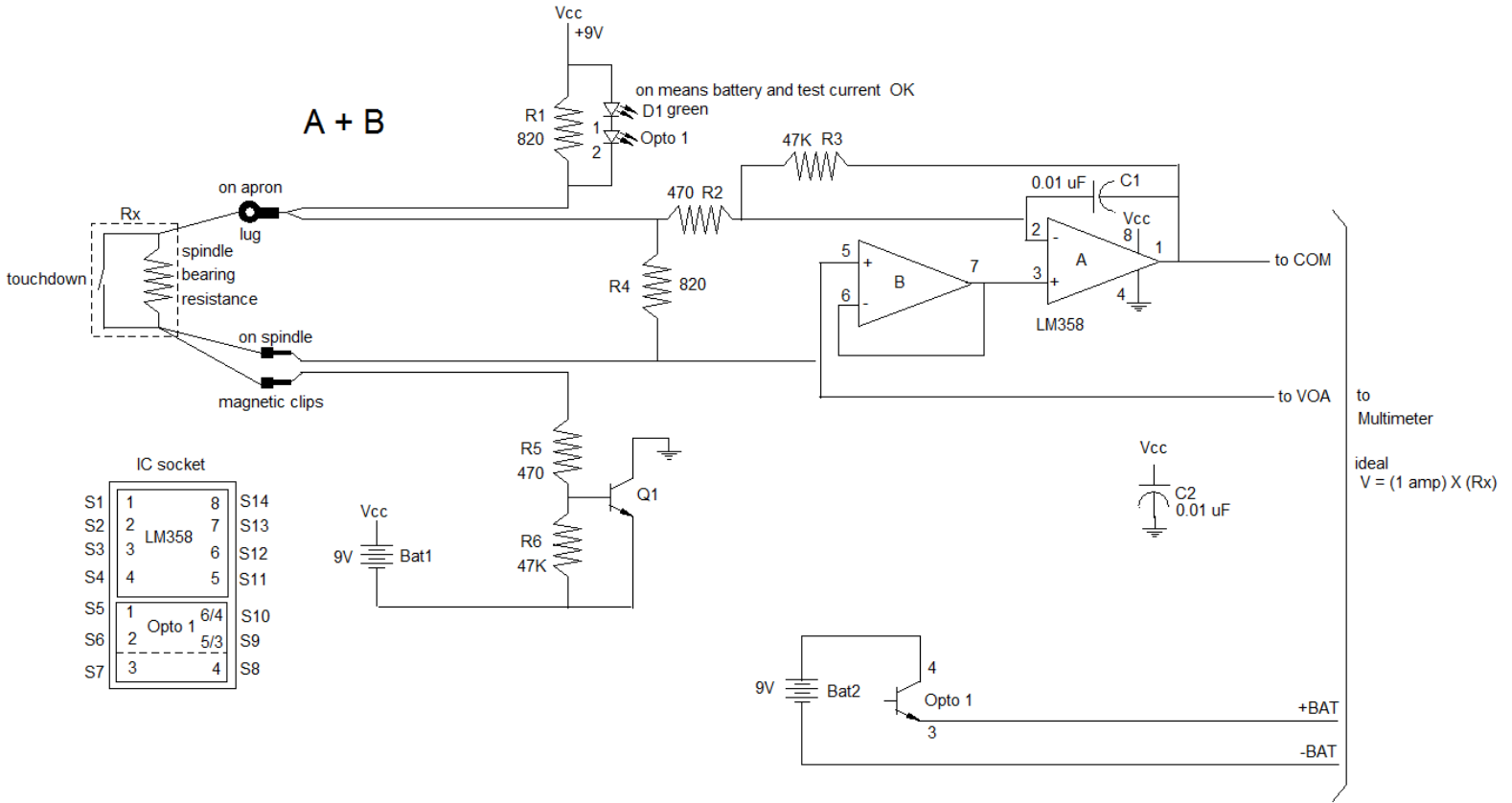If V_{out-B} has the smallest magnitude, the circuit is

B Only
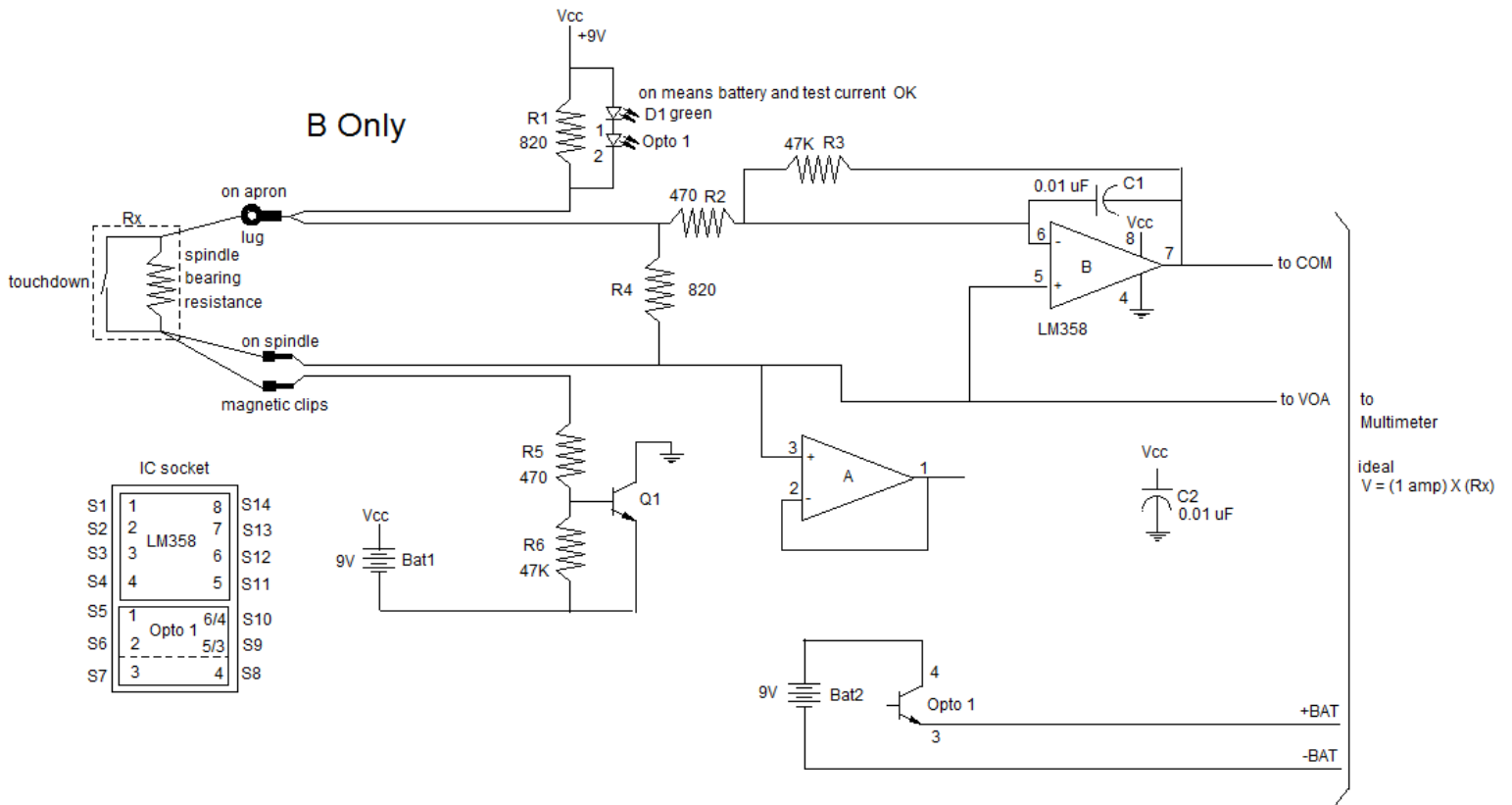
If the difference between V_{out-A} and V_{out-B} has the smallest magnitude, the circuit is

Note that this circuit uses one more resistor, R7.

If the sum of $V_{out\text{-}A}$ and $V_{out\text{-}B}$ has the smallest magnitude, the circuit is

A + B

Vcc
+9V

on means battery and test current OK
D1 green
Opto 1

R1
820

1
2

on apron
lug

470 R2

47K R3

0.01 uF   C1

Vcc
8

2 −
A
1

to COM

Rx

touchdown

spindle
bearing
resistance

on spindle

magnetic clips

R4   820

5 +
B
7

6 −

3 +
4

LM358

to VOA

to
Multimeter

ideal
V = (1 amp) X (Rx)

IC socket

S1	1		8	S14
S2	2	LM358	7	S13
S3	3		6	S12
S4	4		5	S11

R5
470

Q1

Vcc

9V   Bat1

R6
47K

Vcc

C2
0.01 uF

S5	1	Opto 1	6/4	S10
S6	2		5/3	S9
S7	3		4	S8

9V   Bat2

4

Opto 1

3

+BAT

−BAT

Magnetic Clip

The two wires from the EEF must come in contact with the spindle. I have found that this is most easily done with magnets although many other good options exist. The key is that you don't leave the clip on the spindle when you start it spinning. I did that just once and the results were not pleasant.

My version of the magnetic clip uses two ¼" x ¼" x ¼" neodymium magnets, two spade clips, and a few squirts of heat glue. Bits of plastic hold the clips together.

The first step was to open out the spade clip and form a ¼" x ¼" channel.

Hindsight: remove the plastic sleeve and solder the wires to the clips now. Doing it later causes the heat glue to loosen.

Heat glue was applied inside the lug and on the surface of the magnet. I will later reflow this glue with my hot air heat gun.

After making two of these subassemblies, I heat glued them to strips of plastic. The plastic on two sides gives the assembly strength while insulating the parts.

With small clamps holding the subassemblies to the plastic, I played my heat gun over the assembly to reflow the glue. Let it fully cool before removing the clamps. This magnetic clip is part of a Kelvin Connection (see detailed circuit description). As such, the two conductors only need to make contact with the spindle. It is not necessary for them to make a very tight, low resistance, connection. The two magnets inside of the two clips insure that both contacts will be made as long as they are on the spindle. If one of these clips does not make a connection, the circuit and/or meter will indicate the fault.

Battery Enclosure

The battery enclosure is made from 1/8" X 1" X 2" aluminum channel. The top and bottom were cut on my bandsaw and then trimmed to fit on my belt sander.

The 1/8" thick walls may sound like overkill but it let me tap 4-40 holes and avoid using a bunch of nuts.

Note that the position of the enclosure limits the range select switch to the three valid settings (20, 2000 m, and 200 m). If turned full counterclockwise, it can be set to an invalid setting. This will not damage anything but will display a 1 with 3 blanks to the right.

I measured the inside of the channel at the top of the U with a piece of paper. Then I cut a length of the channel to this dimension. Using my belt sander to form the taper, I fit the cut piece into the channel stock. When it was a good fit, I marked where to saw off the second piece. No measuring yet plenty good accuracy. After drawing diagonal lines, I located the center of the enclosure. Then I drilled a 4-40 pilot hole through the top and bottom. The bottom hole was tapped and the top hole opened out for clearance. A single 4-40 screw holds the cover in place.

Mounting the battery enclosure on the meter was also done without measuring.

When I placed the enclosure down on the meter, I discovered that the power switch was too tall.
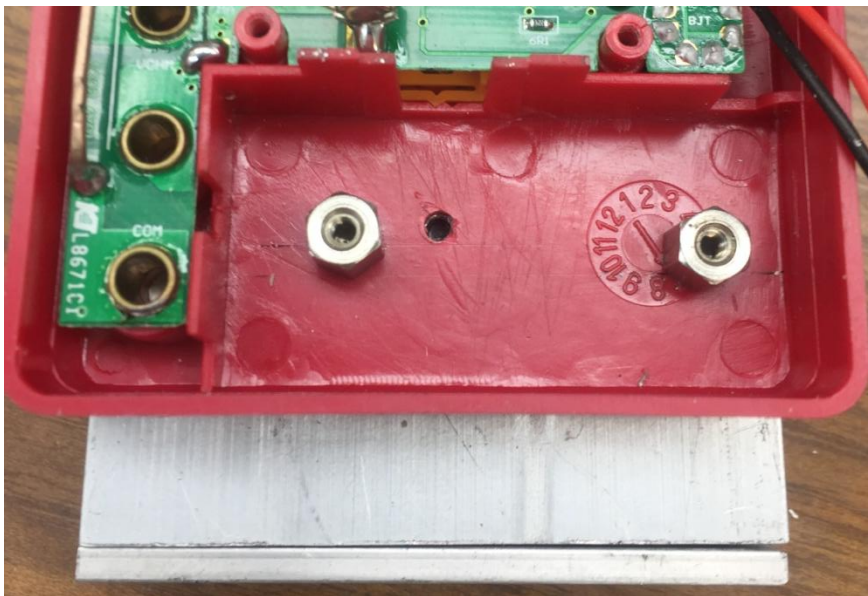

Side cutters took care of that problem. The back of the battery enclosure then sat flat on the face of the meter housing. Be sure to leave the switch in the ON position before covering it up with the battery enclosure.

# Battery Enclosure and Circuit Board Installation

First I drilled 4-40 tap holes along the centerline of the battery compartment about ¼" from each end.

Then the enclosure was positioned where I wanted it and I match drilled with the tap drill. After tapping the holes in the bottom of the battery enclosure, I opened out the plastic to clearance. Then I screwed

in a pair of standoffs. They secure the battery enclosure and also support the circuit board that will go on top.

Ready to build the circuit.
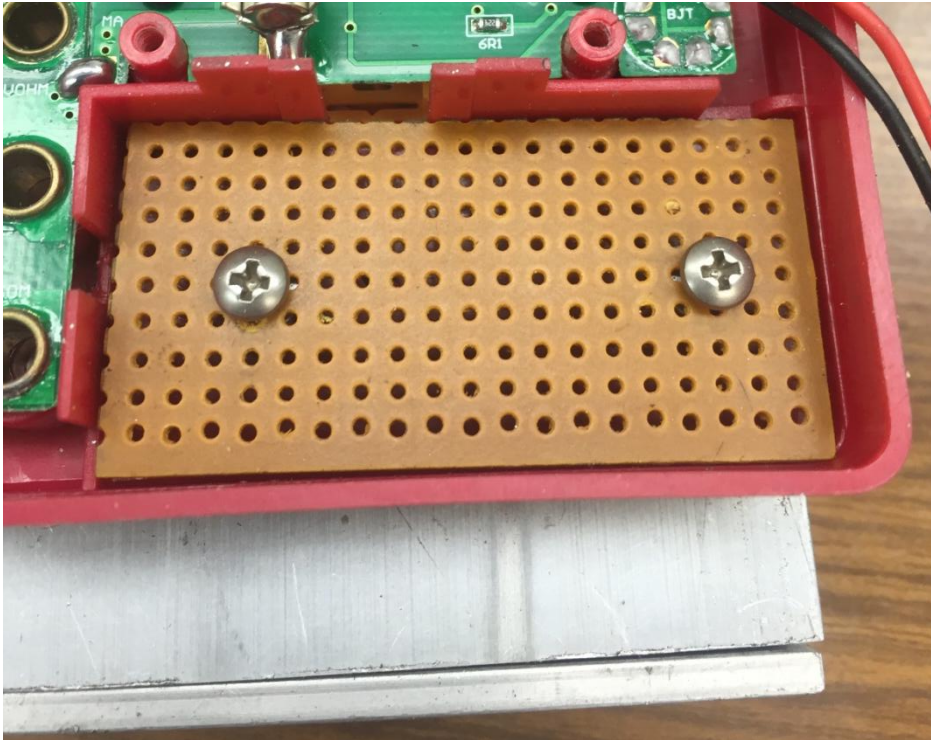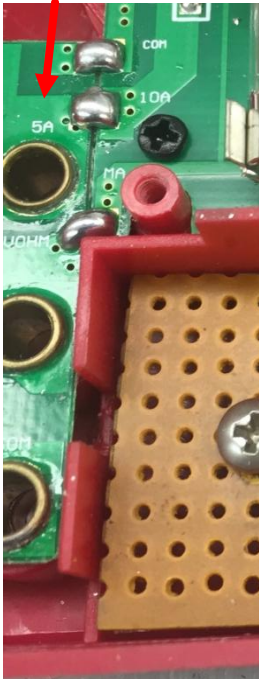
There is a small circuit board (red arrow) to the left of the battery compartment. It supports the probe connectors and the high current shunt resistor. As John Herrmann found out, it is held in place with just solder. Heat the three blobs of solder and it comes right off.

This extra room will come in handy. The center hole is drilled out through the battery enclosure. It carries the battery wires.
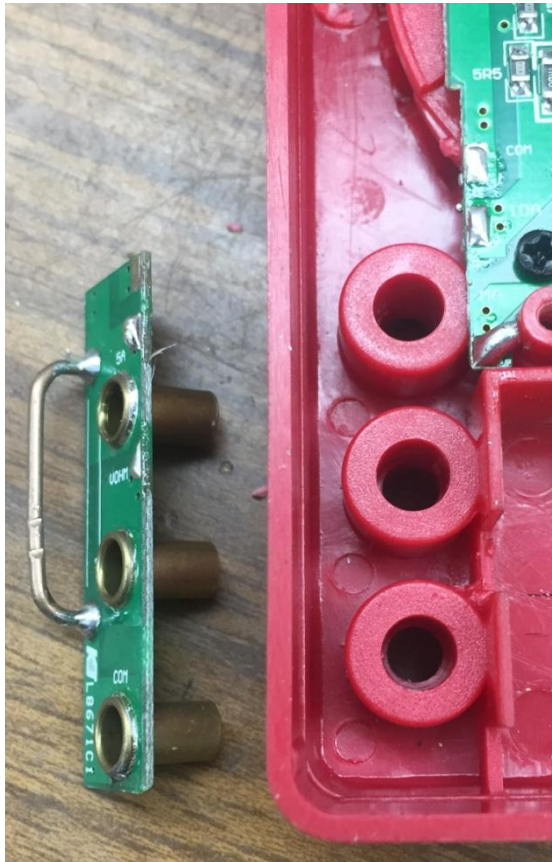
Building the Circuit
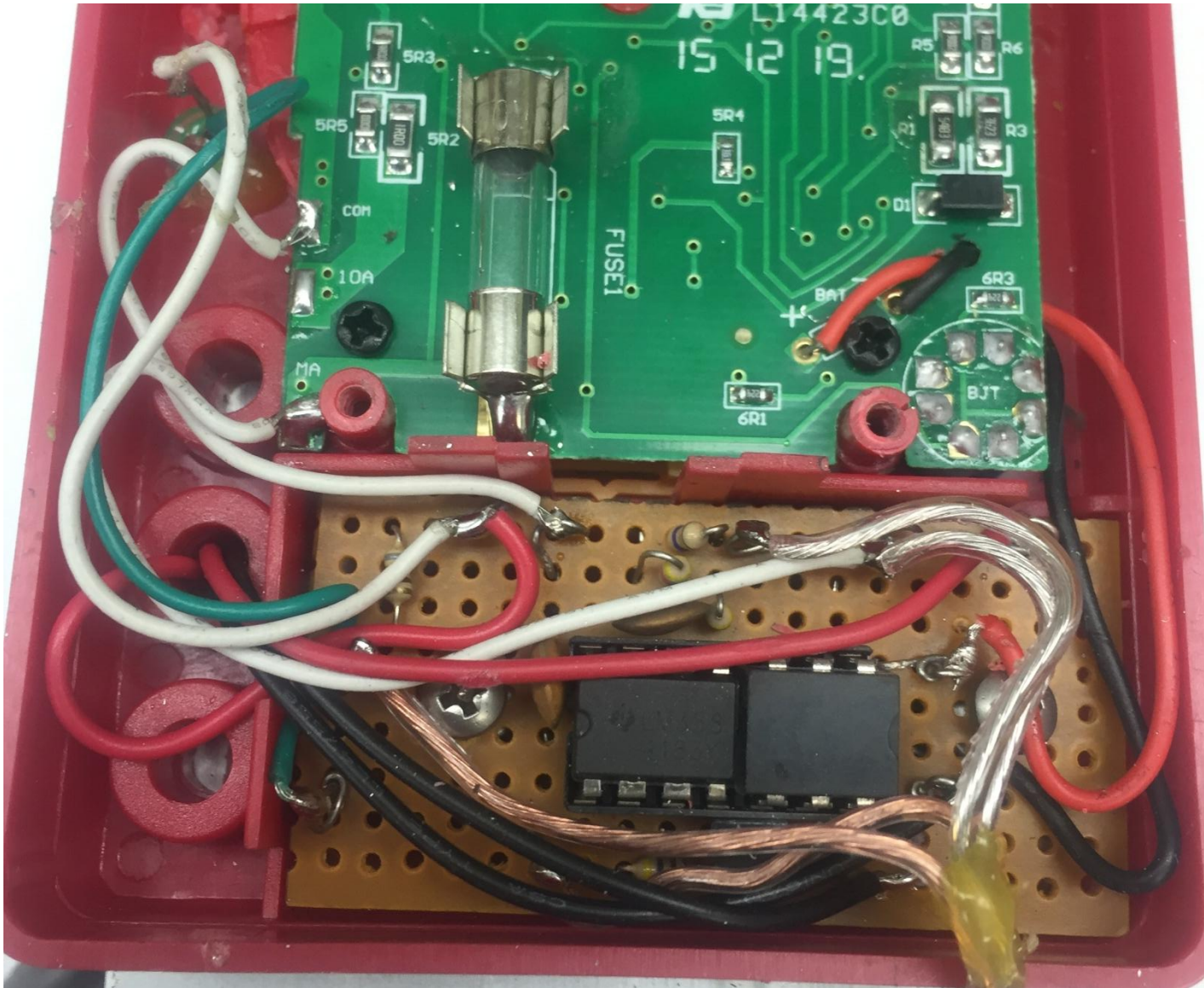
I chose to put the dual op amp IC and the opto coupler in a 14 pin socket. All other components were soldered in using point to point wiring.
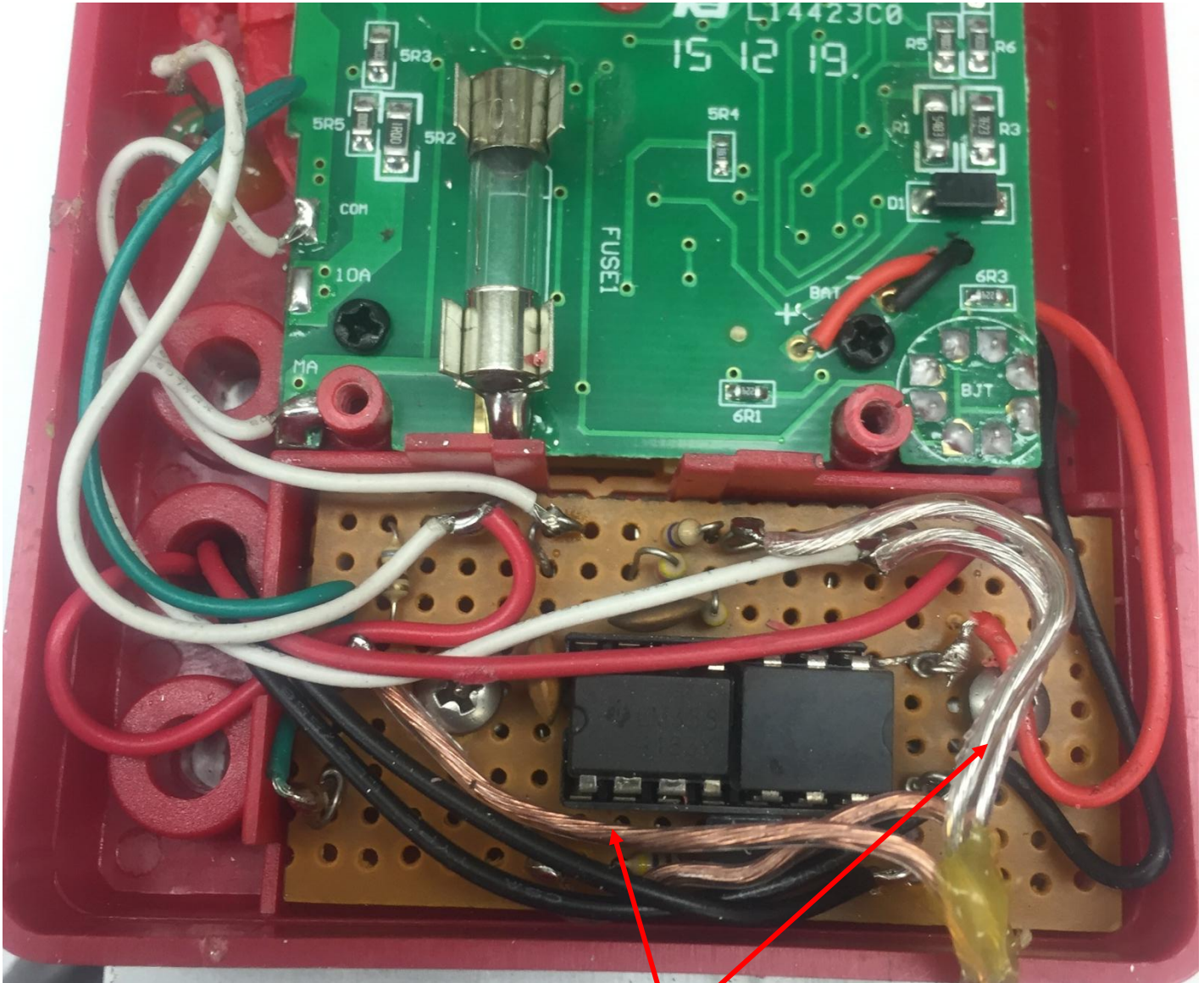

You may have noticed this pictorial on each schematic. It shows where I put the op amps and opto coupler. There is room for either a 4 or 6 pin opto coupler.

I chose to put the green LED just above the battery enclosure. Looking from the inside, it was one of the few places with plenty of room. I dot of heat glue holds it in place.

I used 24 gage speaker wire for the test probes. Here you see them connected to the circuit board. A notch in the back cover provides the exit. A little heat glue was used as strain reliefs.

Circuit Description Overview

Test Current	→	Spindle Resistance (Rx)	→	voltage amplifier	→	volt meter
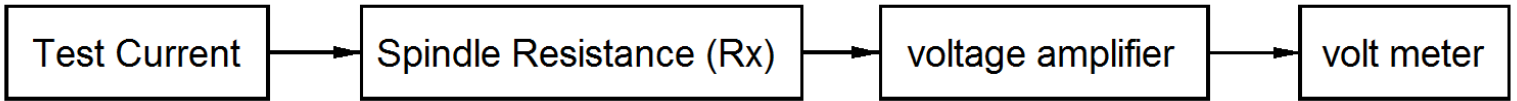
This is just an ohm meter that reads very small resistance changes. A test current is passed through an unknown resistance, R_x, and a voltage is generated. The voltage is amplified and sent on to the volt meter.

We need to measure resistances as small as 0.01 ohms and display the resulting voltage on a meter that can display down to 0.01 volts. Ohms Law says that current equals voltage divided by resistance : $I = \frac{V}{R}$. Given a V equal to 0.01 volts and an resistance of 0.01 ohms, this equation says we need a current of $\frac{0.01\ volts}{0.01\ ohms} = 1\ amp.$. This much current would require a large battery. Furthermore, some people are reluctant to pass 1 amp through their spindle bearings.

Instead, we will use a test current of only 0.01 amps and amplify the resulting voltage by 100. We then have V= (100 × 0.01 amps) × R = (1 amp) × R. Now we have a reasonable current drain on a common 9 volt battery and no risk to the spindle bearings.

It is possible to change the voltmeter to a more sensitive range. How sensitive you can go depends on the voltage read when R_x is zero. This voltage is called output offset. My copy of the circuit shows an output offset of about -6 mV. This means an R_x of zero should give me -6 mV. An R_x of 2 ohms reads approximately 2000 mV. I can see a change in R_x of 0.001 ohms (1 milliohm). So far, I have not found a need to be this sensitive on my mill or lathe.

On the 200 m scale, an R_x of zero also gives me about -6 mV. An R_x of 0.2000 ohms displays around 150.0 mV. I can see a change in R_x of 0.0001 ohms (0.1 milliohms). This might be useful for finding shorts on circuit boards but probably of no use in a machine shop.

The higher the sensitivity of the meter, the more fluctuation you will see. With the meter set to 20, the readings are stable. On the 200 m scale, it only takes a change in voltage across R_x of 1 microvolt to cause the least significant digit to jump. That is an extremely tiny voltage. Consider that the voltage picked up by waving a metal coat hanger overhead is on the order of 5 microvolts.

Detailed Circuit Description
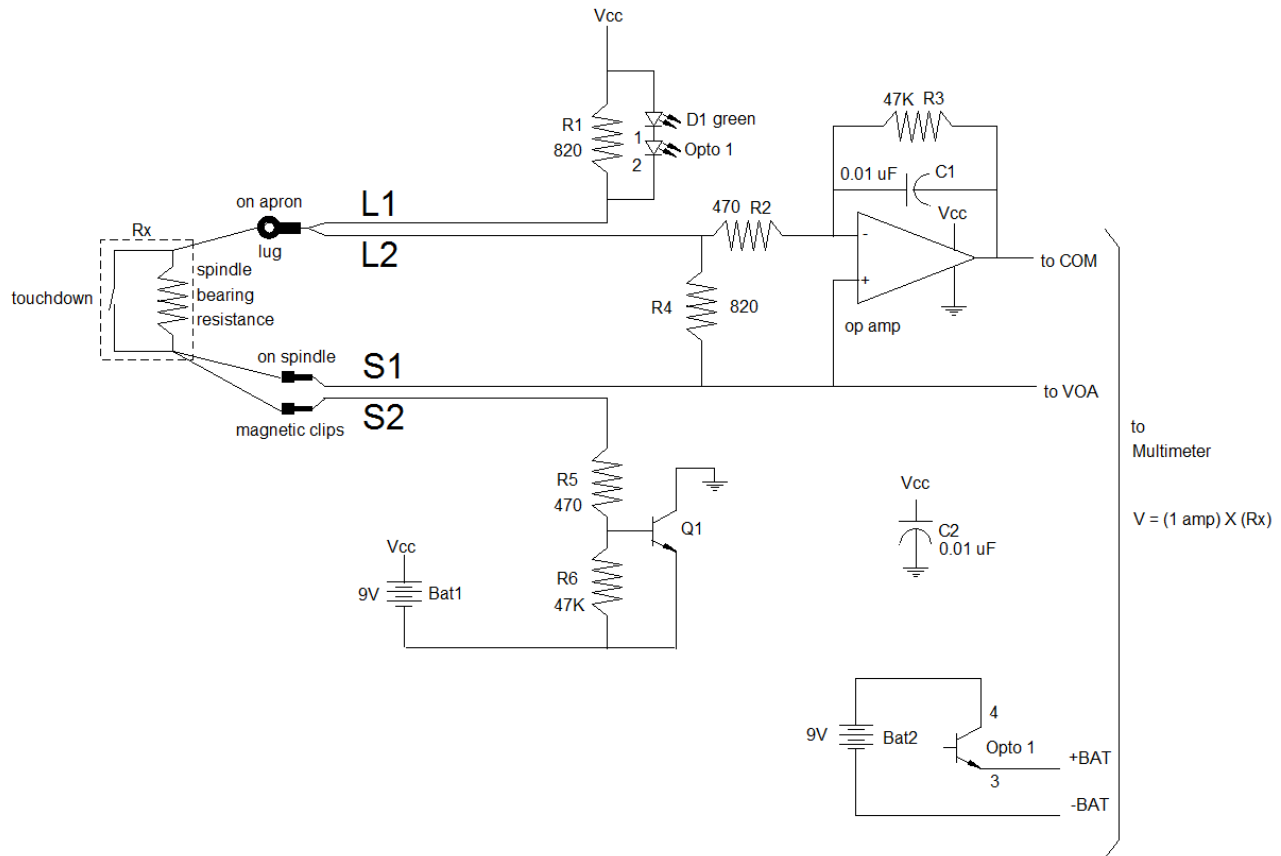
Design Requirements

My design requirements were:

1. use low cost components
2. run on a 9 volt battery
3. detect a change in resistance of 0.01 ohms
4. The starting (pre-touchdown) resistance can be as high as 5 ohms.
5. The maximum touchdown resistance is 0.7 ohms.
6. detect a low battery condition
7. detect when the probes are not connected
8. detect when the spindle's electrical resistance is too small to be used as a starting point
9. operate with any common voltmeter
10. automatic power control when probes attached

Design Considerations

Since I only need to measure changes in spindle resistance, I can tolerate some offset voltage at the output. This means that the multimeter might read, for example, 0.05 when at touchdown. That is fine as long as it reads a much larger number when not at touchdown.

The offset voltage cannot be too much or I run the risk of saturating the op amp. The LM358 can safely swing within 1.5 volts of the positive rail (V_{cc}). With an R_x of zero, I get an input voltage of zero. The output voltage of the op amp is then predominantly a function of "*input offset voltage*". I will later show that input bias and offset currents have a minimal effect. The worst case offset voltage at the output must be more than 1.5 volts below V_{cc}. This means the output cannot be more than 1 volt from the circuit's datum (the node marked S1).

The output voltage can swing down to ground if the output current is small. The plan is to have all output voltages responding to R_x be at or below the datum.

The multimeter has a COM and a VOM input. Note that the output of the op amp goes to COM and the datum is VOA. This flip permits me to generate negative voltages inside the circuit yet have the meter display positive voltages. It is strictly a cosmetic choice. I wanted resistance to show as a positive number.

This circuit must be reliable 100% of the time. One false reading and expensive cutters and/or parts can be ruined.

- To prevent a low battery from causing a missed touchdown, a battery indicator exists within the circuit. Another low battery indicator exists within the meter.
- A poor connection to the spindle either will prevent power up or will display zero on the "20" scale. See page 49 for details.
- On a random basis, the spindle resistance can drop to near the minimum reading. In this state, touchdown does not cause any further drop in resistance. This especially nasty situation is detected by the user looking at the meter's display. They simply give the spindle a little twist and the resistance will go back to a large enough value.

I did spend a lot of time trying to get the circuit and the multimeter to share the same battery. The results were poor so I abandoned that effort. Having separate batteries does let me be totally independent of the unknown inner workings of the meter.

I have never liked having to take the back off of the Harbor Freight Multimeter in order to change the battery. With the battery placed outside of the meter, there was plenty of room for the circuit.

Test Current and Battery Monitors
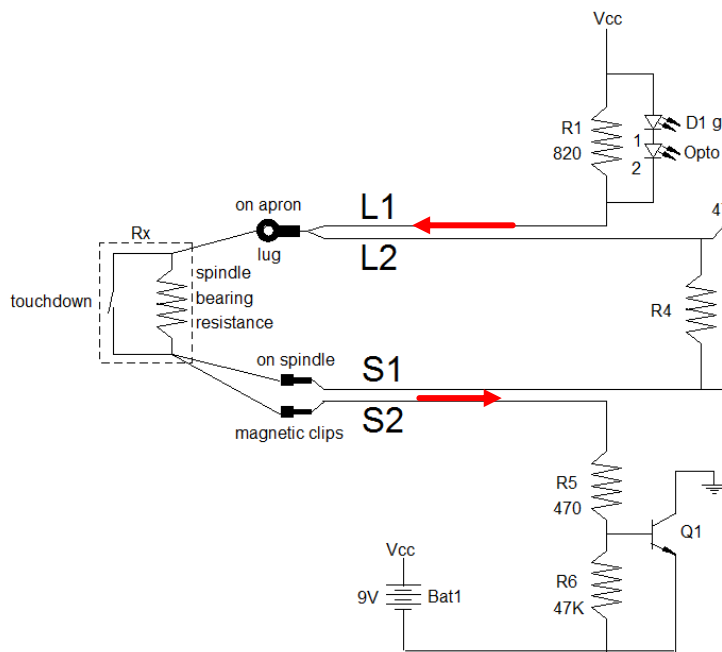
The test current is a function of battery voltage. This is not a problem because we only care about changes in R_x. All that matters is that the current is high enough for us to see a change of 0.01 ohms.

We typically drop 2 volts across the green LED and 1.2 volts across the opto's LED at full battery. This forces about 3.2 volts across R1. Point "L1" is then at 9 - 3.2 = 5.8 volts above the negative terminal of Bat1. The voltage across R_x is tiny so can be ignored.

We are left with the voltage across R5 equal to about 5.8 - V_{BE1} = 5.8 - 0.7 = 5.1 volts. This means S2 is passing $\frac{5.1\ volts}{470\ \Omega} = 10.9\ mA$ at full battery.

The current through R1 is constant at about $\frac{3.2\ volts}{820\ \Omega} = 3.9\ mA$ as long as the current flowing through R5 is at least 3.9 mA.

At full battery, about 10.9 - 3.9 = 7 mA flows through the green LED and opto's input. When the current through R5 drops to around 3.9 mA, the voltage drop across R1 is less than the threshold voltage of the green LED and opto's input so they are dark. The green LED will start to dim before this level and the opto's output will start to drop more voltage which will trigger a low battery indication on the meter.

The 3.9 mA limit occurs at a voltage drop across R5 of 3.9 mA × R5 = 3.9 mA × 470 = 1.8 volts. Add to this a V_{BE1} of 0.7 volts and S2 is 1.8 + 0.7 = 2.5 volts above the negative terminal of Bat1. Add to this the voltage drop across the green LED and opto's input and we get 2.5 + 3.2 = 5.7 volts. This is the battery voltage when the LED and opto are completely dark. The op amp runs fine on this voltage and is able to swing from 2.5 volts down to near 0 so still processes the signal correctly.

Therefore, while the battery good indicator is on, the op amp is guaranteed to be fine (Requirement 4).
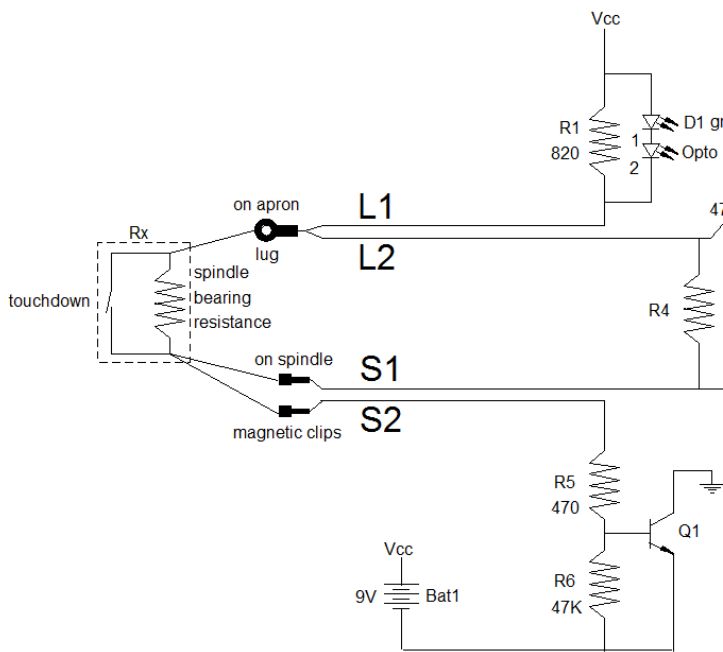
As a sample of one, I swept the circuit's battery voltage from 9 volts down to 4 volts. At about 5 volts the LED was dark. That compares well with the estimate of 5.7 volts.

With the green LED dim, the meter's low battery icon came on. When I swept the meter's battery voltage over the same range, I found that the low battery icon came on at 6.5 volts.

Therefore, if you see a dim green LED and the meter's low battery icon on, replace the circuit's battery. If the green LED is bright but the meter's low battery icon is on, replace the meter's battery.

Auto Power Control
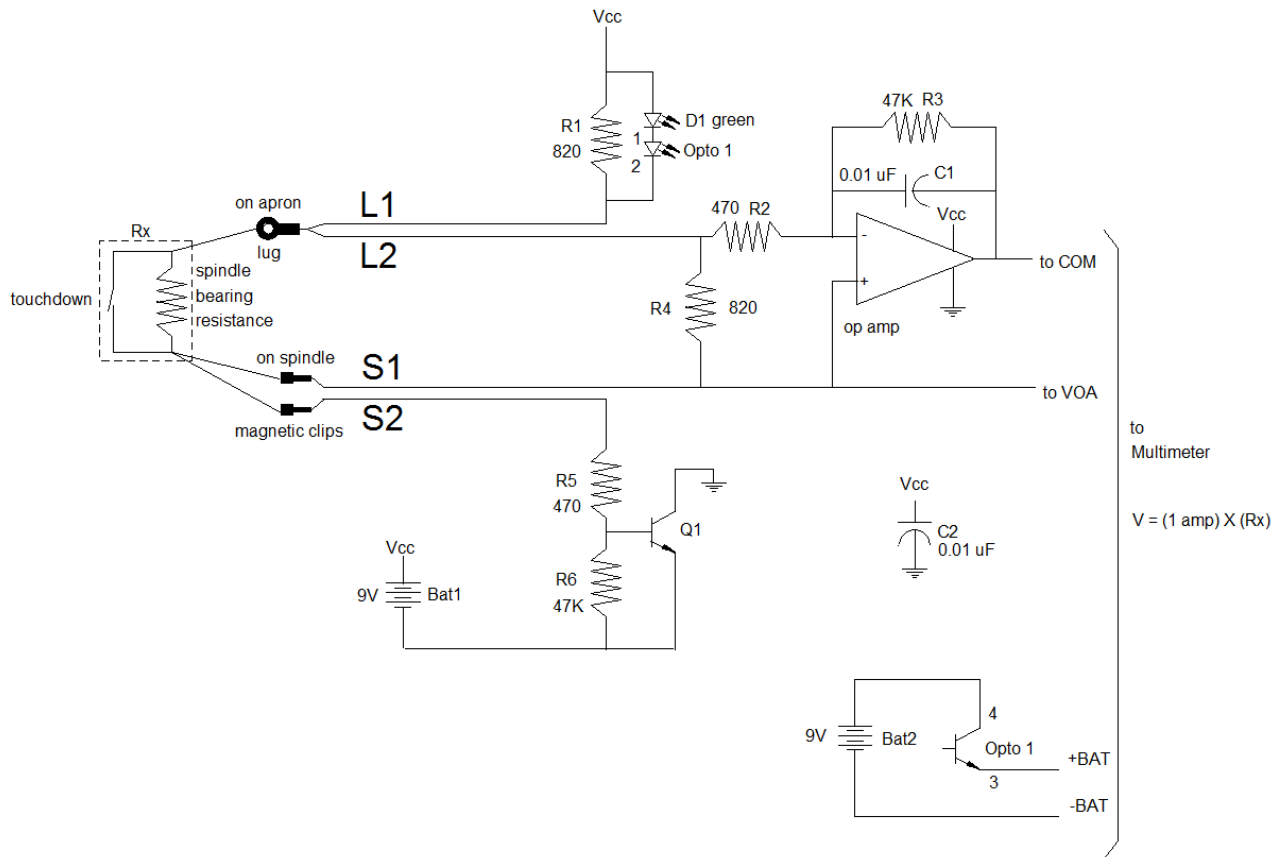
During power down, no current flows through S2. The NPN transistor is off and the negative terminal of battery Bat1 is not connected to ground. No current flows.

When S2 is properly placed on the spindle, current passes out of L1 and into S2. This saturates Q1 and connects the negative terminal of Bat1 to ground. R6 prevents noise currents from partially turning on Q1 and wasting battery power.

Note that this arrangement prevents a poor connection at S2 from causing a missed touchdown.

In a previous design, I had S1/S2 swapped with L1/L2 as shown here.
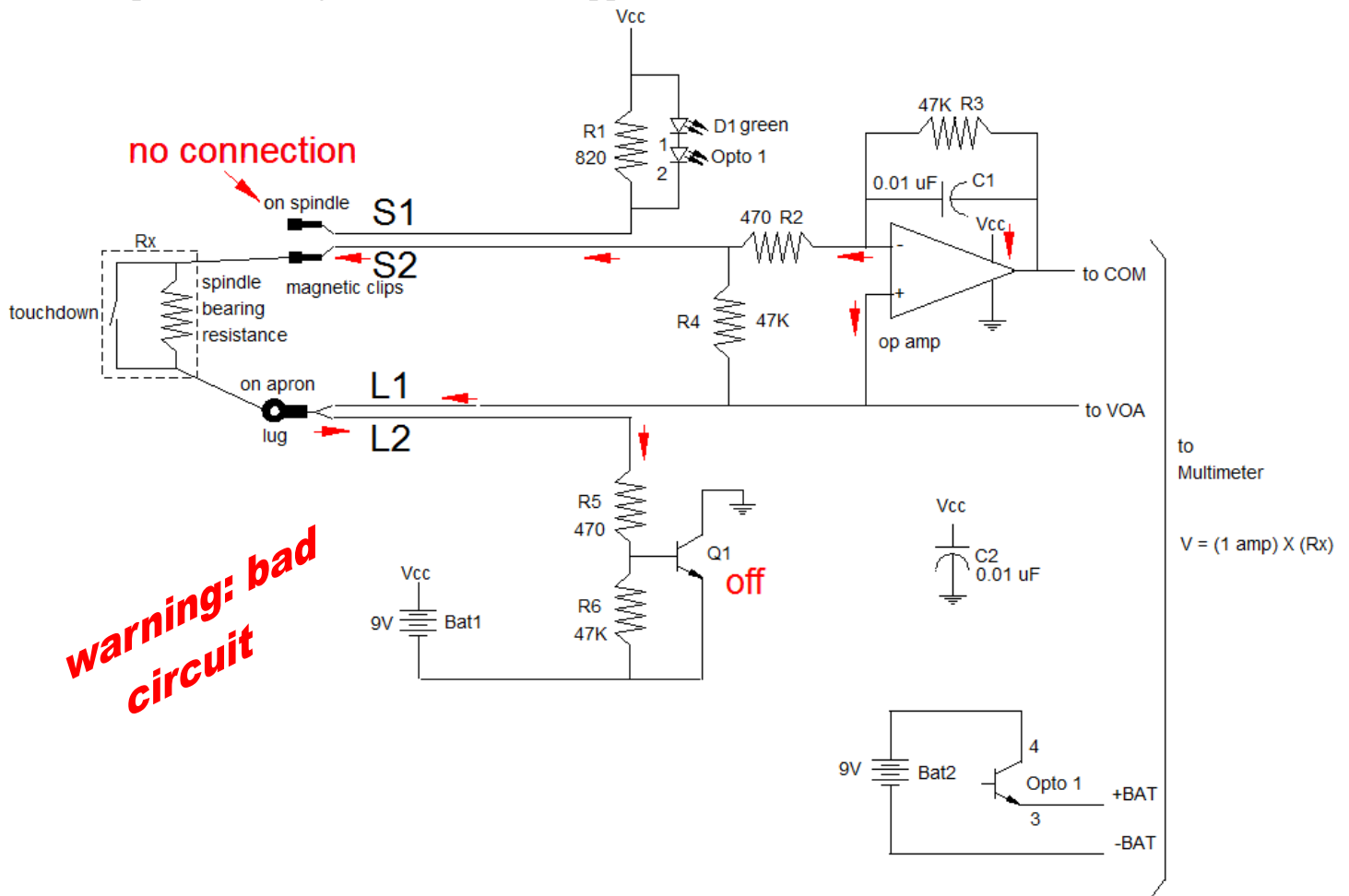
Occasionally I would momentarily start with no connection on S1 while S2 made contact. Current would then flow from Vcc, into the op amp's positive power terminal, out the inverting and non-inverting inputs, and into S2 and L1. It would then flow into L2. This current was not enough to turn on Q1 so no ground was connected to the negative power terminal of the op amp. I was left with my op amp inputs more negative than the negative power terminal. That is a violation of the op amp specifications. Typically this causes "latch up" the op amp.

During latch up, transistors inside of the op amp connect to parasitic junctions within the substrate to form unintended circuits. Typically these circuits have positive feedback so hang up in an odd state. If S1 then made contact, the latched up state would remain although Q1 would saturate, the green LED would come on, and the meter would power up. The only way out is to remove all power and apply it without violating the specifications: S1 first followed by S2. Swapping the lug and magnetic clip avoids this problem.

The Kelvin Connection

The circuit connects to R_x using a Kelvin Connection which involves 4 terminals[8].
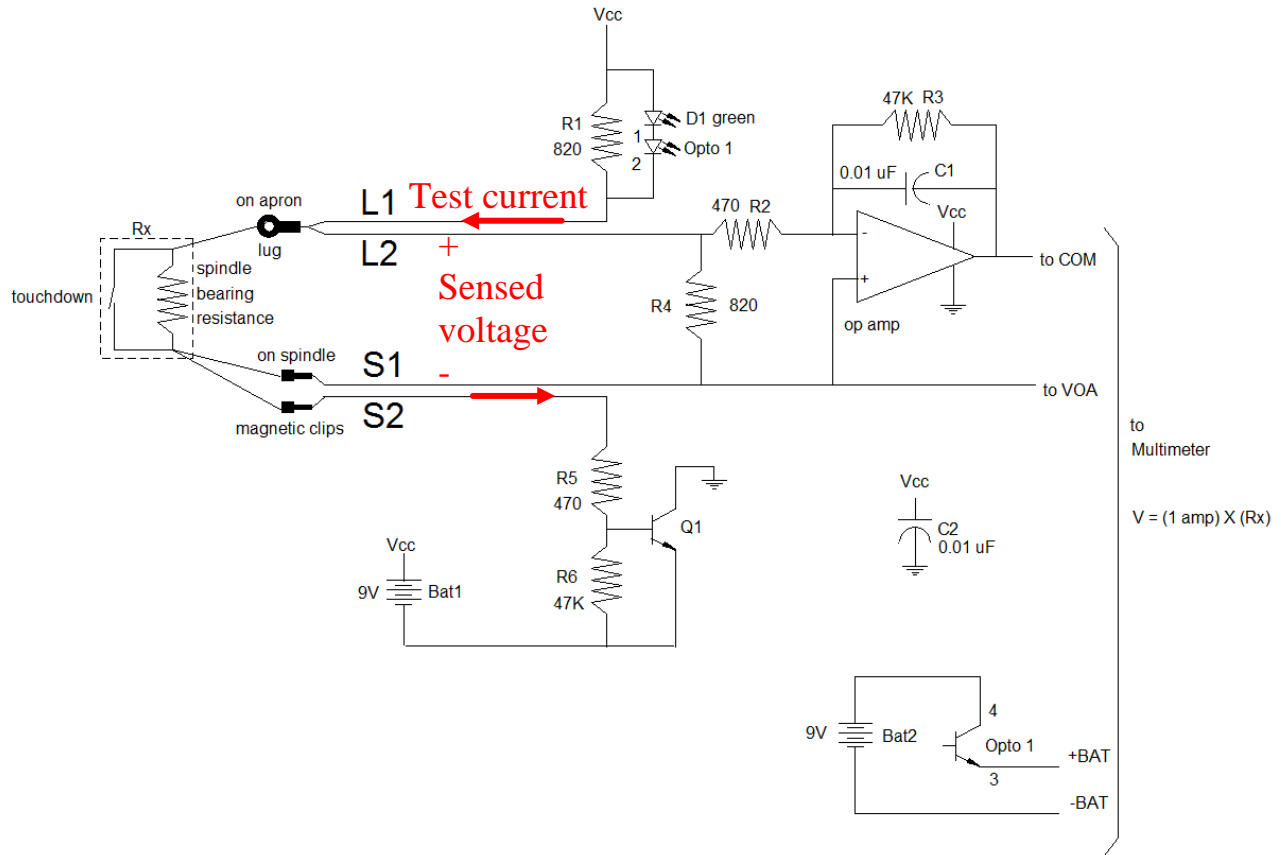

Current flows into R_x through terminal L1 and out through terminal S2. Any contact resistance at these terminals does cause a voltage drop but it has a minimal effect on the test current level.

Terminals L2 and S1 sense the voltage across R_x. Current flow is less than a micro amp so any voltage generated by contact resistance can be ignored.

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[8] Although L1 and L2 terminate on the same lug, they are essentially separate connections. Thanks to John Herrmann for pointing this out.
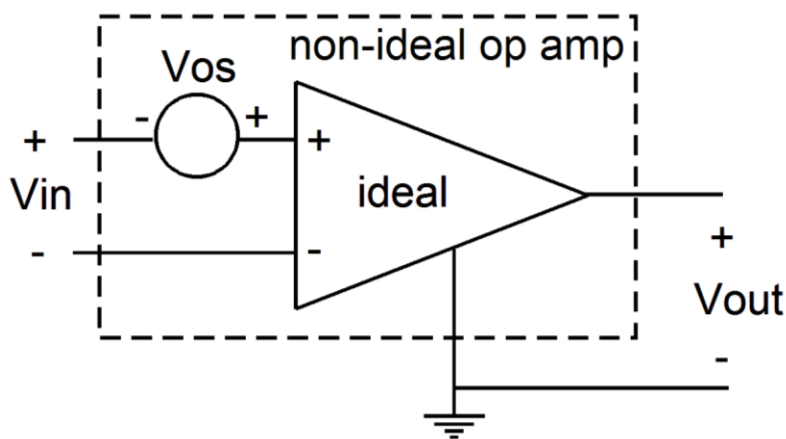
The Voltage Amplifier
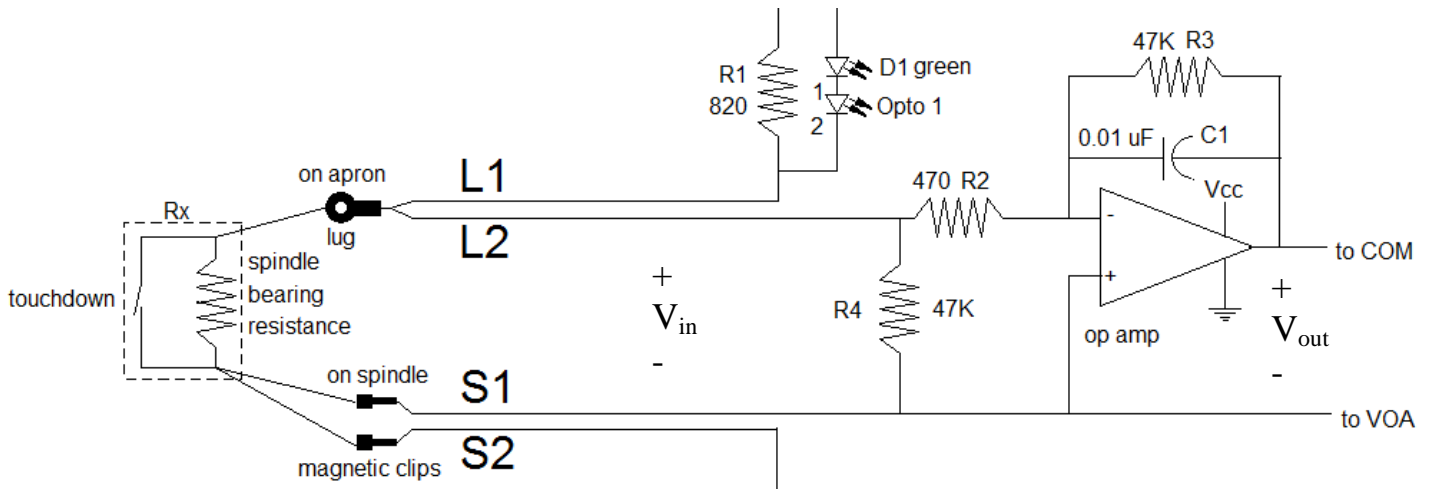
The voltage amplifier is a little odd. As shown, it is a simple inverting voltage amplifier. The ideal gain equals $\frac{-R3}{R2} = \frac{-47K}{470\Omega} = -100$. Vout = -100 × Vin.

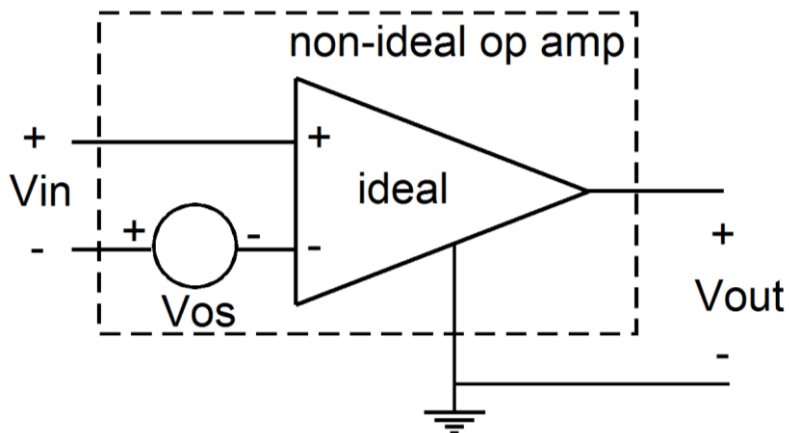In order to understand the actual circuit, I need to first discuss input offset voltages.

An ideal op amp takes Vin, multiplies it by a large number, G, and generates Vout (Vout = G × Vin). Since Vout is only a few volts, Vin must be tiny. As this large number approaches infinity, Vin approaches zero ($Vin = \frac{Vout}{G}$).

One non-ideal parameter of an op amp is input offset voltage, V_{os}. I can model this as a voltage source in series with an input of an ideal op amp. V_{os} is specified to be within a range but the polarity can be positive or negative. Note that when Vin = - V_{os}, Vout will equal zero.

Vout = G × (Vin + V_{os}).

Vout is the same if I put Vos in series with the positive input or the negative input. Think of it as pushing the V_{os} source through the input circuit. I will be using this trick soon.

The goal is to employ the unused op amp such that the overall offset voltage is reduced.

Of course, you could just buy one of the numerous low input offset op amps and avoid the issue. An input offset voltage less than 100 microvolts would be very nice. The OPA27 cost $3.49 at Mousers. You should not need to add the trimmer pot.

Worst case from the LM358 dual op amp spec sheet is a V_{os} of magnitude 7 mV. That is not so easy to measure directly. So instead, we will borrow a few parts from the circuit and build a test set.
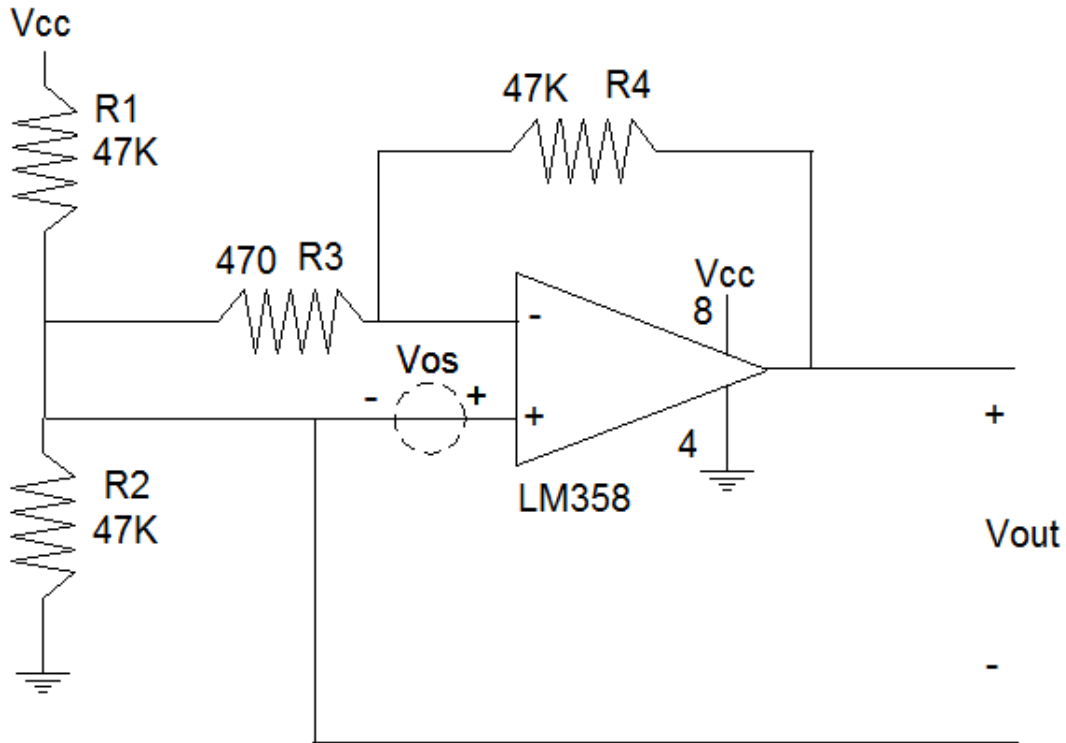
I have a non-inverting voltage amplifier and have drawn in the location of Vos as a reminder but it is actually inside the op amp.

Measure V_{out} for each op amp within the IC you plan to use.

Given V_{out}, we can calculate V_{os} if necessary:

$$Vout = \left(1 + \frac{R4}{R3}\right) \times (Vos)$$

$$Vout = \left(1 + \frac{47K}{470\Omega}\right) \times (Vos)$$

$$Vout = 101 \times (Vos)$$

$$Vos = \left(\frac{Vout}{101}\right)$$

part	op amp A	op amp B
1	104	124
2	720	-599
3	-358	-38
4	-242	214
5	-83	31
6	98	-174
7	820	-452
8	119	-287
9	217	-69
10	108	188
11	50	-90
12	-170	185
13	212	-69
14	631	-99
15	35	-6
16	-27	-11
17	-239	-48
18	-97	8
19	-25	105
20	-86	-6

I chose to use the LM358 and bought 20 of them on eBay for under $2.50. Then I measured the output offset of each op amp in each IC.

Note that part 2 and 7 are out of spec. Given a maximum input offset voltage of 7 mV, we should not see more than ± 707 mV.

Part 15 and 20 have a very low offset. An output offset of -6 mV means an input offset of $\frac{-6\ mV}{101} = -0.06\ mV\ or - 60\ \mu V$. Not bad for a 12.5¢ part.

Finding parts 15 and 20 was a great piece of luck. However, I can reduce the overall offset with any of the devices.

Voltages are in mV. These are measurements of $V_{out.}$

There are 4 possible cases. One will be the smallest number for each device.

1. V_{os-A}
2. V_{os-B}
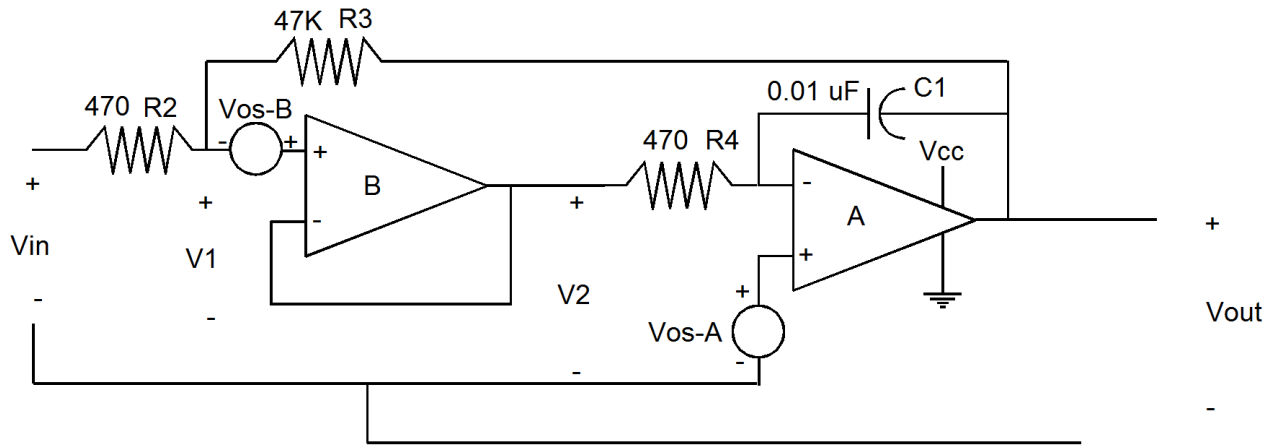3. $V_{os-A} - V_{os-B}$
4. $V_{os-A} + V_{os-B}$

part	op amp A	op amp B	A alone	B alone	A-B	A+B	best
1	104	124	104	124	-20	228	-20
2	720	-599	720	-599	1319	121	121
3	-358	-38	-358	-38	-320	-396	-38
4	-242	214	-242	214	-456	-28	-28
5	-83	31	-83	31	-114	-52	31
6	98	-174	98	-174	272	-76	-76
7	820	-452	820	-452	1272	368	368
8	119	-287	**119**	-287	406	-168	119
9	217	-69	217	-69	286	148	-69
10	108	188	108	188	-80	296	-80
11	50	-90	50	-90	140	-40	-40
12	-170	185	-170	185	-355	15	15
13	212	-69	212	-69	281	143	-69
14	631	-99	631	-99	730	532	-99
15	35	-6	35	-6	41	29	-6
16	-27	-11	-27	-11	-16	-38	-11
17	-239	-48	-239	-48	-191	-287	-48
18	-97	8	-97	8	-105	-89	8
19	-25	105	-25	105	-130	80	80
20	-86	-6	-86	-6	-80	-92	-6

Voltages are in mV. These are measurements of $V_{out.}$

Only part 8 used op amp A alone. That is 5% of the population.

Parts 3, 5, 9, 13, 14, 15, 16, 17, 18, and 20 used op amp B alone. That is 50% of the population.

If I want to use just op amp A, the circuit is

A Only

Vcc +9V

on means battery and test current OK
D1 green
Opto 1

R1 820

47K R3

470 R2

0.01 uF C1

Vcc 8

A 1 — to COM

LM358

on apron
lug
spindle
bearing
resistance

Rx

touchdown

R4 820

on spindle

magnetic clips

to VOA — to Multimeter

ideal
V = (1 amp) X (Rx)

IC socket

S1	1	8	S14
S2	2	7	S13
S3	3 LM358	6	S12
S4	4	5	S11
S5	1	6/4	S10
S6	2 Opto 1	5/3	S9
S7	3	4	S8

R5 470

Q1

B

R6 47K

Vcc C2 0.01 uF

9V Bat1

Vcc

4

9V Bat2 Opto 1

3

+BAT

-BAT

If I want to use just op amp B, the circuit is

B Only

Vcc +9V

on means battery and test current OK
D1 green
Opto 1

R1 820

47K R3

470 R2

0.01 uF C1

Vcc 8

B 7 — to COM

LM358

on apron
lug
spindle
bearing
resistance

Rx

touchdown

R4 820

on spindle

magnetic clips

to VOA — to Multimeter

ideal
V = (1 amp) X (Rx)

IC socket

S1	1	8	S14
S2	2	7	S13
S3	3 LM358	6	S12
S4	4	5	S11
S5	1	6/4	S10
S6	2 Opto 1	5/3	S9
S7	3	4	S8

R5 470

Q1

A 1

R6 47K

Vcc C2 0.01 uF

9V Bat1

Vcc

4

9V Bat2 Opto 1

3

+BAT

-BAT

If we want to subtract input offset voltages, consider this circuit.

Instead of connecting the inverting input of op amp A to the junction of R2 and R3, I have inserted op amp B as a unity gain amplifier. Both op amps are shown as ideal with their input offset voltage external.

Note that $V2 = V1 + V_{os-B}$.
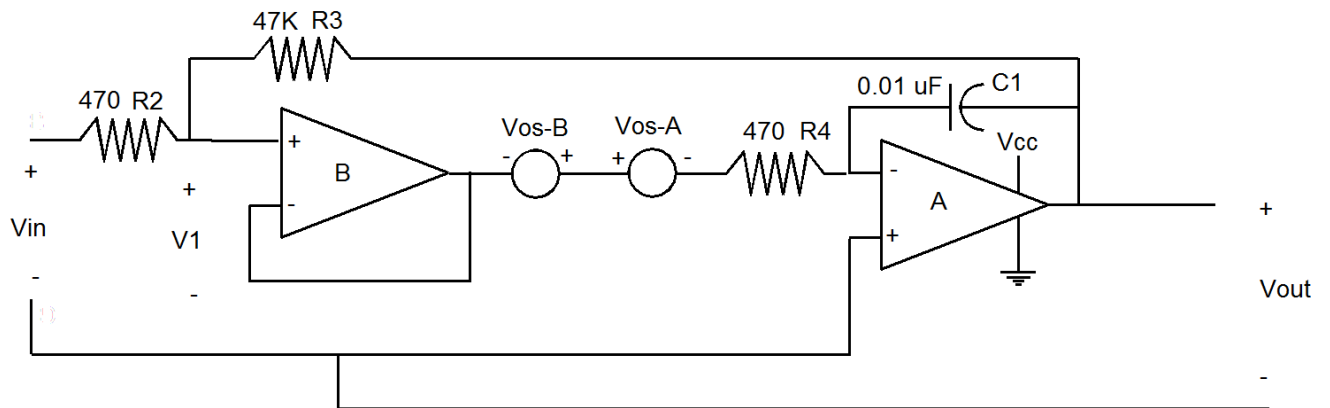
I can write this same equation if V_{os-B} is moved to the output side. Just as I could "push" the input offset voltage through the input, I can, in this case, put it beyond the output. I can only do this because B is configured as a unity gain amplifier.

47K R3

470 R2

B

+

Vin

−

0.01 uF   C1

470 R4

−

A

+

Vcc

+

Vout

−

Vos-B
+

+
Vos-A
−
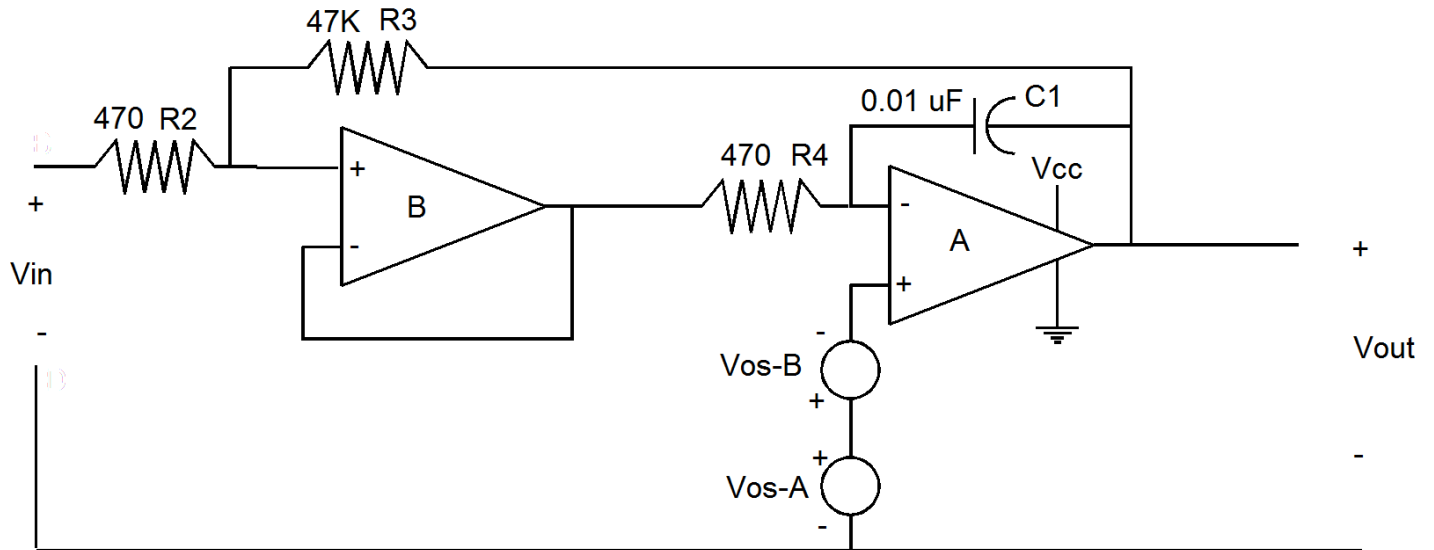
I have now pushed $V_{os\text{-}B}$ through R4 because they are in series and the order doesn't matter. Capacitor C1 is an open circuit at DC so I can ignore it while talking about offset voltages. Then I pushed $V_{os\text{-}B}$ through op amp A's input circuit so it runs into $V_{os\text{-}A}$. Since op amp A is ideal, there is no current flowing from its inputs. This means that there is no DC current flowing through R4 so I can ignore it. Op amp B is ideal so I can remove it. This leaves me with this circuit

47K   R3

470 R2

−

A

+

Vcc

+

Vin

−

Vos-B

+

+
Vos-A
−

+

Vout

−
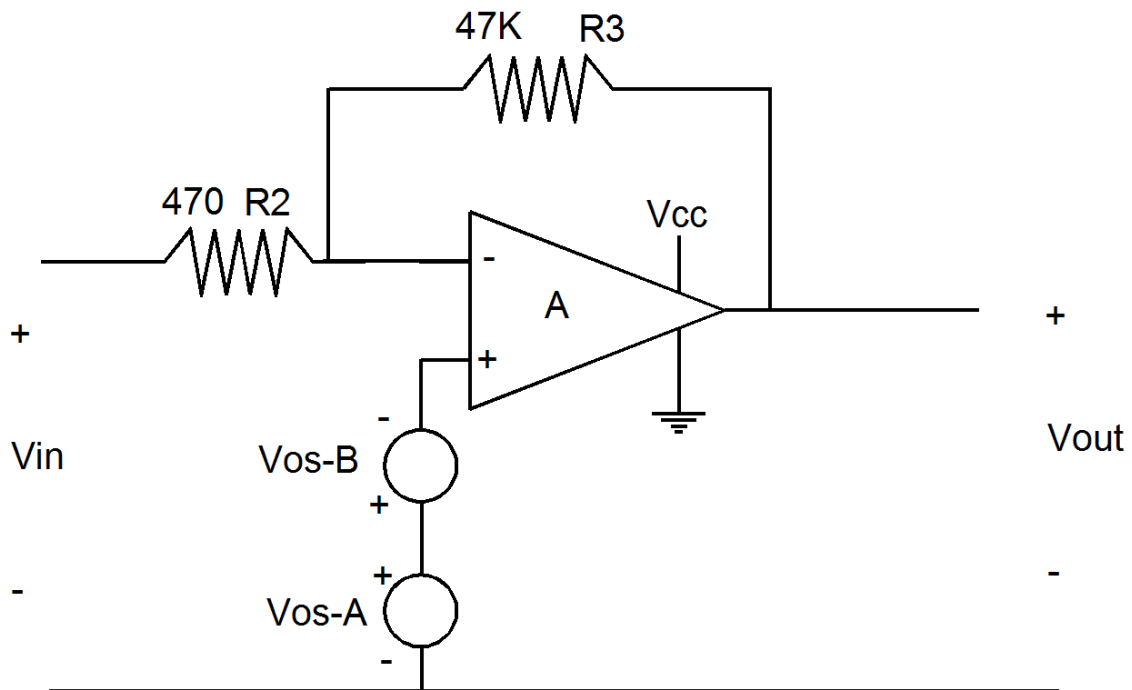
If Vin is zero, Vout will only contain the effects of input offset voltage.
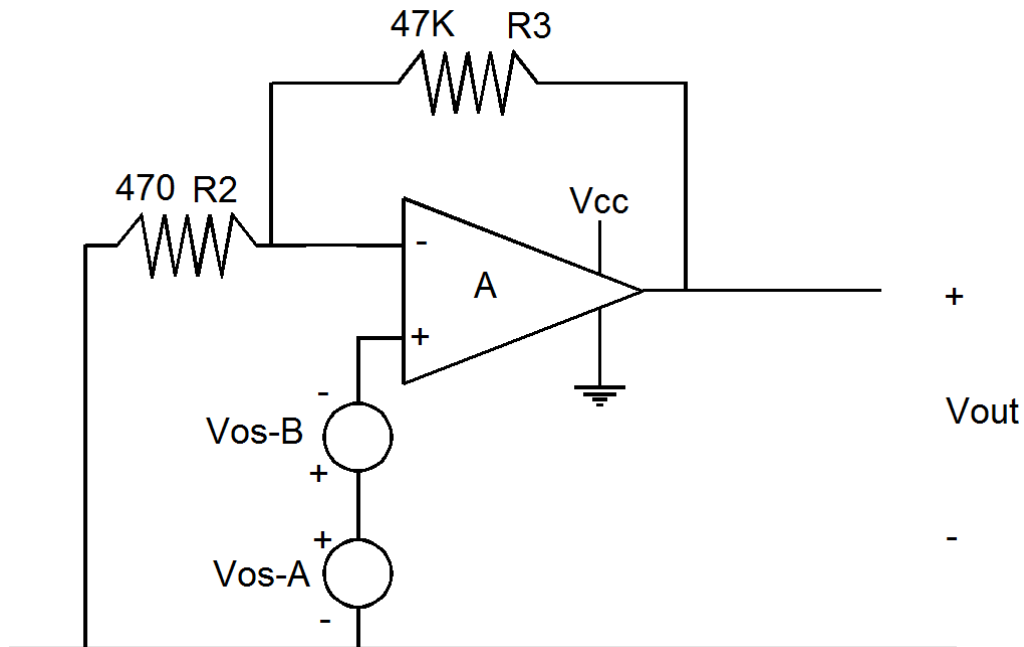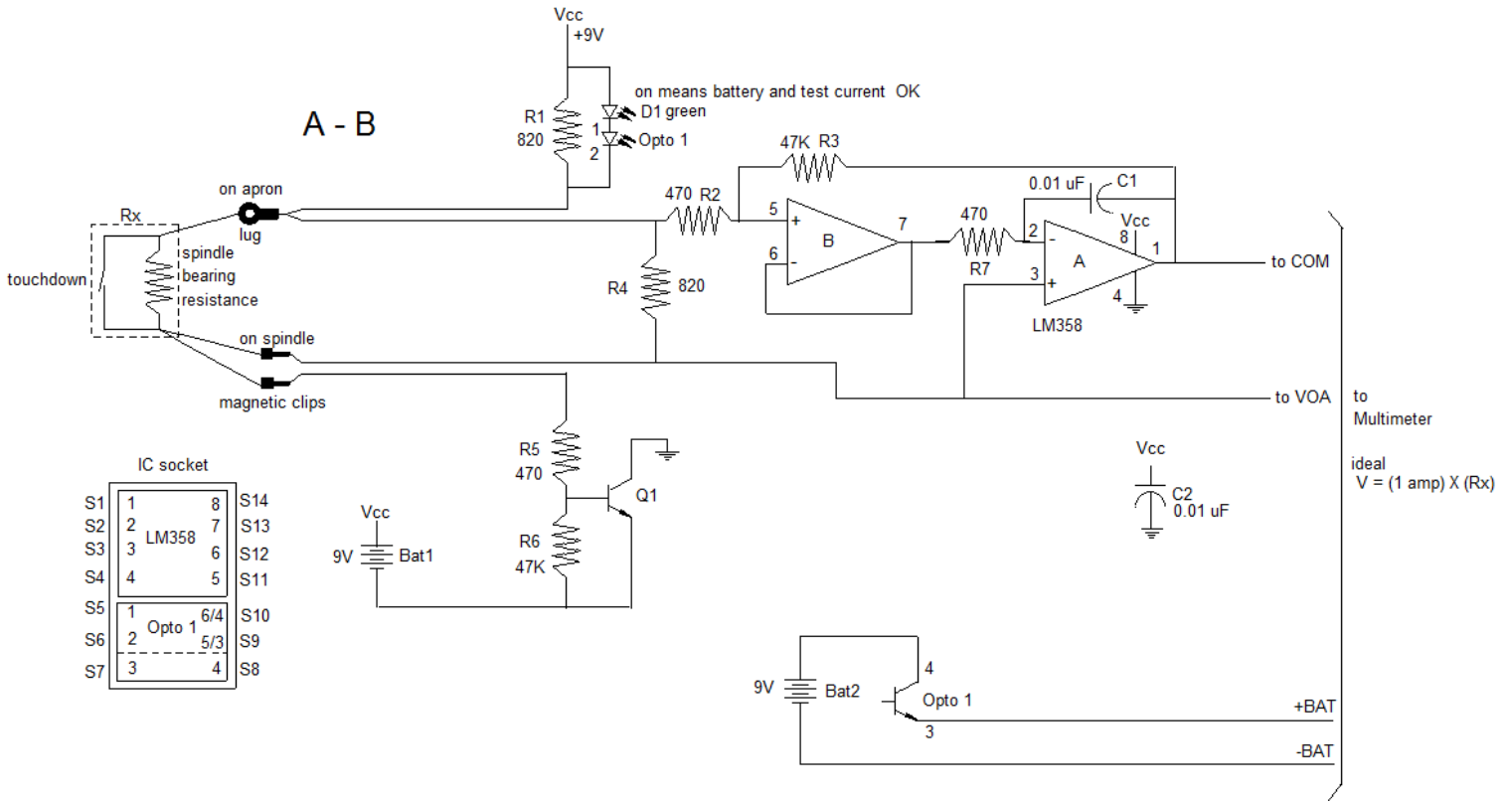

I now have a non-inverting voltage amplifier.

$$Vout = \left(1 + \frac{R3}{R2}\right) \times (VosA - VosB).$$

$$Vout = \left(1 + \frac{47K}{470\Omega}\right) \times (VosA - VosB).$$

$$Vout = 101 \times (VosA - VosB).$$

Here is the actual circuit for subtracting input offset voltages.

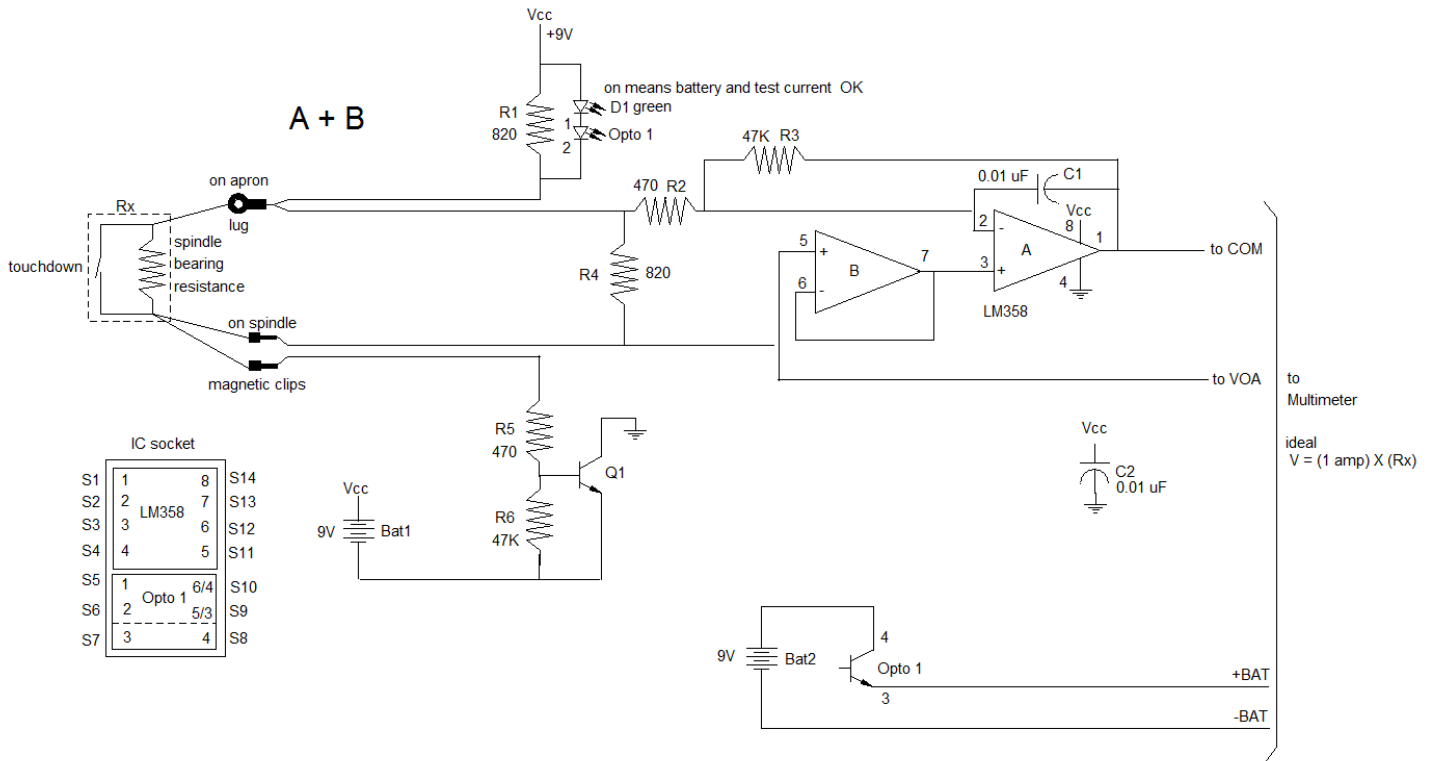| part	op amp A	op amp B	A alone	B alone	A-B	A+B	best
1	104	124	104	124	-20	228	-20
2	720	-599	720	-599	1319	121	121
3	-358	-38	-358	-38	-320	-396	-38
4	-242	214	-242	214	-456	-28	-28
5	-83	31	-83	31	-114	-52	31
6	98	-174	98	-174	272	-76	-76
7	820	-452	820	-452	1272	368	368
8	119	-287	**119**	-287	406	-168	119
9	217	-69	217	-69	286	148	-69
10	108	188	108	188	-80	296	-80
11	50	-90	50	-90	140	-40	-40
12	-170	185	-170	185	-355	15	15
13	212	-69	212	-69	281	143	-69
14	631	-99	631	-99	730	532	-99
15	35	-6	35	-6	41	29	-6
16	-27	-11	-27	-11	-16	-38	-11
17	-239	-48	-239	-48	-191	-287	-48
18	-97	8	-97	8	-105	-89	8
19	-25	105	**-25**	105	-130	80	80
20	-86	-6	-86	-6	-80	-92	-6

Voltages are in mV. These are measurements of V_{out}.

For the 20 dual op amps I bought, only two would benefit from subtracting input offset voltage. See parts 1 and 10. That is 10% of the population.

1	104	124	104	124	-20	228	-20
2	720	-599	720	-599	1319	121	121
3	-358	-38	-358	-38	-320	-396	-38
4	-242	214	-242	214	-456	-28	-28
5	-83	31	-83	31	-114	-52	31
6	98	-174	98	-174	272	-76	-76
7	820	-452	820	-452	1272	368	368
8	119	-287	119	-287	406	-168	119
9	217	-69	217	-69	286	148	-69
10	108	188	108	188	-80	296	-80
11	50	-90	50	-90	140	-40	-40
12	-170	185	-170	185	-355	15	15
13	212	-69	212	-69	281	143	-69
14	631	-99	631	-99	730	532	-99
15	35	-6	35	-6	41	29	-6
16	-27	-11	-27	-11	-16	-38	-11
17	-239	-48	-239	-48	-191	-287	-48
18	-97	8	-97	8	-105	-89	8
19	-25	105	-25	105	-130	80	80
20	-86	-6	-86	-6	-80	-92	-6

Parts 2, 4, 6, 7, 11, 12, and 19 benefit from using this circuit. That is 35% of the population.

I doubt there is any pattern here. But if you take the time to measure the op amps you plan to use, you can get the smallest possible offset.

Voltages are in mV. These are measurements of V_{out}.

Bad S1 Connection

It is essential that a faulty connection via magnetic contact S1 be detected in order to prevent missing a touchdown event. R4 deals with this case by forcing the voltage between S1 and L2 to be almost zero. The meter will then read close to the *touchdown value* which alerts the user to fix the problem before proceeding.
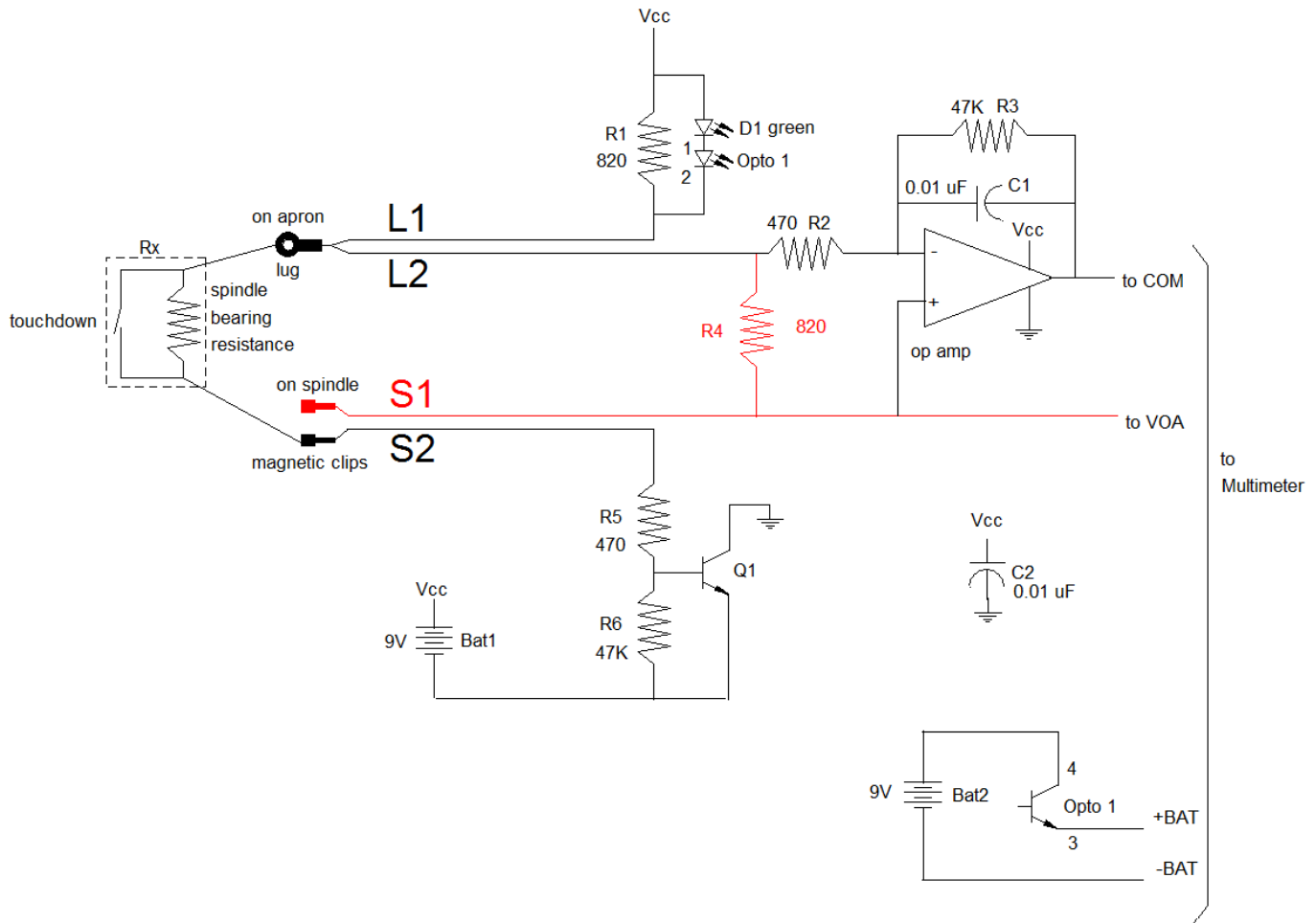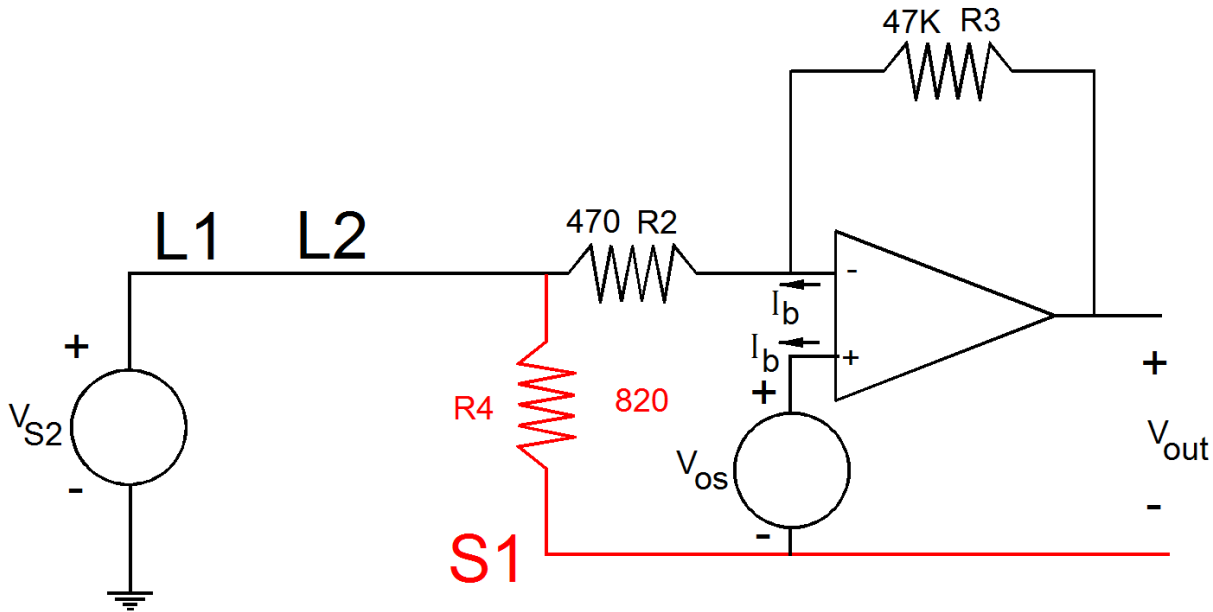
Here is a boiled down version of the circuit showing only the important bits. The op amp has an input offset, V_{os} and input bias currents, I_b. Assume that the load from the meter connected to VOA is small. V_{S2} is a DC voltage set by the test current. We only need to know that it keeps the op amp out of saturation.

We can use "superposition" to analyze the circuit. First we set V_{os} to zero and look at the effect of I_b on V_{out}. Then we set I_b to zero and look at the effect of V_{os}. And finally, we add the effects together.
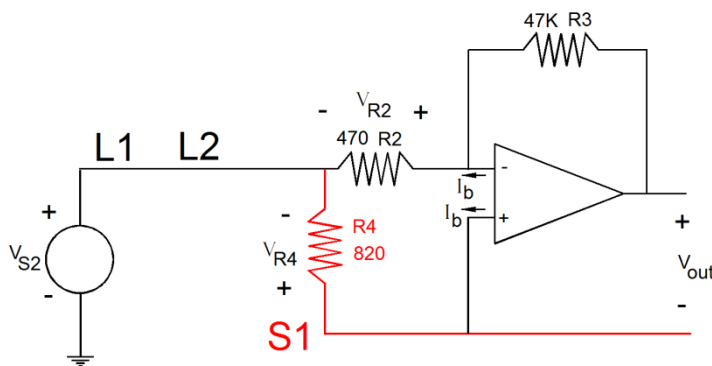
Looking at just the effect of I_b, we have a voltage across R2 and R4 that is seen by the op amp's input. I_b always flows out of this op amp and has a maximum value of 0.250 microamps. The maximum input offset current is 0.150 microamps. This means that I_{b+} differs from I_{b-} by no more than 0.150 microamps. The largest V_{out} will be generated if the positive input has an I_b of 0.250 microamps and the negative input has an I_b of 0.250 - 0.150 = 0.100 microamps. V_{R4} will equal $(820\Omega \times 0.250\,\mu A) - (470\Omega \times 0.100\,\mu A) = 0.16\,mV$. This voltage is then amplified by the op amp, R2, and R3 to set V_{out} at $-100 \times \{-0.16\,mV\} = 16\,mV$. At the other extreme, if I_b was zero, V_{out} would be zero.
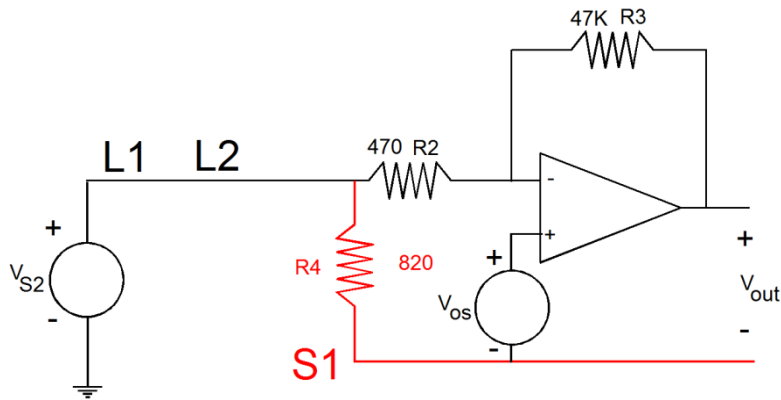
Next we will set the bias currents to zero and only look at the effect of input offset voltage. Now I have a non-inverting amplifier with a gain of

$$\left(1 + \frac{R3}{R2+R4}\right) = 37.4$$

The worst case V_{os} is ±7 mV so the worst case V_{out} is $37.4 \times \{\pm 7\ mV\} = \pm 262\ mV$.

Combining the effects of input bias and input offset voltage we can say that the worst case positive V_{out} is 262 mV + 16 mV = 278 mV. The worst case negative V_{out} is -262 mV. Therefore, when S1 is open, V_{out} could be as large as about 300 mV in magnitude. When S1 is connected and R_x is zero, Vout could be as large as 700 mV in magnitude. Therefore, an open S1 looks like touchdown. The user can see that they are not at touchdown so are alerted to a fault condition.

My copy of the EEF shows -156 mV with $R_x = 0$ and -154 mV when S1 is not connected. Both values are within expected results.

Frequency Response
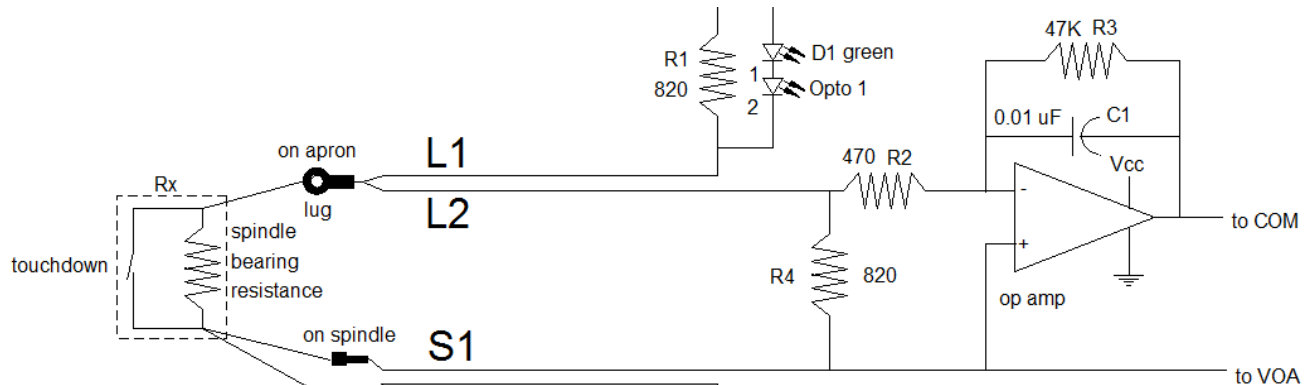
The circuit only needs to pass DC although the op amps are capable of megahertz operation. This high frequency capability is a problem since uncontrolled oscillation can cause erratic behavior. The solution is to reduce the gain as we go up in frequency. Placing a capacitor across R3 might tames the op amp.

As the frequency rises, the impedance of C1 decreases. This reduces the gain. When the impedance of C1 equals in magnitude the value of R2, the gain is down to $-\frac{Z_{C1}}{R2} = -\frac{-j470\Omega}{470\Omega} = j$ which is a gain of 1 at a 90° phase angle. Above that frequency, the gain is less than 1 so is absolutely stable.

$$X = \frac{1}{\omega C_1}$$

$$470\Omega = \frac{1}{2\pi f(0.01\mu f)}$$

Solving for f, I get 34 KHz. This is sufficiently low to prevent stray capacitance from causing oscillations within the circuit.
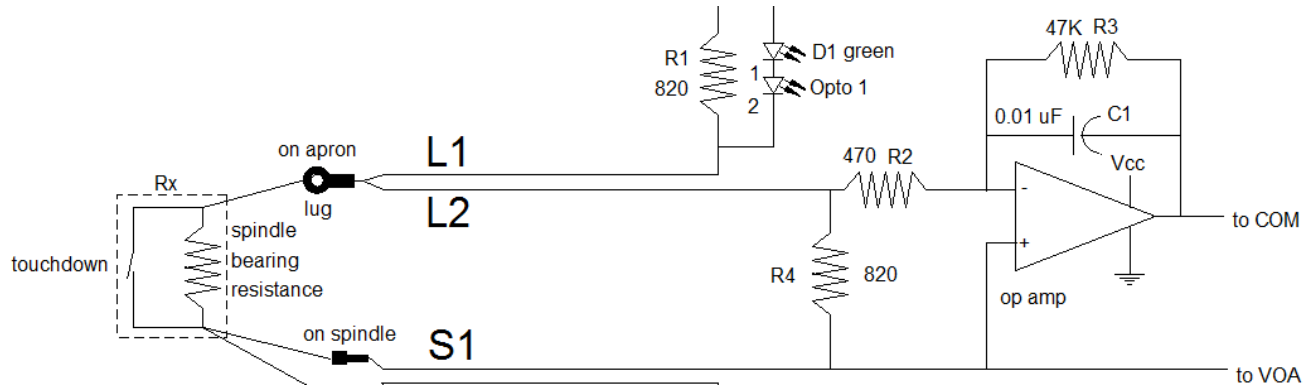
In the time domain, the circuit is an integrator. A step voltage at the input (L2-S1) causes a step current through R2. This current charges C1 and the voltage at the output (COM - VOA) changes linearly. If the input jumped by 2 volts, R2's current would change by 4.3 mA. That would charge C1 at the rate of $\frac{4.3 \ mA}{0.01 \ \mu f} = 43 \frac{volts}{mS}$.

The maximum possible voltage change is 9 volts so the transient must be over in less than 0.2 mS. The meter takes around ½ second to settle down so the user will never notice the delay caused by R2 and C1.

Battery Life

This graph shows a starting current drain of $\frac{9V}{270\Omega} = 33$ mA which goes down to 22 mA at 6 volts. My circuit only draws around 13 mA at 9 volts and about 7 mA at 6 volts. It is safe to say that the battery will last longer sourcing current to my circuit than to a 270 ohm resistor.

Given a standard alkaline battery starting at 9 volts and discharging down to 7 volts, it will last more than 15 hours[9]. Assume it takes 1 minute to take a reading. This means you will get more than 900 readings from a battery.

270 ohm 1 hr/day

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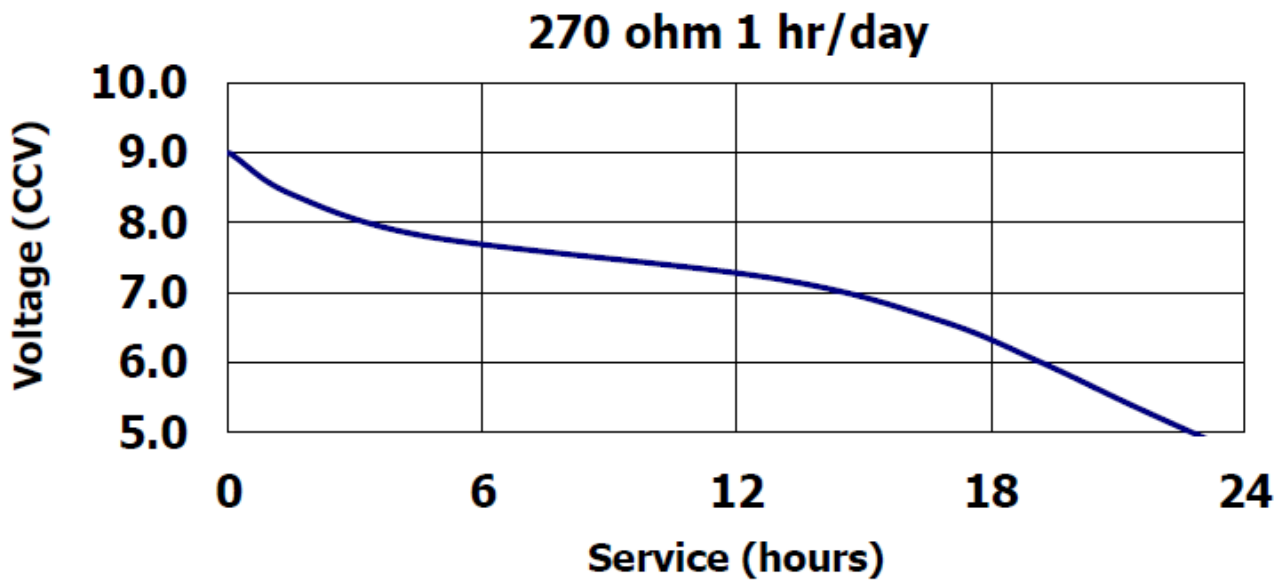
[9] See http://data.energizer.com/PDFs/522.pdf for graph.

Another Build: Glenn Combs

Glenn built the version of the circuit shown in Home Shop Machinist. His craftsmanship is first rate. For ease of maintenance, he put both batteries in the enclosure.
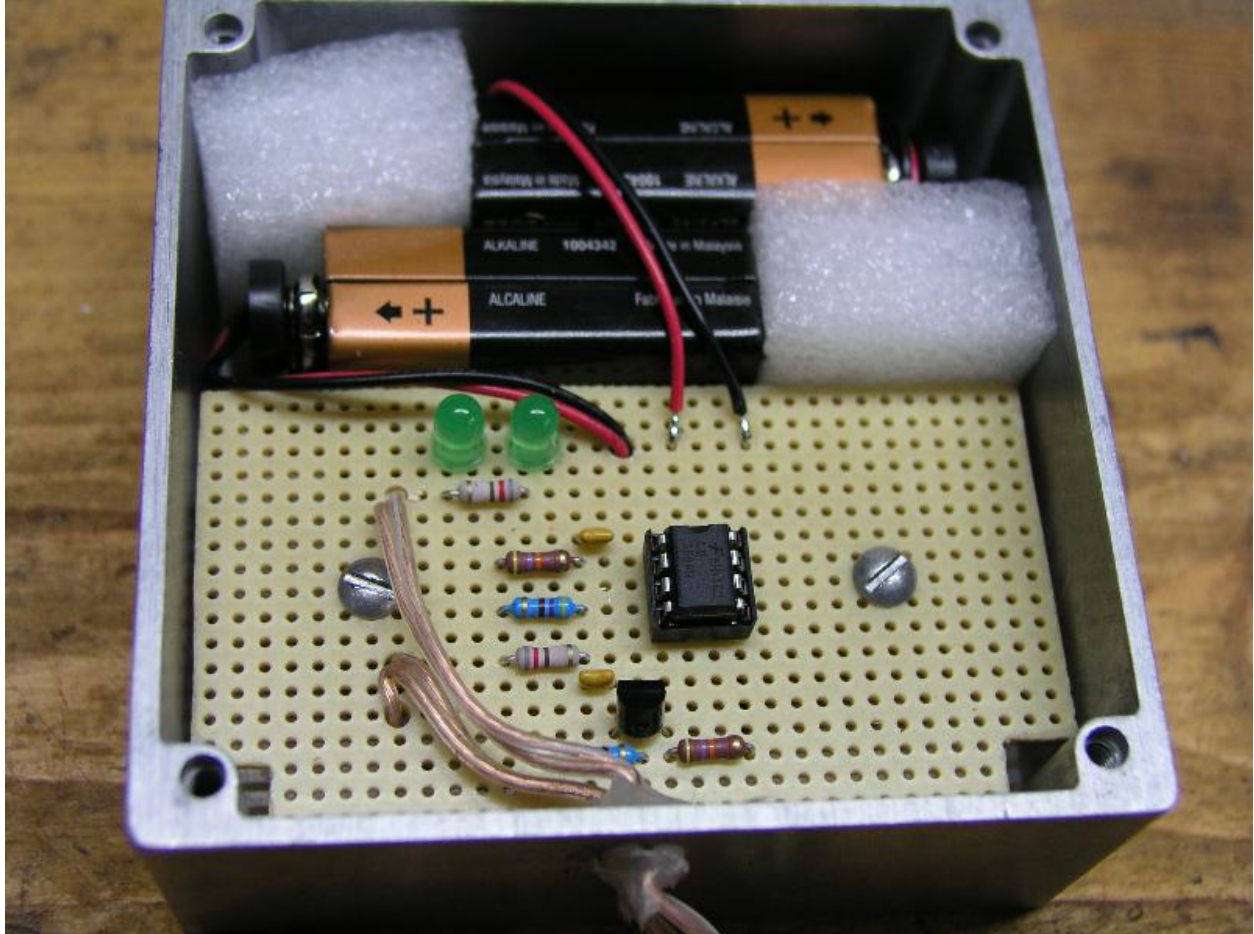
Acknowledgments

I wish to thank John Herrmann essential editorial assistance, testing an earlier version of this circuit, plus providing insight into the Kelvin connection. Thanks to Dave Kellogg for numerous suggested improvements to this article. Thanks to Glenn Combs for sharing his build pictures.

I welcome your comments and questions.

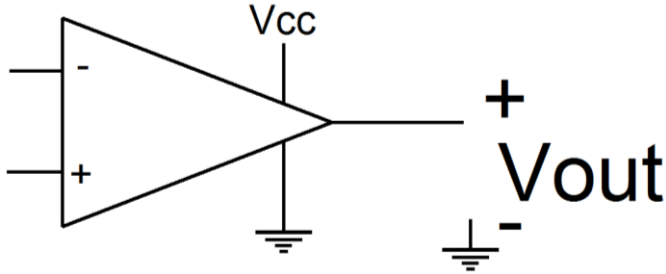If you wish to be contacted each time I publish an article, email me with just "Article Alias" in the subject line.

Rick Sparber
Rgsparber.ha@gmail.com
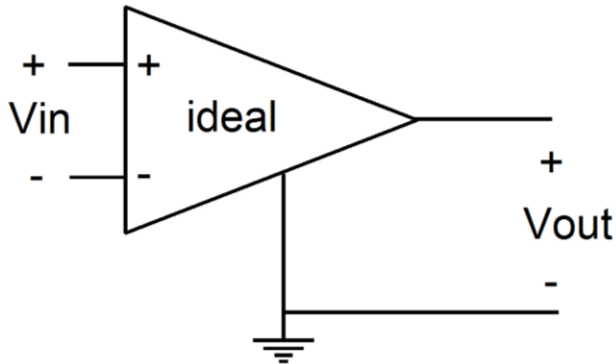Rick.Sparber.org

Appendix 1: Op Amp Saturation

Let's first review how an ideal op amp works. It receives power by being connected across a voltage difference. Here you see it connected to a positive voltage source, Vcc, and to a zero voltage source, ground.

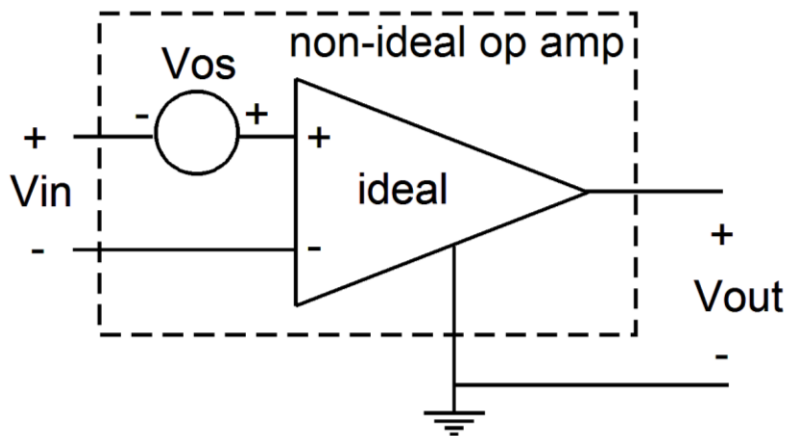Ideally, the output voltage can move freely between ground and Vcc.

In an actual op amp, the output voltage cannot usually move all the way to Vcc and ground. For the LM358, Vout can reach 1.5 volts below Vcc. This is called its upper saturation point. If the current flowing in the output is small, Vout can get very close to ground. That is its lower saturation point.

Appendix 2: Input Offset Voltage

In order to understand the actual circuit, I need to first discuss input offset voltages.
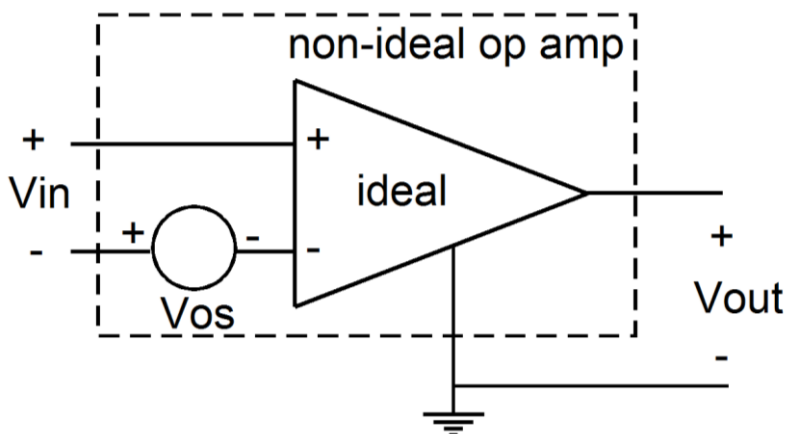
An ideal op amp takes Vin, multiplies it by a large number, G, and generates Vout (Vout = G × Vin). Since Vout is only a few volts, Vin must be tiny. As this large number approaches infinity, Vin approaches zero ($Vin = \frac{Vout}{G}$).
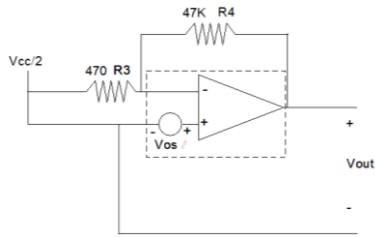
One non-ideal parameter of an op amp is input offset voltage, V_{os}. I can model this as a voltage source in series with an input of an ideal op amp. V_{os} is specified to be within a range but the polarity can be positive or negative. Note that when Vin = - V_{os}, Vout will equal zero.

Vout = G × (Vin + V_{os}).

Vout is the same if I put Vos in series with the positive input or the negative input. Think of it as pushing the V_{os} source through the input circuit. I will be using this trick soon.

The goal is to employ the unused op amp such that the overall offset voltage is reduced.

Worst case for the LM358 dual op amp is a V_{os} of magnitude 7 mV. That is not so easy to measure directly. So instead, we will borrow a few parts from the circuit and build this test set.

I have here a non-inverting voltage amplifier.

$$Vout = \left(1 + \frac{R4}{R3}\right) \times (Vos)$$

$$Vout = \left(1 + \frac{47K}{470\Omega}\right) \times (Vos)$$

$$Vout = 101 \times (Vos)$$

$$Vos = \left(\frac{Vout}{101}\right)$$

Measure Vout and divide the reading by 101 to get Vos. If Vos is 7 mV, the reading will be $7\ mV\ \times 101 = 0.707\ volts$.