An Analog Electronic Edge Finder, Version 2.2

By R. G. Sparber

Overview

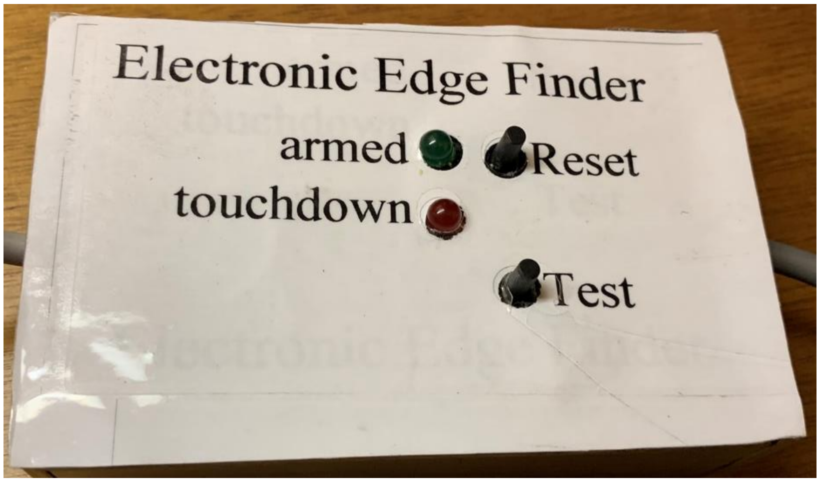
Exactly when does the end mill touch down on the stock?

Using this Electronic Edge Finder (EEF), you place the magnetic clip on the spindle, the box on the mill table, and connect the USB to power. Push the Reset button to make the green LED light.

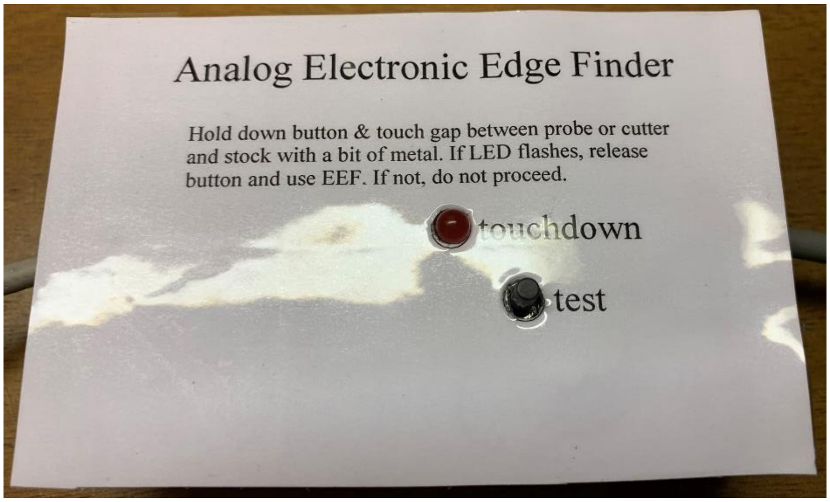
Then lower the end mill until the green LED goes out and the red LED lights.

You can't get any more exact than this.

Replace the end mill with a dowel pin, and you can touch down on vertical reference surfaces.



Version 1 of this circuit requires the user to push the reset button. I have made a nicer faceplate but the circuit is the same as on the last page.



Hold down button & touch gap between probe or cutter and stock with a bit of metal. If LED flashes, release button and use EEF. If not, do not proceed.

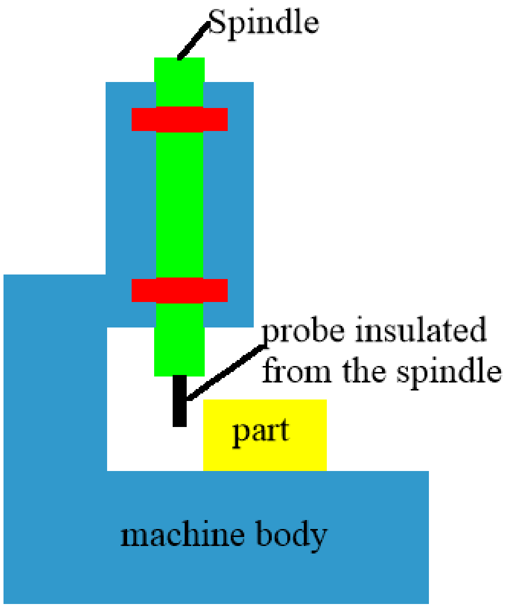
Version 2 contains a timer, so the touchdown LED is on for about 1/3 second, and then the circuit automatically resets.

By changing the value of one resistor, the LED can be set to be on for a longer period of time.

Contents

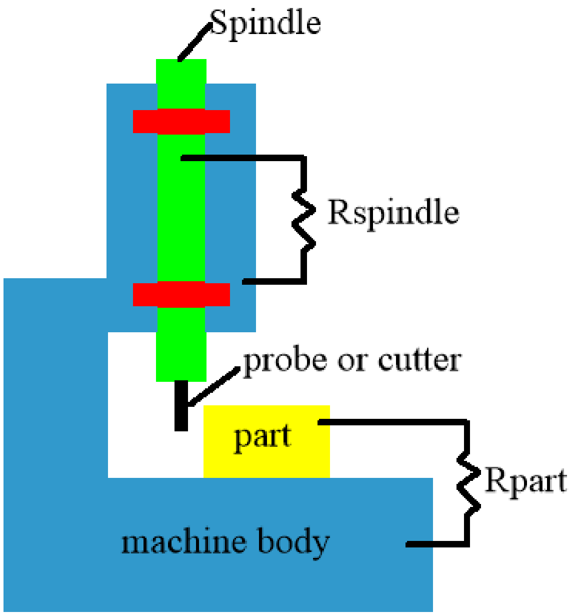
Background

Classic Electronic Edge Finders



An Electronic Edge Finder (EEF) detects when a probe or cutter comes in contact with a reference surface on a part. A machinist uses it to define the exact location of a part relative to the machine. This point in space is called Part 0. Many EEFs utilize electrical conduction. When an ***insulated*** probe contacts a grounded reference surface, a circuit is completed so it knows it has touched down. However, this insulation distorts and introduces error.

My Electronic Edge Finder



My version of an EEF does not use electrical isolation. It measures the *change* in resistance caused by the probe or cutter touching the reference surface. The electrical resistance between spindle and machine body is $R_{spindle}$. The electrical resistance between the part and the machine body is R_{part}. The probe or cutter is mounted in the spindle. Before touchdown, the resistance between probe or cutter and machine body is $R_{spindle}$. After touchdown, this resistance drops to $R_{spindle}$ in parallel with R_{part}. Touchdown is detected by looking for this drop. Any $R_{spindle} - R_{part}$ greater than 0.3 ohms works. The resistance before touchdown can be 0.3 to 4 ohms.

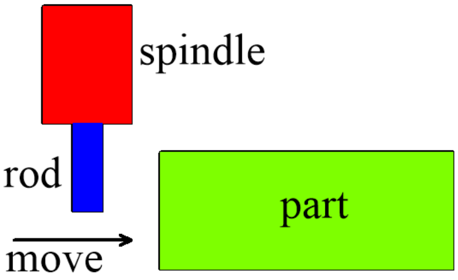
The cost is under $10 for the electronics.

How to Use the EEF

Here is a video.

Any installed end mill can be used to set Z on a mill. This makes the EEF handy for setting up Part 0 on the Z-axis.

It is also useful for setting up tool heights in a Computer Numerical Control (CNC) environment.



With a rod mounted in the spindle, like a 1 inch long dowel pin[2], we can set Part 0 on the X and Y axes. When at touchdown, we are the rod's radius from the reference surface.

On a lathe, the cutter can set touchdown on the stock held in the chuck. Here is a video showing the technique with an older EEF design.

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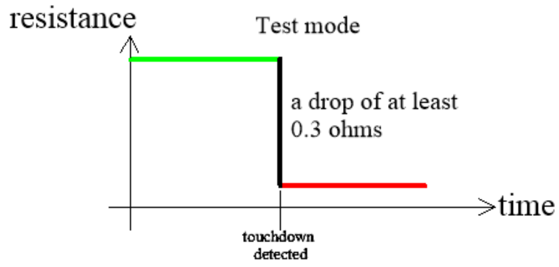
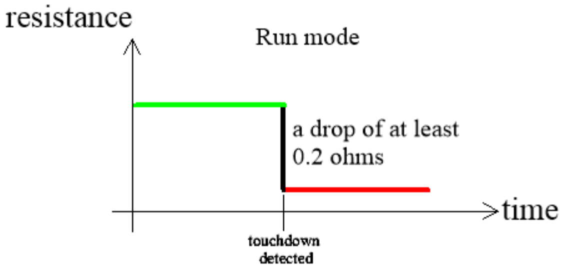
[2] A dowel pin sticking out about ¾ inch can flex a few thousandths of an inch and spring back with no distortion.

Test and Run Modes



The circuit has two thresholds.

In the Test mode, seeing touchdown means there has been a drop of at least 0.3 ohms.



In the Run mode, it only takes a drop of 0.2 ohms to trigger touchdown.

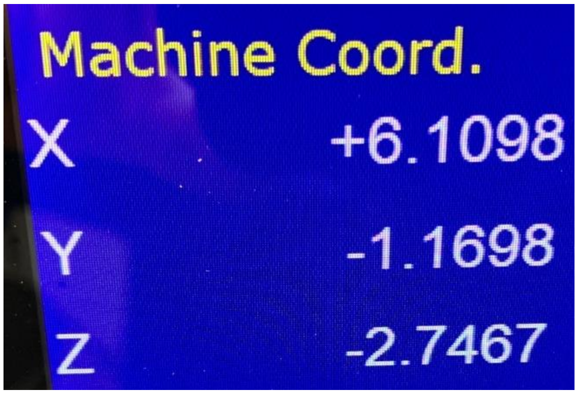
By running the Test mode first, we guarantee that the drop in resistance is enough to solidly trigger it in the Run mode.

For example, say there is a drop in resistance of 0.5 ohms at touchdown. The Test mode will see this drop which is more than 0.3 ohms and detect touchdown. In the Run mode, this 0.5 ohm drop is more than enough to trigger given our 0.2 ohm threshold.

However, if the drop was 0.25 ohms, the Test mode would not detect touchdown so the user must not proceed. The Run mode would barely detect this drop but it would be only 0.05 ohms from the threshold. That would not be reliable.

Accuracy

This is a potentially tricky topic. If I limit my focus to just the accuracy of the EEF, it has zero error. The probe or cutter is either in contact with the part or it is not. The test voltage is too small to cause arcing. Accuracy is entirely a function of the play in the spindle bearings and runout in the probe. I can touchdown on a surface, set zero, and retest to see a variation of +0.0000 to -0.0001 inches. This is likely round off error in the CNC system since we are looking at the least significant digit.



Machine Coord.

X	+6.1098
Y	-1.1698
Z	-2.7467

Feeding my end mill down on a reference surface, the EEF was armed at Z = -2.7467 inches.

Machine Coord.

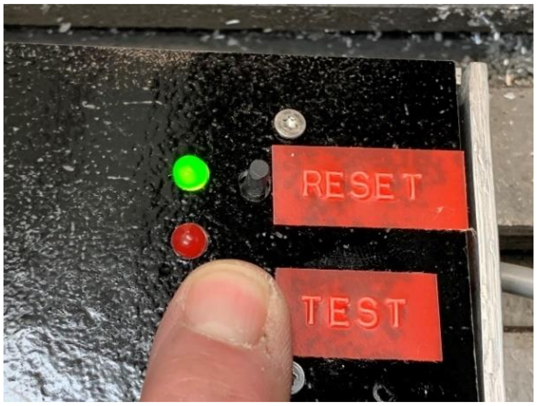
X	+6.1098
Y	-1.1698
Z	-2.7468

Each time I reached Z = -2.7468 inches, the EEF detected touchdown. This is a change of 0.0001 inches or 100 millionths of an inch.

The Procedure for Setting a Z Reference

We first verify touchdown detection is reliable. Then we can trust the EEF. If the spindle's electrical resistance is too small or the resistance between the stock and the table is too large, it won't be possible to detect touchdown.

1. Wipe the bottom of the EEF enclosure and the corresponding area of the mill table clean[3].
2. Wipe the surface of the magnetic probe clean along with the corresponding area on the spindle.
3. Places the magnetic probe on the spindle and the EEF down on the mill table[4]. Plug the USB cable into a power source.



The green LED comes on.

4. While holding down the Test button,

momentarily bridge the gap between the end mill and the reference surface with a bar. Let go of the Test button.

The green LED goes out and the red LED lights. We can now trust the EEF to detect touchdown.

5. Push the Reset button and slowly feed the end mill down until the red LED lights. This is touchdown.

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[3] Any rocking of the enclosure can cause false triggers.
[4] This also works on a lathe.

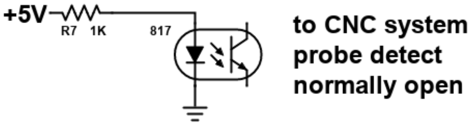
The Procedure for Setting an X or Y Reference

Replace the end mill with a cylinder of known diameter. Dan Benoit, of blessed memory, taught me to use a 1 inch long 1/8 inch diameter dowel pin sticking out about ¾ inch.

The procedure is identical to the Z reference case except you are moving on the XY plane. Don’t forget to account for the radius of the cylinder when setting your zero.

A CNC System Version of the EEF

I can replace the red LED with an opto connecting to my CNC System’s probe touchdown input.

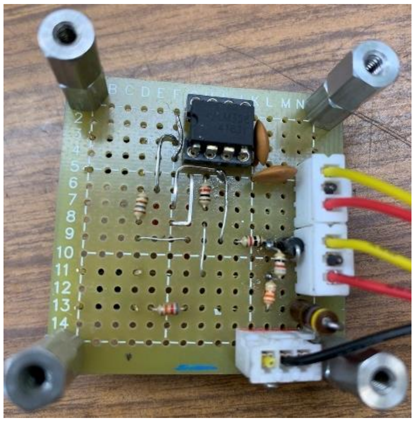


A second opto can connect to the probe detect input. This opto is driven by a 1K resistor connected to +5V.

One minor annoyance exists. The CNC system moves the probe during automatic touchdown until it received a touchdown signal. Then it backs the probe away. The user must press Reset before the CNC system begins to feed in for the final touchdown.

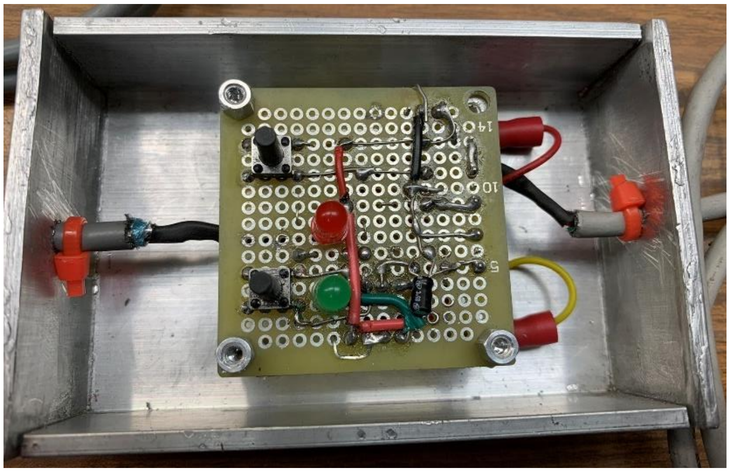
What's Inside?

Physical Layout of the Prototype

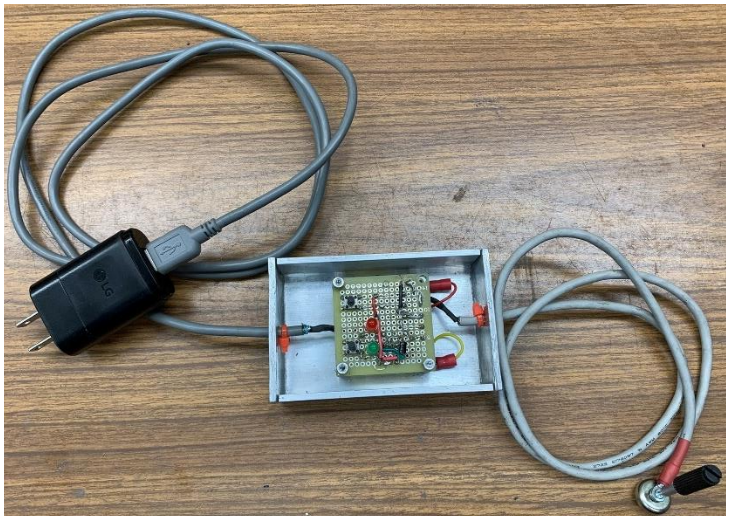


I built the circuit on a 1½-inch square "prototype board" using all through-hole devices.

A finished version could use a commercially etched board and Surface Mount Technology parts which would be much smaller and cost less.

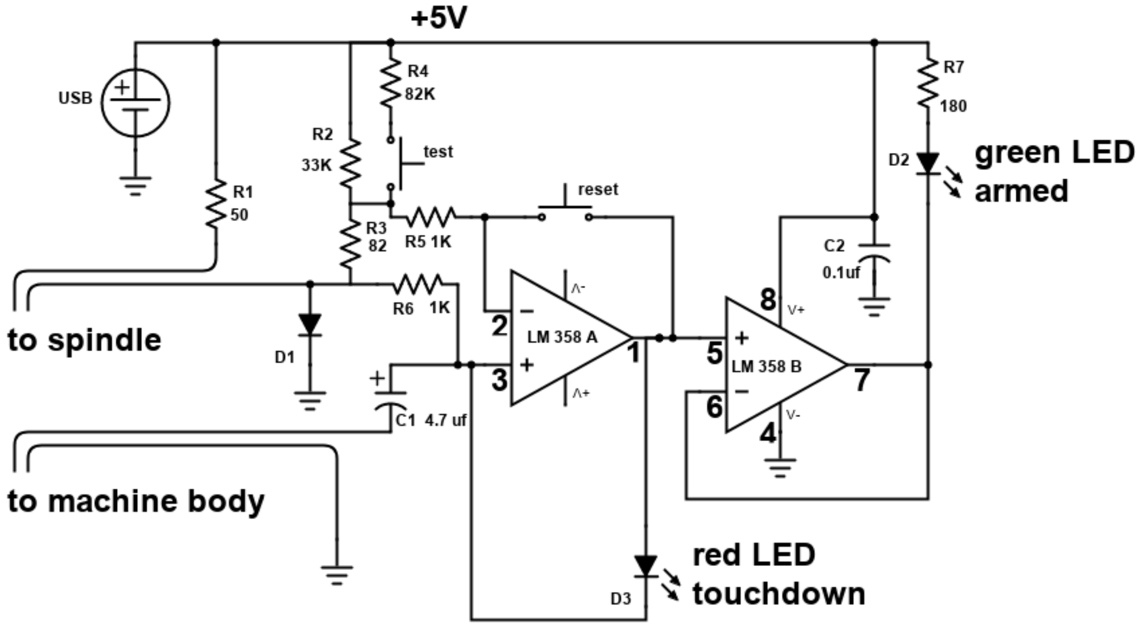


This enclosure is a bit roomy, but I had it on hand. It was no surprise to me that I couldn't get that last screw to go in. Murphy's Law.



Power is supplied by a USB wall wart or battery pack.

Schematic



Just about any opamp can be used to drive the green LED. The opamp connected to C_1 must have an Input Offset Voltage of less than 9 mV and be able to accept an input voltage down to the voltage on pin 4. The output voltage must be able to reach the voltage on pin 8 minus 1.5V. Of course, these opamps must be able to run on 5V.

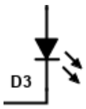
This schematic was drawn using the tool at digikey.com:
https://www.digikey.com/schemeit/project/

Parts List

Name	Value (+/- 5%)
R1	50 ohms 3/4 watt
R2	33K 0.1 watt
R3	82 ohms 0.1 watt
R4	82 K 0.1 watts
R5, R6	1K 0.1 watts
R7	180 ohms 0.1 watts
C1	0.1 µ*f*
C2	4.7 µ*f 16V*
D1	Diode; I_f > ½ amp
Dual opamp	LM358B
Red LED	
green LED	
Pushbutton switch	Two needed
USB cable	

Notes for the novice

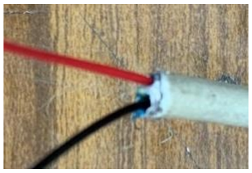
Here is the spec sheet for the LM358B.



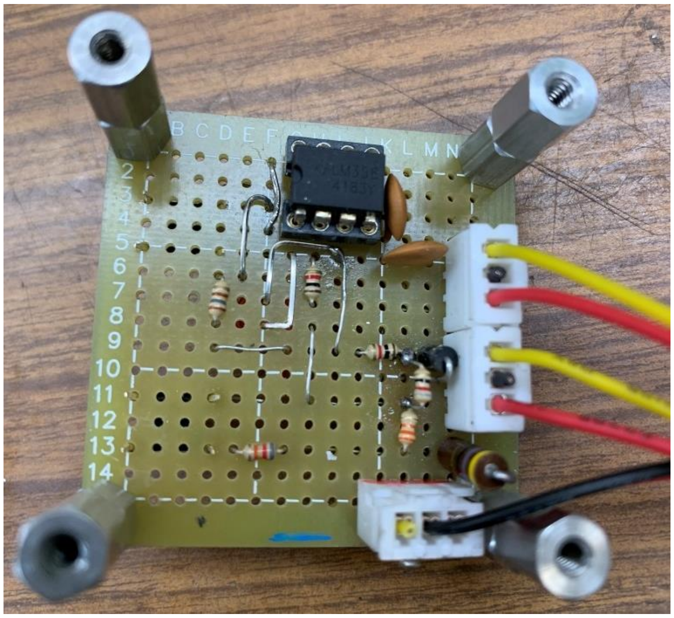
Diodes have a cathode and anode. The cathode is the end with the bar on it. When the anode is more positive than the cathode by enough voltage, current will flow. If this is an LED, it will light. Often, the anode’s wire is about 0.1 inches longer than the cathode. In this 5 volt circuit, you will not damage an LED if you put it in backwards.

C_2 has a positive and negative terminal marked on its body. You can damage it if connected backward for even a few seconds.

Construction Hints



I took a scrap USB cable and cut off the non-USB plug end. Then I removed an inch of the outer insulation and inner shield from the end. I cut off the green and white wires. The red wire connects to +5V, and the black wire connects to ground.

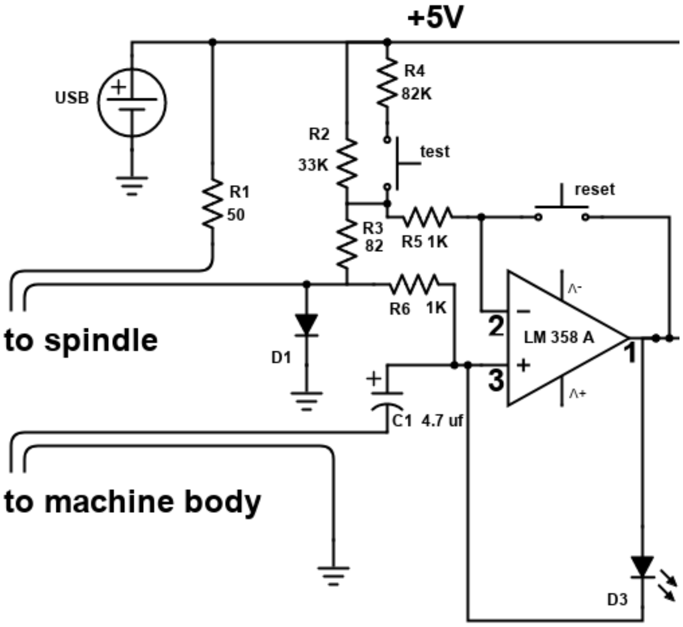


I socketed the dual opamp on the off chance of blowing it up during development. Yup, I fried it when I somehow swapped power and ground.

Having all cables connectorized makes it easier to remove the board to work on it during development. You may choose to hardwire all cables.

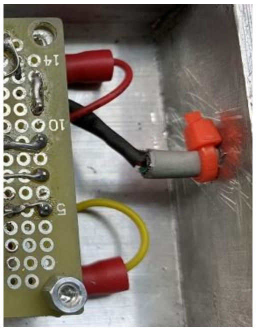
It may seem wasteful to run two wires from the board only to solder them together at the lug of the magnetic clip. As explained in the Appendix I, this configuration is essential.

I used a pushbutton for the Test switch rather than a toggle. This encourages the user to not forget, and leave the EEF in the Test mode. It is not difficult to have one finger on the Test button while shorting the cutter or probe to the machine body with a bar using the other hand.



Place R5 right at pin 2 of the opamp to minimize noise pickup. Similarly, place R6 next to pin 3.

Two wires run from the circuit to the spindle. At the spindle, they can be soldering to the same lug.



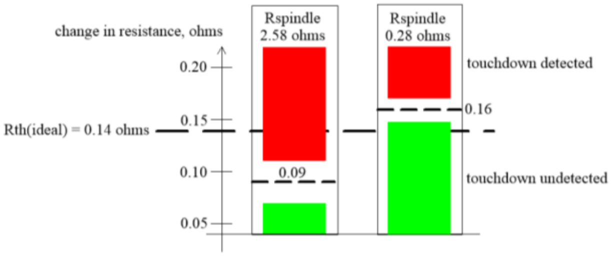
Two wires run to the machine’s body. I cheat a little here and run the wires to the inside of the EEF’s metal enclosure. We get a low resistance connection with this enclosure sitting on the mill’s table.

The circuit will falsely trigger if there is poor contact between the bottom of the enclosure and the mill table or lathe ways.

You can achieve a solid connection by filing and or sanding the bottom of the enclosure truly flat and having enough weight in the enclosure to prevent sideways movement as you push the buttons. Even the slightest movement can cause the circuit to trigger falsely.

Testing

Conclusion



Given an $R_{spindle}$ of 2.58 ohms, the measured threshold was 0.09 ohms. Given an $R_{spindle}$ of 0.28 ohms, the measured threshold was 0.16 ohms.

The ideal threshold, calculated by ignoring input offset voltage, was 0.14 ohms. In the worst-case, the threshold should be between 0.007 and 0.264 ohms range. We are within this range.

Details

See Appendix II for details and discussion.

Tony McCann's Build

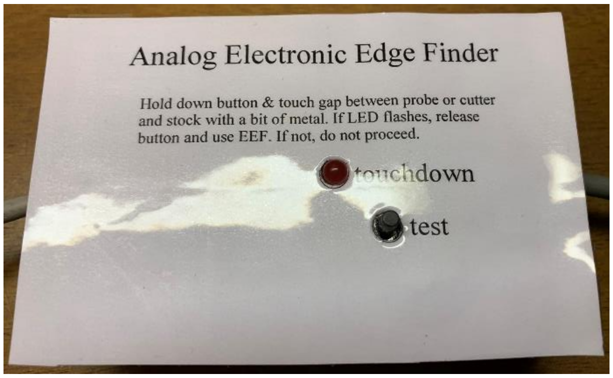
Tony McCann told me he has minimal experience with electronics yet did an excellent job building the Analog Electronic Edge Finder.

He chose to mount the enclosure on his mill and run wires to the machine.

The magnetic clip (green) is on the drill chuck.

With his probe in contact with a bar held in his vise, the circuit has detected touchdown and the red LED is on.

Version 2



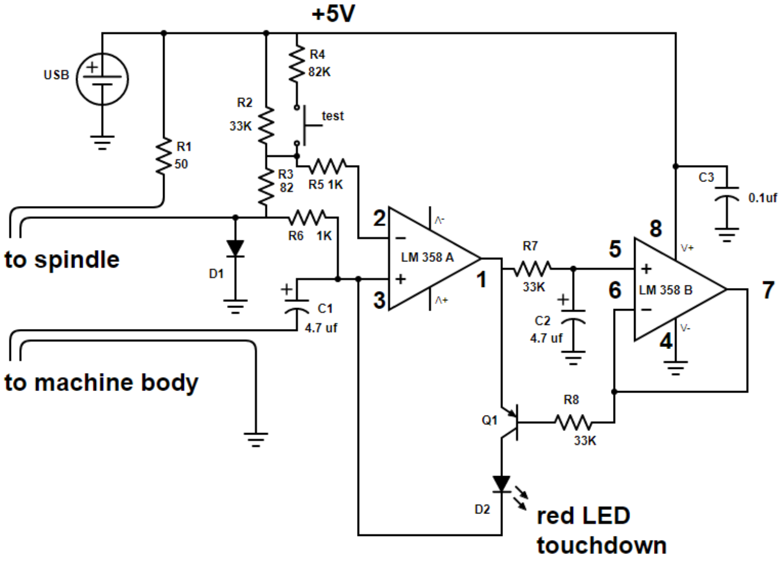
Analog Electronic Edge Finder

Hold down button & touch gap between probe or cutter and stock with a bit of metal. If LED flashes, release button and use EEF. If not, do not proceed.

touchdown

test

Using the EEF, I realized that pushing the reset button was annoying. This irritation inspired me to evolve the circuit, so the LED flashes for about 1/3 second and then is ready for another touchdown.



I have removed the green LED and added a PNP transistor, Q_1. Replace D2 with an opto as in version 1 for CNC compatibility.

Name	Value (+/- 5%)
R1	50 ohms 3/4 watt
R2, R7, R8	33K 0.1 watt
R3	82 ohms 0.1 watt
R4	82 K 0.1 watts
R5, R6	1K 0.1 watts
C1, C2	4.7 µ*f 16V*
C3	0.1 µ*f*
D1	Diode; I_f > ½ amp
Dual opamp	LM358B
Red LED	
Q1	Any general-purpose PNP transistor
USB cable	

See Appendix III for the circuit description.

I used a 2N4402 for Q_1, but the 2N3906 would perform slightly better.

Acknowledgment

Thanks to “Claudio H.G. of Accidental Science” of homemadetools.net for his many suggestions.

Thanks to Tony McCann for sending me pictures plus background information.

I welcome your comments and questions.

If you want me to contact you each time I publish an article, email me with “Subscribe” in the subject line. In the body of the email, please tell me if you are interested in metalworking, software plus electronics, kayaking, and/or the Lectric XP eBike so I can put you on the right distribution list.

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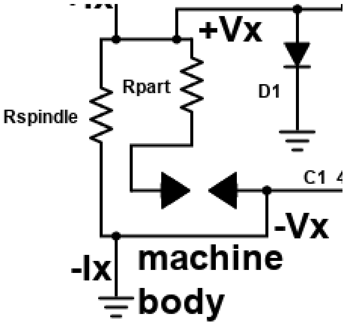
Appendix I: Detailed Circuit Description

I will focus on the circuit one section at a time.

The Resistance Being Measured

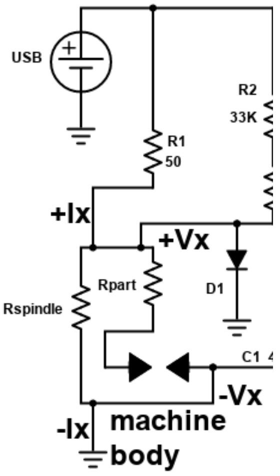


The EEF measured the resistance between the spindle and the body of the machine (see page 5). Before touchdown, this resistance is dominated by the electrical resistance of the spindle bearings[5].

At touchdown on a mill, this resistance is shorted out by the electrical resistance between the part and the machine's body[6]. On a lathe, it is the resistance between part and chuck. This resistance will not be a problem if the part is solidly bedded down. For more details, click here.

You may be wondering how to tell if these two resistances are in range before using the EEF. The test mode confirms all is well and there is an adequate margin.

The Kelvin Connection



The EEF uses a Kelvin connection to prevent voltage drops in the test current wire from disturbing the sense voltage. The test current, I_x flowing through R_1, goes into one side of this clip. The test voltage connection, V_x, goes to the other side of this clip. The negative test current flows through the machine's body and into the heavy aluminum case that rests on the mill table or lathe ways to provide a very low resistance connection. The datum for the test voltage is to this same aluminum case and machine body.

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[5] The circuit can tolerate a resistance from 0.15 ohms up to 5 ohms.

[6] The maximum part resistance the circuit can tolerate is 0.15 ohms less than the spindle resistance.

Simplifying Assumptions

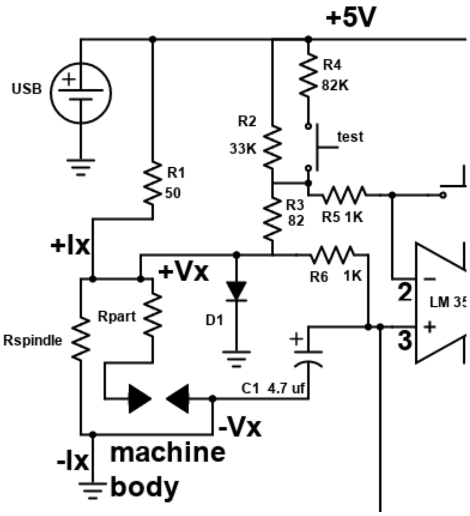
Before I start the analysis, a few approximations will make the equations easier.

Assume the supply, V_{cc}, is exactly 5 volts and R_1 is exactly 50 ohms. The spindle resistance, $R_{spindle}$, is much less than 50 ohms and the part resistance, R_{part}, is much less than $R_{spindle}$. Therefore, the test current before touchdown is

$$I_x = \frac{V_{cc}}{R_1 + R_{spindle}} \qquad (1)$$

$$I_x \approx \frac{5\ volts}{50\ ohms} = 0.1\ amps \qquad (2)$$

After touchdown, $R_{spindle}$ is in parallel with R_{part} but given my assumptions, the resulting resistance is essentially just R_{part}.

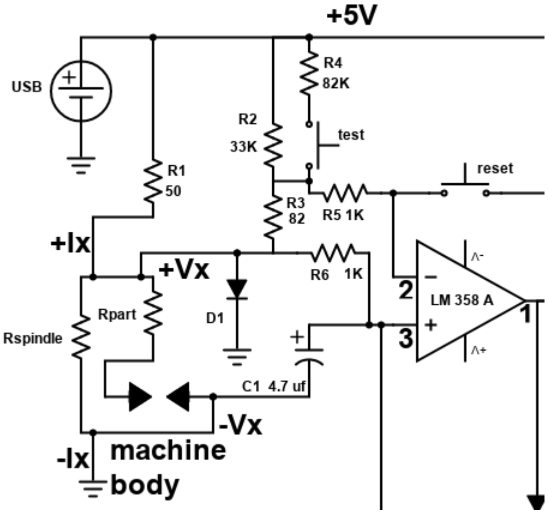


At touchdown, $+V_x$ is almost zero compared to +5V. With the test button held down, This means that the voltage across R_2 and R_4 is almost constant, so the current through them must also be almost constant. This current flows through R_3. The voltage across R_3 is almost constant over the full range of $+V_x$ voltages.

When the test button is released, the voltage across R_3 is slightly less.

Analysis

Before Touchdown



Before touchdown,

$$+V_x = (I_x \times R_{spindle}) \qquad (3)$$

relative to $-V_x$.

When C_1 charges up,

$$V_{pin\ 3} = (I_x \times R_{spindle}) \qquad (4)$$

relative to $-V_x$.

At all times,

$$V_{pin\ 2} = +V_x + V_{os} \qquad (5)$$

relative to $-V_x$.

Where V_{os} ideally equals the voltage across R_3. More on this later.

Before touchdown, the opamp sees an input voltage of

$$V_{pin\ 3} - V_{pin\ 2} = (I_x \times R_{spindle}) - \left[(I_x \times R_{spindle}) + V_{os}\right]$$

$$V_{pin\ 3} - V_{pin\ 2} = -[V_{os}] \qquad (6)$$

V_{os} has three contributors. The first is the voltage drop across R_3. In the test mode, R_2 and R_4 are in parallel with their current flowing mostly through R_3. In the Run mode, R_4 is removed. The USB voltage is 5.00 ± 0.15 volts. All resistors are ± 5%. This boils down to a worst-case voltage range in the Test mode for R_3 of 15 mV to 20 mV. In the Run mode, it is 11 mV to 14 mV. Note that the Test mode and Run mode voltages track. For example, if one is low, the other will also be low.

Secondly, we have the voltage drop across R_5 due to the opamp's Input Bias current. I chose 1K for R_5 to minimize this effect. The worst-case input bias current is 0.2 µA[7] so the maximum drop across R_5 of $1K \times 0.2\ \mu A = 0.2$ mV is small enough to be ignored.

The third contributor to V_{os} is input offset voltage. For the LM358, it can be as large as 9 mV. This means that I can short the input pins together, and the internal circuit can see anything from -9 mV to +9 mV.

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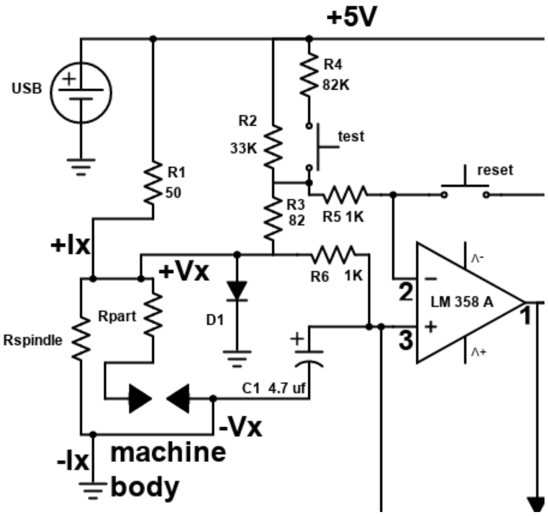
[7] https://www.ti.com/lit/ds/symlink/lm158-n.pdf page 6

Therefore, in the Test mode, the absolute worst-case range for V_{os} is 6 mV to 29 mV. In the Run mode, the absolute worst-case range for V_{os} is 2 mV to 23 mV.

Nominally, V_{os} in the Test mode is 17 mV, and in the Run mode, it is 12 mV.

By design, V_{os} is never less than 2 mV. This ensures that before touchdown and when armed, we do not indicate a false touchdown due to component variation.

At the Instant of Touchdown



At the instant of touchdown,

$$+V_x = I_x \times R_{part} \qquad (7)$$

relative to $-V_{x,}$ assuming that R_{part} is much smaller than $R_{spindle}$, so their parallel combination is approximately R_{part}.

We know that

$$V_{pin\ 2} = +V_x + V_{os} \quad (5)$$

relative to $-V_x$.

and

$$V_{pin\ 3} = (I_x \times R_{spindle}) \qquad (4)$$

relative to $-V_x$

From (7) and (5) at the instant of touchdown we get

$$V_{pin\ 2} = [I_x \times R_{part}] + V_{os} \qquad (8)$$

From (4) and (8), we can calculate the opamp's input voltage at the instant of touchdown

$$V_{pin\ 3} - V_{pin\ 2} = [I_x \times R_{spindle}] - [I_x \times R_{part}] + V_{os} \quad (9)$$

The threshold is when the ideal input[8] to the opamp is zero -

$$\left[I_x \times R_{spindle}\right] = \left[I_x \times R_{part}\right] + V_{os}$$

$$R_{spindle} - R_{part} = \frac{V_{os}}{I_x} \qquad (10)$$

During the Test mode, V_{os} can be as low as 6 mV

$$R_{spindle} - R_{part} = \frac{6\ mV}{0.1\ amps} = 0.06\ ohms$$

V_{os} can be as high as 29 mV

$$R_{spindle} - R_{part} = \frac{29\ mV}{0.1\ amps} = 0.29\ ohms$$

During the Run mode, V_{os} can be as low as 2 mV

$$R_{spindle} - R_{part} = \frac{2\ mV}{0.1\ amps} = 0.02\ ohms \quad (11)$$

V_{os} can be as high as 23 mV

$$R_{spindle} - R_{part} = \frac{23\ mV}{0.1\ amps} = 0.23\ ohms$$

In all cases, $R_{spindle} - R_{part}$ must be larger than this limit.

These extremes do track: If we are in the test mode and have a threshold of 0.06 ohms, we will be around 0.02 ohms in the Run mode. If at 0.29 ohms in the Test mode, we will be around 0.23 ohms in the Run mode.

As the opamp sees its input voltage change from negative to positive, it will slew its output voltage from near 0 to about 3.5 volts. The minimum gain is 25,000, which means a change of no more than 0.14 mV so has minimal effect on the threshold.

---

[8] The actual input does not contain input offset voltage but that is included in the equation.

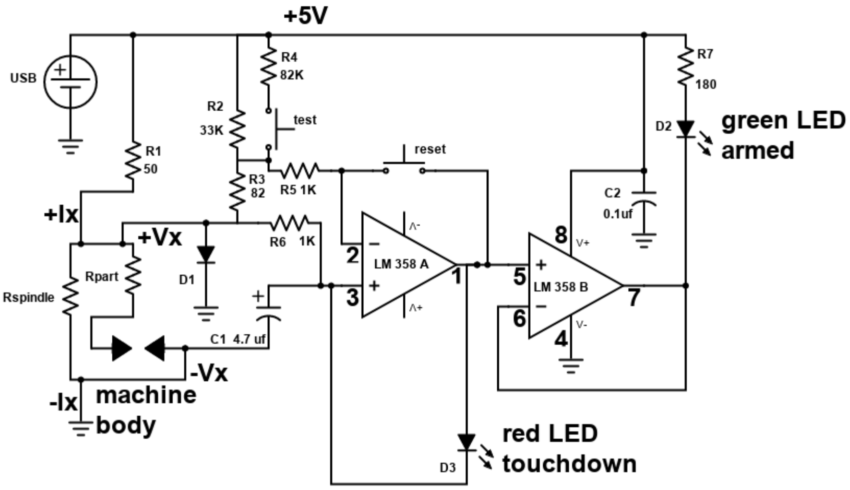
When the opamp's output slews positive, we call touchdown.

In the absolute worst-case, the circuit will detect a drop in resistance of 0.29 ohms.

Nominally, the circuit will detect a drop in resistance of 0.17 ohms.

On my mill, $R_{spindle}$ is around 1.3 ohms and R_{part} is around 0.06 ohms. $R_{spindle} - R_{part}$ is therefore around 1.2 ohm which is much larger than the 0.29 ohm threshold. If $R_{spindle}$ fell below 0.35 ohms, the Test mode would indicate a failure.

After Touchdown



Due to D_1, we know that $+V_x$ cannot be greater than about 0.7V. After touchdown, $V_{pin\ 1}$ is around 3.5V. The forward voltage of D_3 is around 1.6V. The voltage across R_6 is therefore at least 3.5 – 1.6 – 0.7 = 1.2V so the current is 1.2 mA, enough current to make D_3 visible.

With D_3 on, the opamp sees a large positive voltage on its input which further drives the output high. The result is the opamp latches up with its output high. By pushing the Reset button, the opamp's gain falls to 1. This drops $V_{pin\ 1}$ enough to turn off D_3. Then, when Reset is released, the opamp's output returns to near 0 volts.

This opamp can output a voltage of 20 mV if it doesn't sink more than 0.5 mA[9]. If it sinks 5 mA, the output voltage can rise to 2V. Had I connected the green LED to pin 1, it could pull this node up to about 2V and cause D_3 to conduct. Instead, I isolate the green LED's current by driving it from the second opamp. Opamp A then only sinks the leakage current of D_3 plus the bias current of the positive input of opamp B. This is no more than 10 μA if D_3 is an LED or opto[10] and 0.2 μA for the opamp[11].

---

[9] spec sheet, bottom of page 6. V_{OL}

[10] See page 9 for details. I looked at this opto.

[11] Spec sheet, page 6

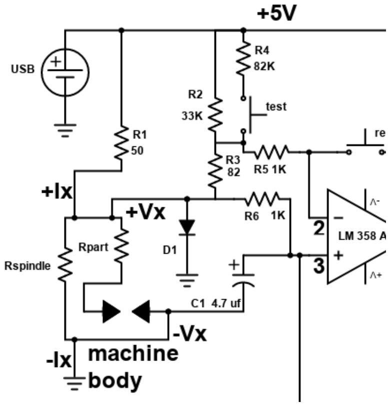
The green LED nominally drops 2.2V. Given a V_{cc} of 5V and the opamp's output voltage of 2V, we can select a limiting resistor such that the current is 5 mA:

$$\frac{5V - 2.2V - 2V}{5\ mA} = 160\ ohms$$

The closest standard value is 180 ohms.

Appendix II: Testing Details

Estimated Threshold



The voltage across R_3 in Run mode was estimated[12] at 12.0 mV at touchdown. The test current measured 87.2 mA. This puts the Run mode threshold at $\frac{12.0\ mV}{87.2\ mA} = 0.132$ ohms when assuming zero input offset voltage. Input offset is ±9 mV or $\pm\frac{9\ mV}{87.2\ mA} = \pm 0.103$ ohms.

Case 1

I measured V_x at 224.7 mV which says $R_{spindle}$ $\frac{224.7\ mV}{87.2\ mA}$ = 2.58 ohms. With R_{part} = 50 ohms, I measured 218.0 mV, a drop of 224.7mV – 218.0mV = 6.7 mV, and the circuit did not detect the drop. With 38.8 ohms, I measured 215.1 mV, a drop of 9.6 mV and did detect touchdown. Averaging these two readings, the threshold is a drop of around 8.2 mV, so a resistance threshold of 0.09 ohms.

Case 2

Rspindle = 0.283 ohms. No detect for a drop of 12.7 mV. There was detection for a drop of 15 mV. The estimated threshold is 13.9 mV, so a resistance threshold of 0.16 ohms.

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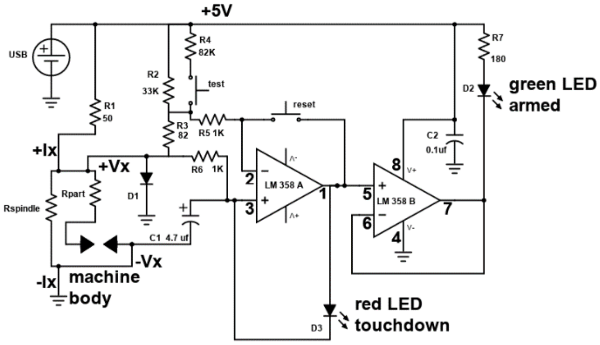
[12] I screwed up here because I could have measured this voltage with $R_{spindle} = 0$. However, my estimate should be good enough here.

Discussion



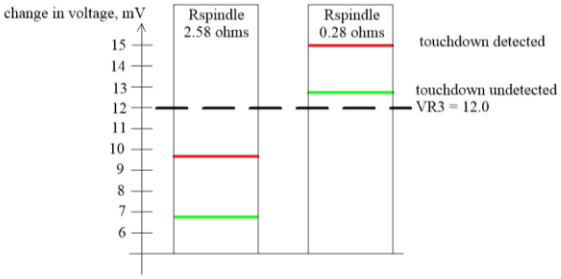
I measured V_{R3} at 11.5 mV with $R_{spindle}$ = 2.58 ohms. Then I measured I_x at 87.2 mA with the DVM replacing $R_{spindle}$.

Assuming R_3 is 82 ohms, and the supply is at 5.00V, R_2 is $\frac{5.00v - 0.2247v}{\left(\frac{11.5\ mV}{82\ ohms}\right)} = 34.06K$.

I did not measure V_{R3} at touchdown when $+V_x$ is about zero, but, given my estimates above, expect it to be $82\ ohms \times \frac{5.00v}{34.06K} = 12\ mV$.

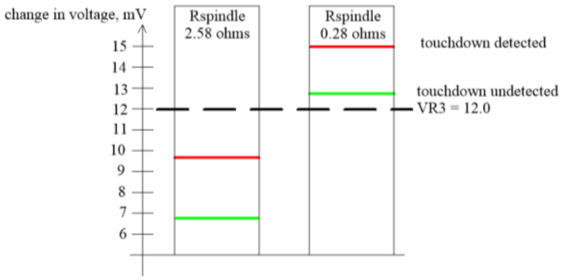
The ideal threshold, ignoring Input Offset Voltage, is therefore $\frac{12\ mV}{87.2\ mA}$ = 0.14 ohms in Run mode.

Range	2.58 ohm $R_{spindle}$	0.28 ohm $R_{spindle}$
Pre-touchdown, mV	224.7	24.5
No detect, mV	218.0 (6.7 drop)	12.0 (12.5 drop)
Detect, mV	215.1 (9.6 drop)	9.5 (15 drop)
Estimated threshold, mV	8.2 mV drop	13.8 mV drop
Estimated threshold, ohms	0.09	0.16



The 2.58 ohm $R_{spindle}$ data shows an estimated Run mode threshold of 0.09 ohms while the ideal threshold is 0.14 ohms assuming zero Input Offset Voltage. This discrepancy can be explained by assuming an Input Offset Voltage of 11.5 mV – 8.2 mV = 3.3 mV.

Range	2.58 ohm Rspindle	0.28 ohm Rspindle
Pre-touchdown, mV	224.7	24.5
No detect, mV	218.0 (6.7 drop)	12.0 (12.5 drop)
Detect, mV	215.1 (9.6 drop)	9.5 (15 drop)
Estimated threshold, mV	8.2 mV drop	13.8 mV drop
Estimated threshold, ohms	0.09	0.16



When I look at the 0.28 ohm $R_{spindle}$ data, I see that an Input Offset Voltage of 11.5 mV – 13.8 mV = -2.3 mV is needed. Input Offset Voltage should not change over the Common-Mode Input Voltage Range so I don't understand this shift of 5.6 mV.

I don't know if it is a coincidence that the average estimated threshold between the upper end and the lower end of the $R_{spindle}$ range is 0.13 ohms which matches the ideal threshold. This won't be the first time that Murphy[13] has tried to fool me.

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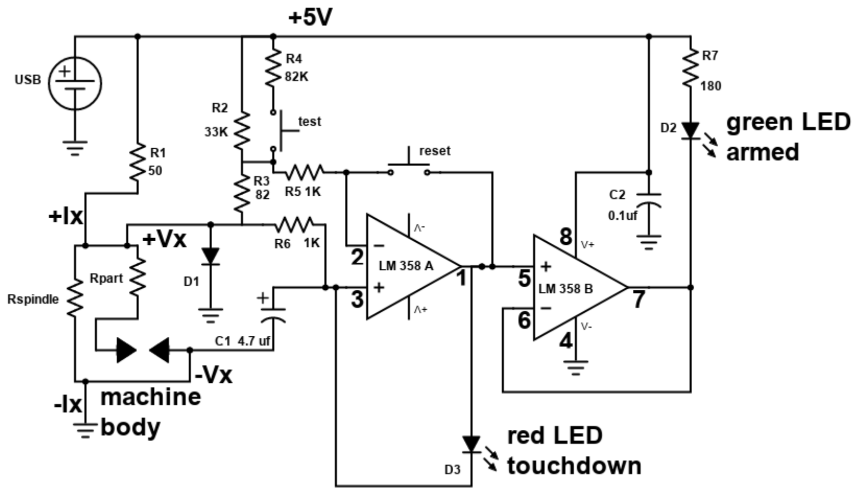
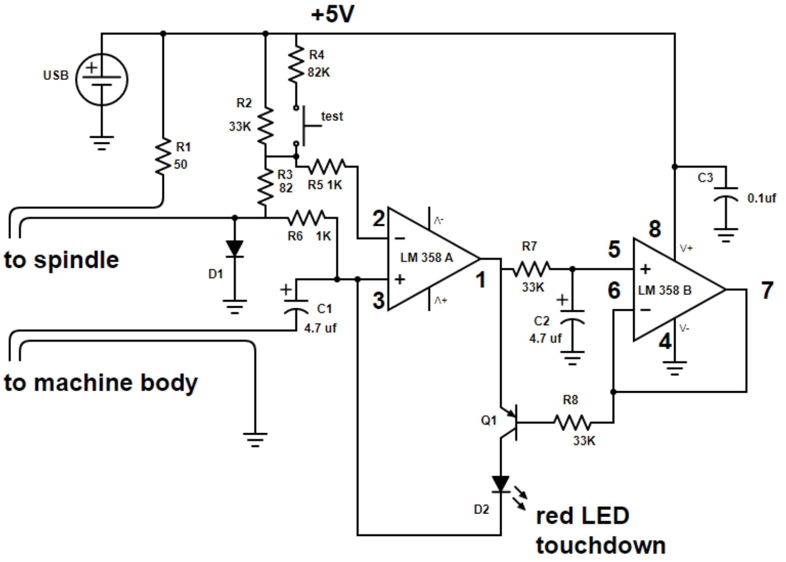
[13] Of Murphy's Law fame

Appendix III: Version 2

Comparison



An essential feature of version 1 is the positive feedback through the red LED. It provides a snap action at touchdown. As soon as opamp A detects touchdown, pin 1 rises. Then D3 turns on, locking in the state. This positive feedback gives us the maximum sensitivity and fastest response. I like that and didn't want to give it up.

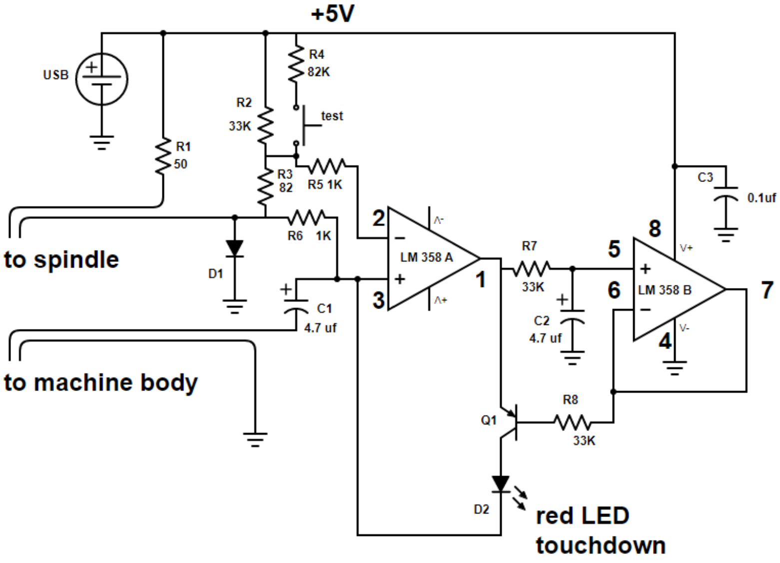


Version 2 adds a switch, Q_1, in series with D_2. Opamp A, but the circuit to the left of it is unchanged.

I repurposed the second opamp and added R_7, R_8, and C_2.

Q_1 is any low power, general purpose PNP transistor.

Overview



At touchdown, the voltage on pin 1 quickly rises to about 3.5V. C_2 has zero voltages across it. Pin 7, therefore, has close to zero volts on it. We then have about 3.5V across the series combination of the emitter-base junction of Q_1 and R_8. The result is a current flowing out of Q_1's base that turns it fully on[14]. D2's anode is essentially connected to pin 1. Therefore, at touchdown, this version acts the same as version 1.

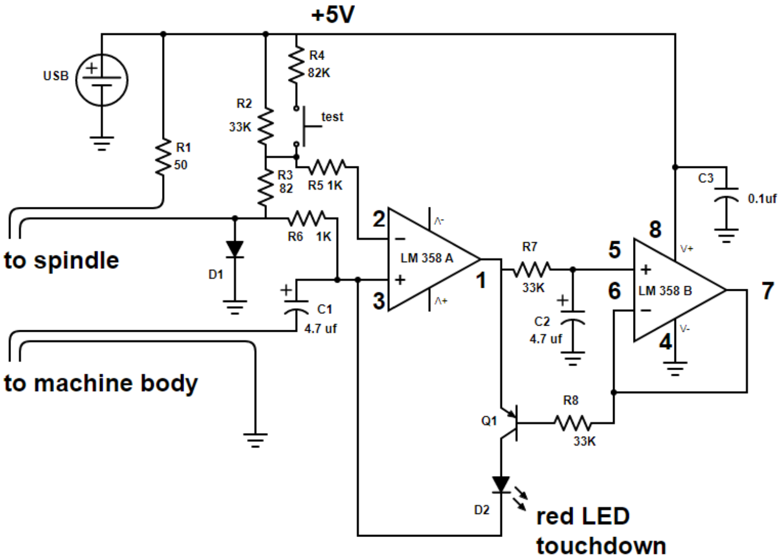
C_2 charges up, which causes the current in R_8 to fall. At some point, this current is not enough to keep Q_1 fully on. The voltage between emitter and collector will rise as the current out of the collector falls. At some point, this current is small enough that pin 3 falls below pin 2, causing pin 1 to drop to near 0V. D_2 is then off, and C_2 discharges back to 0V. The cycle has ended.

---

[14] By "fully on", I mean saturation. The voltage between emitter and collector is less than 0.2 volts.

Version 2 Details

Before Touchdown



Pin 1 is near 0V, and C_2 is fully discharged. This sets pin 7 near 0V. No current flows out of Q_1's base, so Q_1 is off. Therefore, D_2 is dark.

At Touchdown

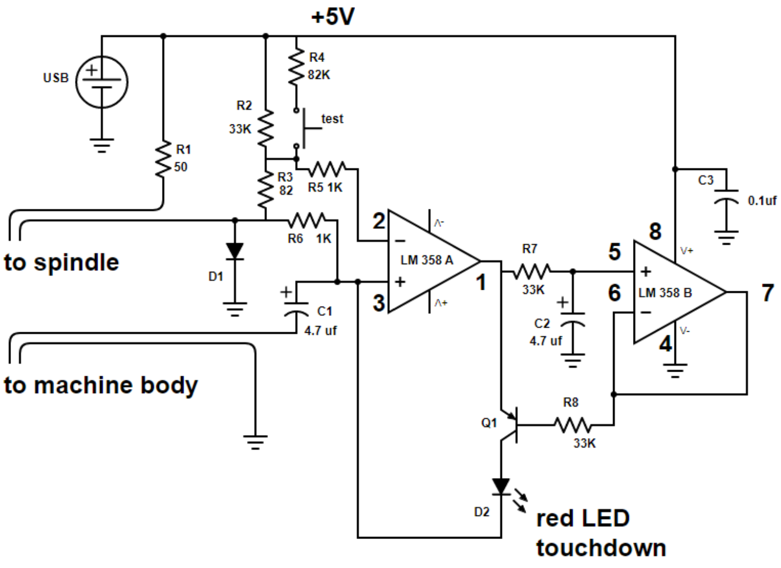
At the instant of touchdown, pin 1 quickly rises to about 3.5V. C_2 charges from 0 volts towards 3.5V. This causes pin 7 to follow it. The voltage across R_8 is set by the voltage at pin 1 minus the emitter-base voltage of about 0.65V minus the voltage at pin 7. Assuming[15] pin 7 is at 0V, the voltage across R_8 would be 3.5 – 0.65 = 2.85V, forcing a current of $\frac{2.85v}{33K} = 86\ \mu A$.

The maximum current through D2 is at the instant pin 1 jumps up to 3.5V as C1 charges. The voltage at pin 3 is near zero so the current through D2 is limited by the opamp to be at least 40 mA. While in this overload state, C1 is being charged from near 0v to a valued limited by R6.

The left end of R_6 is essentially 0v at touchdown. The voltage across D2 is around 1.7V, so the current through D2 is around $\frac{3.5v-1.7v}{1K} = 1.8\ mA$ after C1 has charged up. This put the final voltage at pin 3's at $1K\ \times 1.8\ mA = 1.8v$ just after pin 1 slews to 3.5v.

---

[15] The spec sheet for the opamp states that pin 7 will be less than 20 mV if it sinks 50 μA and less than 200 mV if it sinks 20 mA. Compared to 3.5V, even 200 mV can be ignored.



For C1,

$$I = C_1 \frac{dv}{dt} \qquad (1)$$

The current is at least 40 mA, C is 4.7 µf, and *dv*, the change in voltage, is 1.8v. solving for *dt*, I get

$$dt = 4.7\mu f \frac{1.8v}{40\ mA}$$

$$dt = 0.2\ ms$$

In other words, I can ignore the time it takes to charge up C1 because it is much smaller than the other times calculated here.

While the Red LED is On

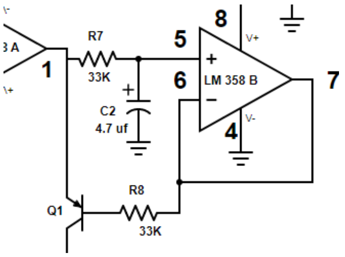
D2 is lit as long as Q1 is on. The emitter of Q1 is at about 3.5v, and its base current depends on the voltage at pin 7. As R7 charges C2, the voltage at pin 7 rises. At some point, this voltage is high enough that insufficient base current flows. Then Q1 starts to turn off. The current through D2 to fall, which causes the voltage at pin 3 to fall. Ideally[16], when the voltage at pin 3 is less than the voltage at pin 2, pin 1 drops from 3.5v down to 0v.

Nominally, pin 2 is 12 mV above the anode of D1. This means that when the current flowing from right to left through R6 drops below $\frac{12\ mv}{1k} = 12\ \mu A$, pin 1 starts to fall to 0v.

The spec sheet for a 2N3906 shows a minimum gain of 80. Given a base current of $86\ \mu A$ and a collector current of 1.8 mA (page 31), our forced gain is $\frac{1.8\ mA}{86\ \mu A} = 21$. This tells us that we have more base current than needed to support the collector current. In other words, the transistor is in saturation and its emitter-collector voltage is less than 0.2v. We will remain in saturation until the base current is somewhere below $\frac{1.8\ mA}{80} = 22\ \mu A$. Given pin 1 is at 3.5v, this sets pin 7 at $3.5v - 0.65v - (33K \times 22\ \mu A) = 2.1v$.

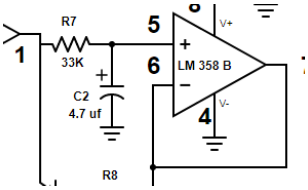
---

[16] Input offset voltage can shift this point by ± 9 mV.



We know that Q1 will be off when its emitter-base voltage is 0.5v. Assuming Q1 has a very large gain, the base current approaches zero. This means pin 7 would be at $3.5v - 0.5v - (33K \times 0\ \mu A) = 3v.$

Therefore, we can say that Q1 will turn off when pin 7 is somewhere between 2.1v and 3v.



R7 and C2 form an RC circuit. The initial voltage across C2 is 0v and the final voltage, if Q1 doesn't turn off, is 3.5v.

I will assume C2 is ideal[17]. Given this information, I can jump to the equation that describes this standard RC circuit:

$$V_{C2}(t) = 3.5v\left(1 - e^{\frac{-t}{\tau}}\right) \qquad (2)$$

where $\tau = R_7 \times C_2$.

Nominally, R7 is 33K, and C2 is 4.7 μ*f*, so τ = 155 ms.

We can use this equation to bound when Q1 turns off after pin 1 rises to 3.5V.

The shortest time is when we change state at 2.1v:

$$2.1v = 3.5v\left(1 - e^{\frac{-t}{155ms}}\right)$$

Solving for t,

$$e^{\frac{-t}{155ms}} = 1 - \frac{2.1v}{3.5v}$$

$$\frac{-t}{155ms} = ln(0.4)$$

t = 142 ms

---

[17] It does have a parasitic shunt resistance but it should be much larger than R7 so I can ignore it.

The longest time is when we change state at 3v.

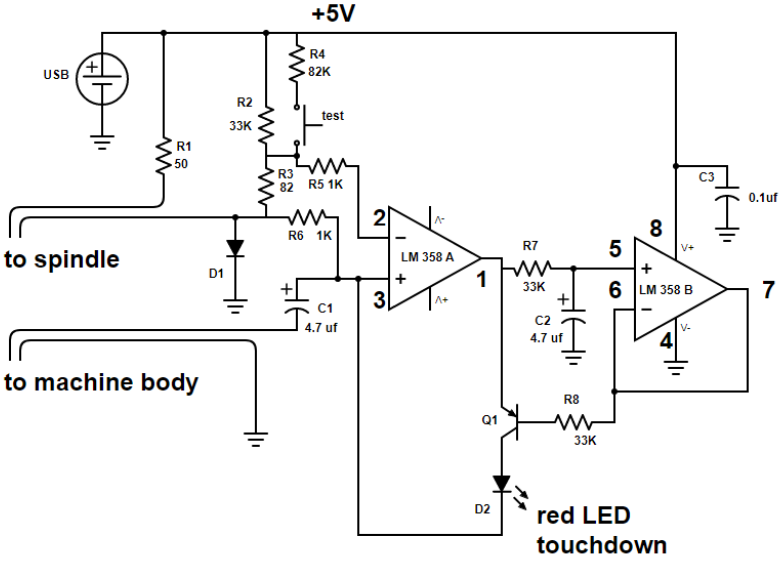
$$3v = 3.5v\left(1 - e^{\frac{-t}{155ms}}\right)$$

This gives us t = 302 ms.

Therefore, the red LED will stay on between 142 and 302 ms.

You can change R7’s value to adjust the nominal on-time.

Reset Times



C1 and C2 must each discharge back to their non-touchdown voltages.

When Q1 turned off, C1 was charged up to 1.8V (page 31). It must discharge back to the voltage between spindle and machine body. The maximum change is when this voltage difference is 0. Ideally, pin 1 will drop from 3.5V to 0V when pin 3 is less than pin 2. Nominally, pin 2 is 12 mV above the anode of D1. Therefore, we want to know how long it takes C1 to discharge from 1.8V down to 12 mV. This is the standard RC circuit so we already have the equation:

$$V_{C1}(t) = 1.8V\left(e^{\frac{-t}{\tau}}\right) \qquad (3)$$

where τ = $R_6 \times C_1$ so 47 ms.

I want to find the time that $V_{C1}(t) = 12\ mV$

$$12mV = 1.8V\left(e^{\frac{-t}{47ms}}\right) \qquad (4)$$

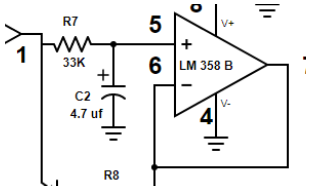
Solving for t, I get 236 ms which is the upper bound.

If the spindle resistance was large enough, D1 would turn on and set the voltage on its anode at about 0.75V. Then

$$0.75V + 12\ mV = 1.8V\left(e^{\frac{-t}{47ms}}\right) \qquad (5)$$

Solving for t, I get 40 ms which is the lower bound.

Therefore, it takes between 40 and 236 ms for C1 to discharge back to its non-touchdown state. At this time, pin 1 will fall from about 3.5V to about 0V.



After pin 1 drops to 0V, C2 needs time to discharge. We can write

$$V_{C2}(t) = 3v\left(e^{\frac{-t}{\tau}}\right) \qquad (6)$$

where $\tau = R_7 \times C_2$.

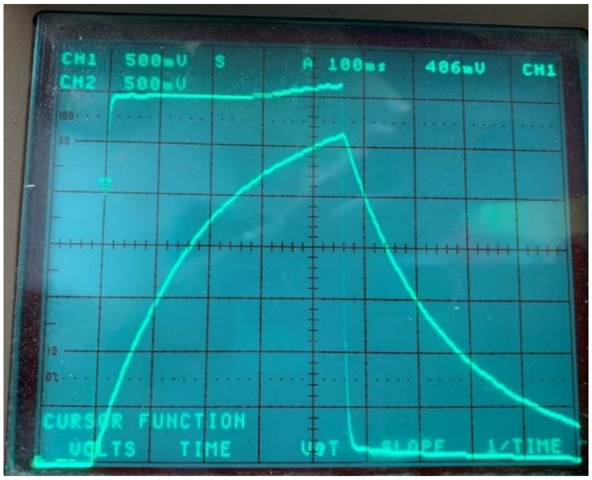
This assumes C2 charged all the way to 3v so tells us the maximum reset time. Say that C2 is at minimum when it reaches 0.2v. Then

$$0.2v = 3v\left(e^{\frac{-t}{155\ ms}}\right)$$

Solving for t, I get 420 ms. We must wait this long before starting the next touchdown cycle.

Reality

So much for theory. It is time to look at how the circuit actually behaves.



Both of these trances have a scale of 500 mV per vertical graticule. The time base is 100 ms per horizontal graticule.

Channel 1 is connected to pin 1 and shows a square pulse. Channel 2 connects to pin 5 and shows the voltage on C2.

About 280 ms after pin 1 rises to 3.5V, notice that the voltage rises linearly another 0.3V. This signals the opamp's output current going to zero. Therefore, it is signaling the time when Q1 turns off. From page **Error! Bookmark not defined.**, see that I predicted that Q1 would stay on between 142 and 302 ms after pin 1 rose to 3.5V.

Pin 1 drops to near 0V after an additional 170 ms. From page 35, I predicted this delay to be between 40 and 236 ms.

The picture is consistent with my predicted times.