A CNC Compatible Analog Electronic Edge Finder, Version 2.4

By R. G. Sparber

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Note: This is a significant redesign from Version 1.0 so I decided to release it as a new article.

Conclusion

My analog[2] Electronic Edge Finder matches the Starrett rotating edge finder within the uncertainty[3] of the Computer Numerical Control (CNC) system. Unlike the Starrett, my edge finder is compatible with Computer Numerical Control systems. The cost of the electronic components is under $5.

Background

Electronic Edge Finders (EEFs) come in three types.

- A precision switch opens or closes at touchdown
- An electrically isolated rod comes in contact with the reference surface, so acts as a switch
- the drop in resistance between a non-isolated rod and the reference surface is detected at touchdown. My EEF is of this third type.

Precision switches cost over $100. An electrically isolated rod starts at around $30. However, neither of these types permit a cutter as a probe. This option is useful when detecting touchdown with an end mill along the Z-axis or when using a boring bar at the bottom of a hole.

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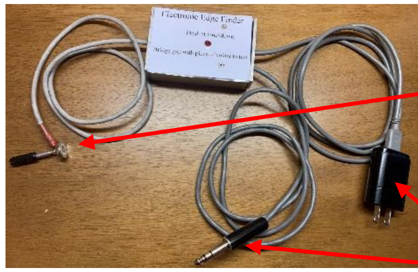
[2] For an Arduino based Electronic Edge Finder, look here.

[3] As explained in Appendix II, this is ±0.0003 inches which is also referred to as 3 tenths.

Overview

Exactly when does the probe[4] touch the stock?



Before using my Electronic Edge Finder, I place the magnetic clip on the spindle, the box on the mill table, connect power, and plug into the CNC's probe interface.

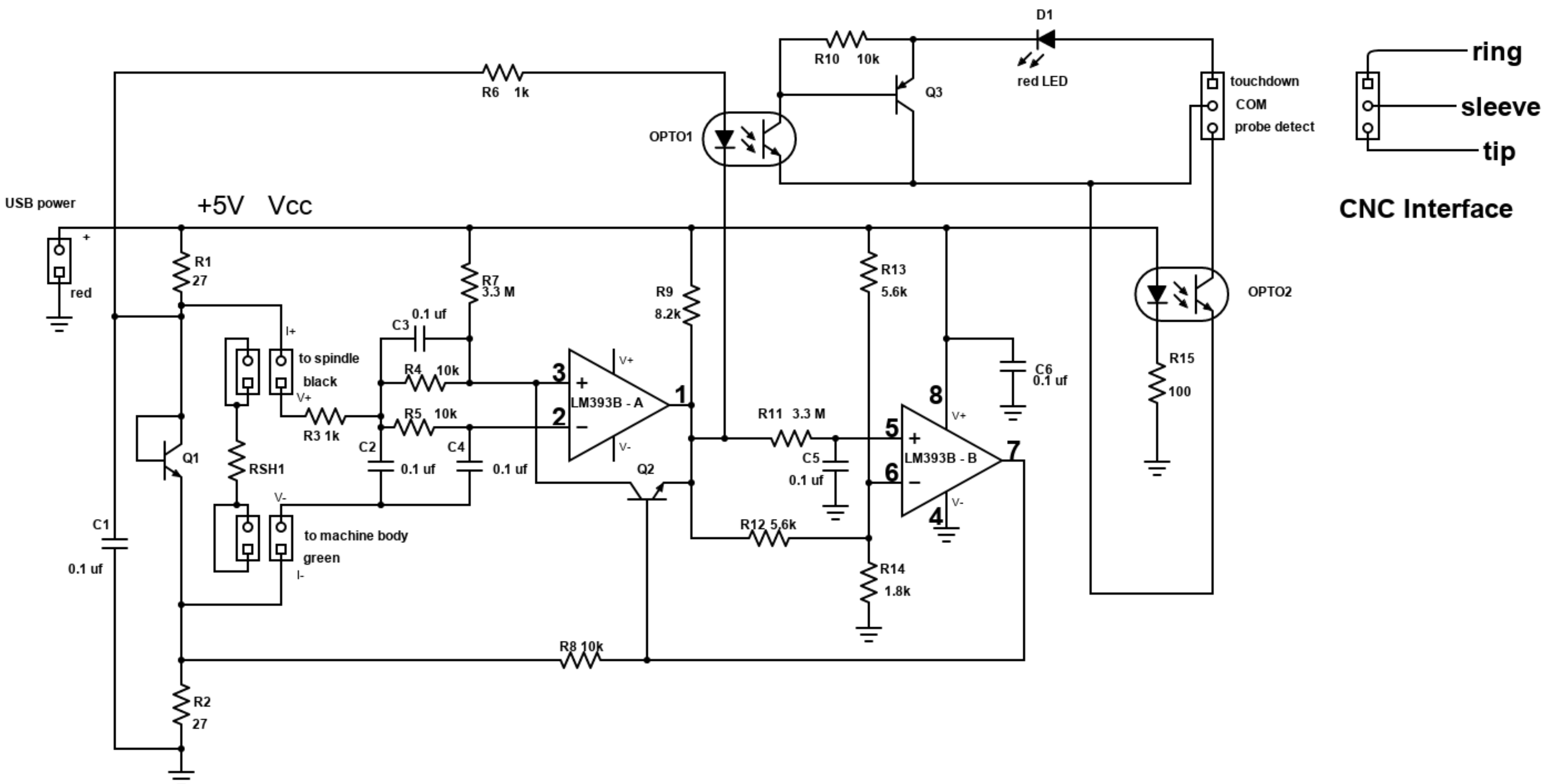
Then I command the CNC auto touchdown feature to move the probe until it detects a touchdown signal. The LED also flashes bright red for ½ second.

I see no variation between repeated touchdowns while monitoring with a finger Dial Test Indicator with a resolution of 0.1 thou[5]. Note that this is far better than the stability seen via the CNC display.

The EEF works equally well on horizontal and vertical reference surfaces. I can use an endmill as a vertical touchdown probe.

The circuit works by detecting the drop in resistance between the spindle and machine body at touchdown. A decrease in resistance of more than 0.124 ohms is sufficient. An ordinary ohmmeter sees this as a dead short.

[4] My probe was machined in place to minimize runout.
[5] A thou is 0.001 inches.



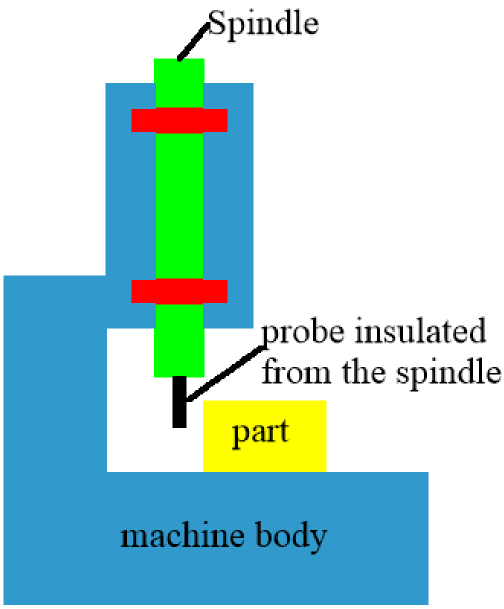
The circuit uses 28 components, of which 13 are unique values. All resistors and capacitors are ± 5%.

The only critical part is the LM393B due to its low input offset voltage.

Contents

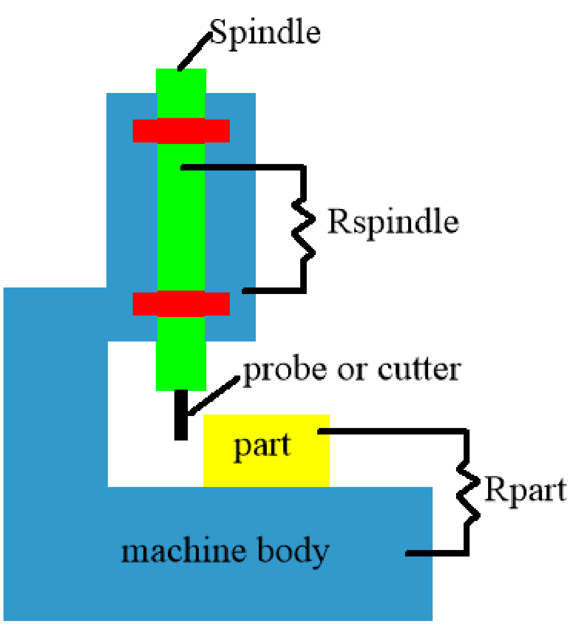
Detailed Background

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. Some EEFs utilize electrical conduction. When an ***insulated*** probe contacts a grounded reference surface, a current can flow to indicate touchdown. However, this insulation distorts and introduces error. You are also stuck with this probe and cannot substitute a cutter for a Z-axis touchdown.

My Electronic Edge Finder



My version of an EEF does not use electrical isolation. It measures the *reduction* in resistance caused by the probe or cutter touching the part. The probe or cutter is mounted in the spindle.

The electrical resistance between the spindle and machine body is $R_{spindle}$. The electrical resistance between the part and the machine body is R_{part}. 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 drop greater than 0.124 ohms is detected.

On my mill, $R_{spindle}$ varies between 0.3 and 4 ohms. R_{part} is under 0.05 ohms.

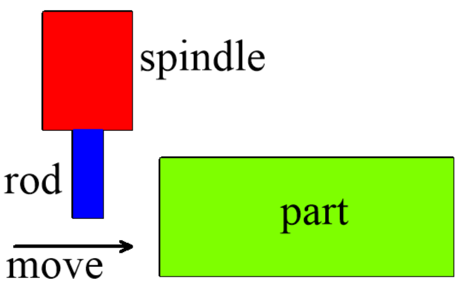
Some readers will be concerned about my test current and voltage causing damage to the spindle bearings. See Appendix III for a discussion.

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.



I can set Part 0 on the X and Y axes with a rod mounted in the spindle.

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. This arrangement permits the user to touchdown at the bottom of a hole using a boring bar.

Accuracy

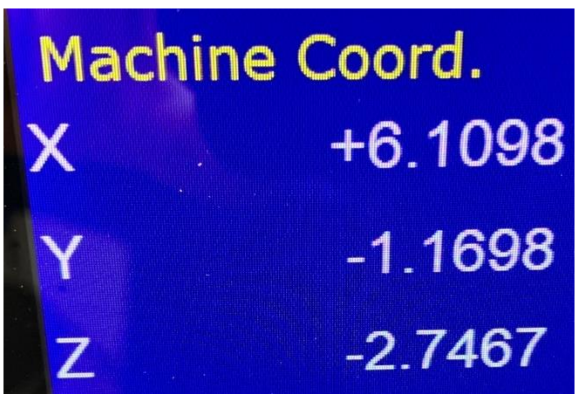
Accuracy is a tricky topic. If I limit my focus to just the accuracy of the EEF, it has zero error. The probe or cutter has only two states: in contact with the part or it is not in contact.

When the distance between probe and part is under a tenth, any vibration can cause fast transitions between these states. However, the circuit is around 1000 times faster than this mechanical movement, so it catches the first transition to touchdown.

The test voltage is too small to cause arcing, so this is not an issue. Therefore, accuracy is entirely a function of the play in the spindle bearings and runout in the probe.

As shown in the above video, there is no measurable error using a finger Dial Test Indicator.

Using my Centroid CNC system, I can touch down on a surface, set zero, and retest to see a variation of +0.0000 to -0.0001 inches. This is due to round-off error in the CNC system since we are looking at variation in the least significant digit.



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

Each time I reached Z = -2.7468 inches, the EEF detected touchdown. This is a change of a tenth.

See Appendix II for why I say the EEF is within 3.5 tenths of the result from a Starrett rotating edge finder after calibration.

The Procedure for Setting a Z Reference

I first verify touchdown detection is reliable. Then I 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[6].
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[7]. Plug the USB cable into a power source. Collect the CNC cable.
4. Bridge the gap between cutter and reference surface with a piece of solder and expect the LED to flash on for ½ second. If you do not see the flash, do not proceed.
5. Move the cutter until you see the LED flash for ½ second. This is touchdown.

The Procedure for Setting an X or Y Reference

Use a cylinder of known diameter.

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.

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

The CNC Interface

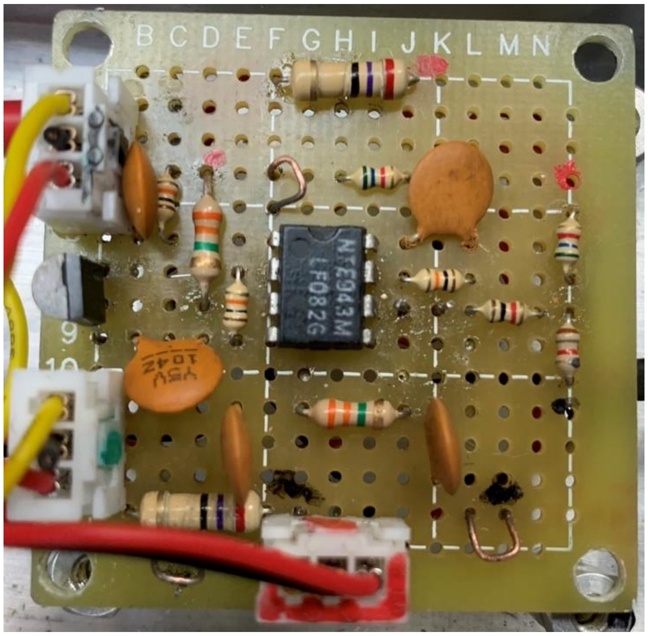
My Centroid CNC System requires two signals.

- Probe detect – tells the system I have connected the EEF. You only get an active signal when the EEF is connected and powered up
- Touchdown – this signal goes active for about ½ second at touchdown. The LED flashes only if current flows from the CNC interface board to the EEF.

I have chosen to use a ¼ inch diameter stereo plug, but any three-conductor plug and jack can be used.

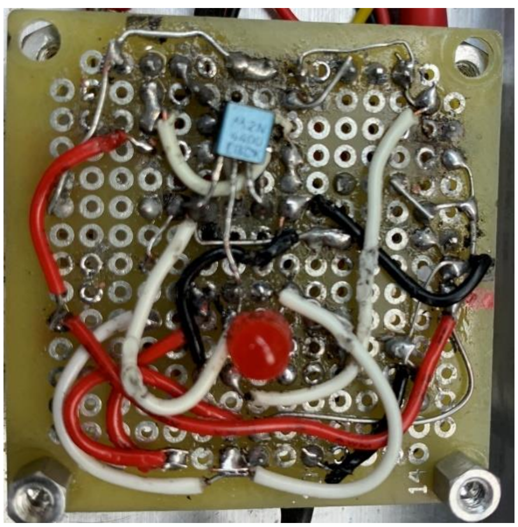
What's Inside?

Physical Layout of the Prototype

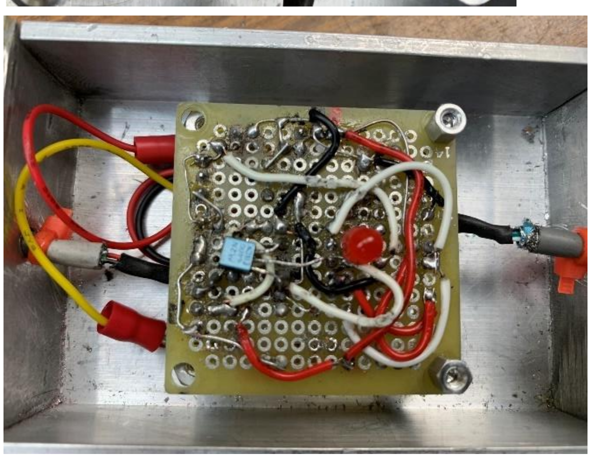


I built the circuit on a 1½-inch square "prototype board" using all through-hole devices.

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



This awful mess is the result of numerous revisions to the design. But hey, it works reliably.

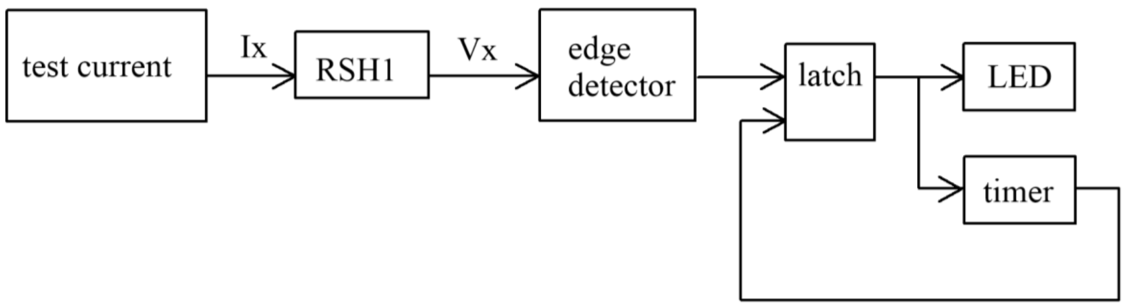


This enclosure is a bit roomy, but I had it on hand. It was no surprise that I couldn't get the second set of screws to go in. Murphy's Law.

A USB wall wart or battery pack supplies the power.

High-Level Circuit Description

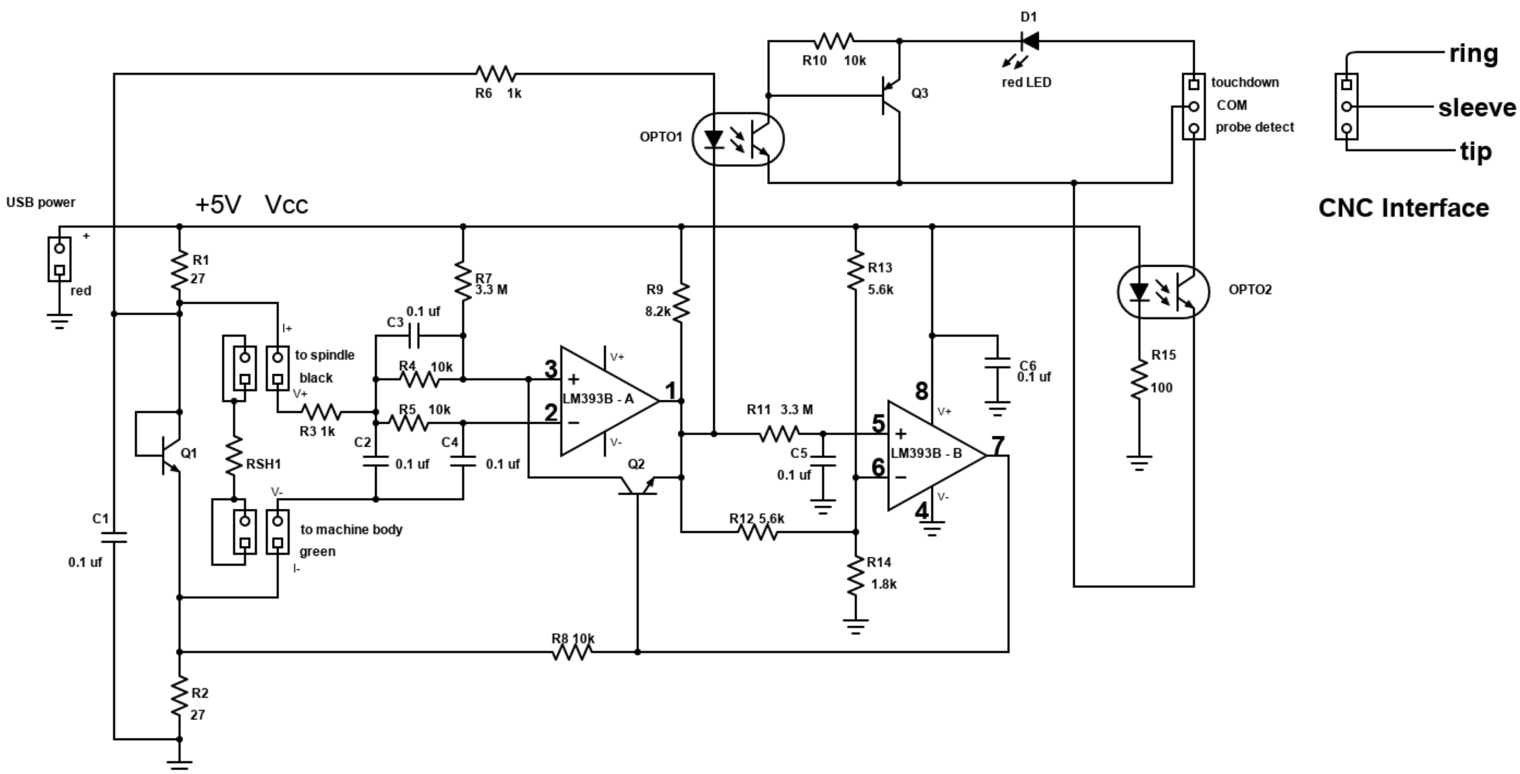
The EEF detects touchdown by looking at the resistance, R_{SH1}, between the spindle and machine body. When at touchdown, it sees a drop in this resistance of more than 0.124 ohms which causes the LED to turn on for ½ second. When I move the spindle away from the reference surface, the circuit is ready to detect touchdown again.



A test current of approximately 100 mA, I_x, is applied to $R_{SH1,}$ which generates the test voltage, V_x, which is applied to the edge detector. When RSH1 drops by more than 0.124 ohms, V_x drops by more than 0.0124V (12.4 mV). The edge detector sees this drop and causes the latch to fire, which turns on the LED and starts a timer. After ½ second, the timer releases the latch, and the LED turns off. The LED is tied to the touchdown lead on the CNC system.

See Appendix I for more information.

Schematic



I drew the schematic using the tool at digikey.com: https://www.digikey.com/schemeit/project/

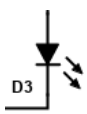
RSH1 is the resistance between the spindle and the machine body. It is not a component.

Parts List

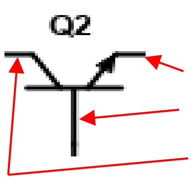
Name	Value	Quantity	Description
RESISTOR	10k	4	10K OHM 5% 1/10W
RESISTOR	27	2	27 OHM 5% 1/2W AXIAL
RESISTOR	3.3 M	2	3.3M OHM 5% 1/10W
RESISTOR	1k	2	1K OHM 5% 1/10W
RESISTOR	5.6k	2	5.6K OHM 5% 1/10W
RESISTOR	1.8k	1	1.8K OHM 5% 1/10W
RESISTOR	8.2k	1	8.2K OHM 5% 1/10W
RESISTOR	100	1	100 OHM 5% 1/4W
NON POLARIZED	0.1 uf	6	0.1UF 25V
red LED		1	HI EFF RED
NPN		2	GENERAL PURPOSE TRANSISTOR
PNP		1	GENERAL PURPOSE TRANSISTOR
LM393B - A		1	DUAL COMMERCIAL GRADE STANDARD C
Optoisolator	PC817	2	MIN 50% CTR

Notes for the novice

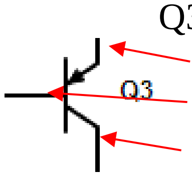
Here is the spec sheet for the LM393B.



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 backward.

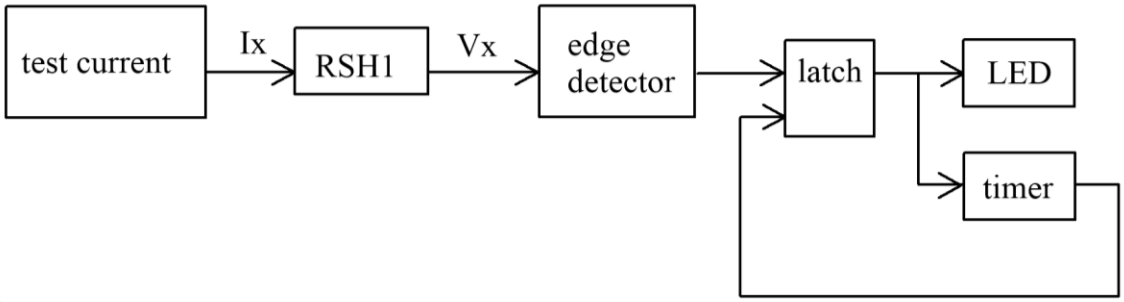


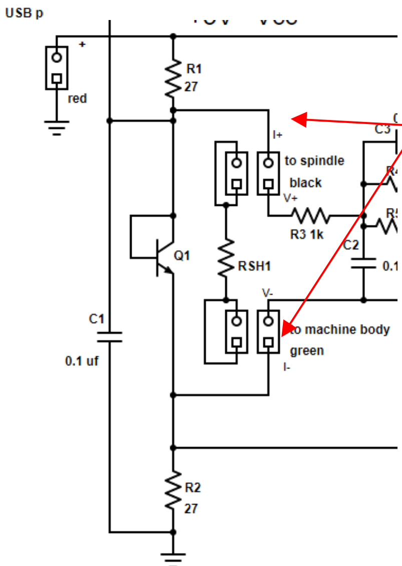
I use an NPN transistor for Q1 and Q2. It has an
emitter,
base, and
collector. The physical placement of these pins depends on the packaging.



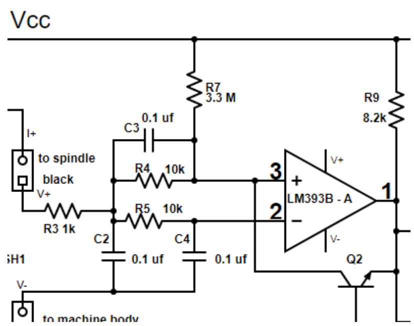
Q3 is a PNP. It has an
emitter,
base, and
collector. The physical placement of these pins depends on the packaging.

High-Level Circuit Description



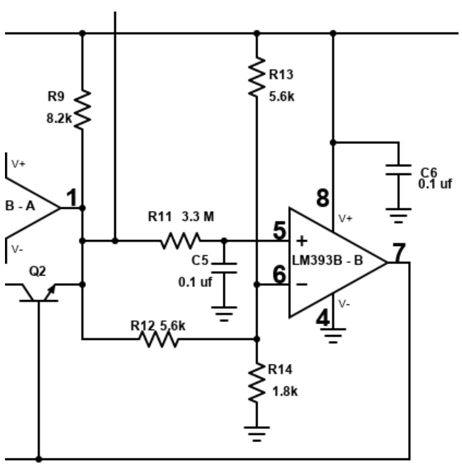


R1 and R2 generate the test current.
It is applied via connections I_+ and I_-. V_+ and V_- define V_x.
Q1 limits V_x to under 0.7V.



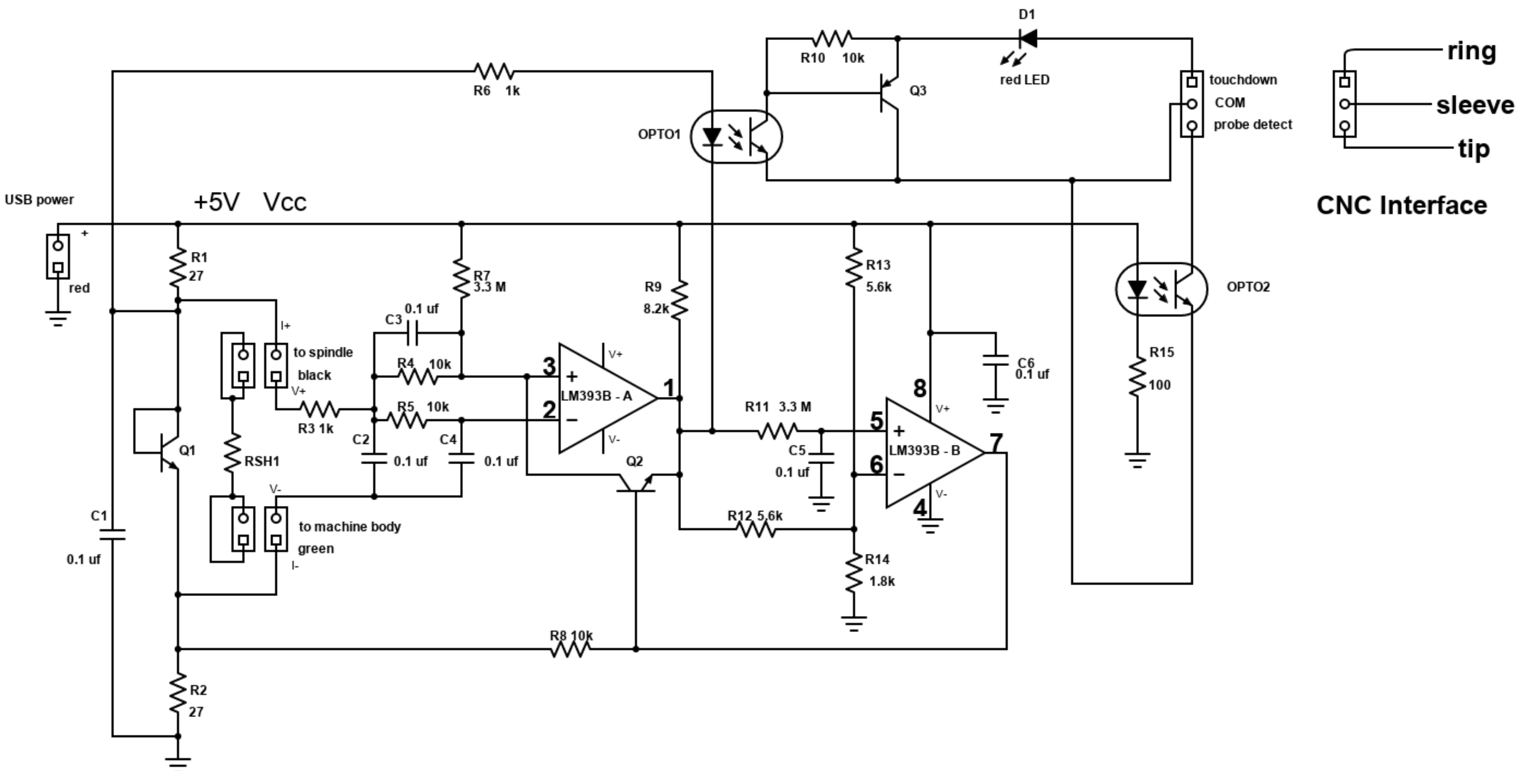
The edge detector consists of R4, R5, R7, C2, C3, and C4, which feed into LM393B – A[8]. R3 and C2 filter out high-frequency noise.

Q2 is part of the latch. When it is on, pin 1 is held low.



R11 and C5 generate an exponentially rising and falling voltage at pin 5 as a function of the voltage at pin 1. R12, R13, and R14 set the switching threshold as a function of the voltage at pin 1. When pin 5 is lower than pin 6, pin 7 pulls to near ground to ensure Q2 is off.

[8] This is half of a dual comparator integrated circuit. LM393B-A is used in the edge detector and LM393B-B is used in the timer.

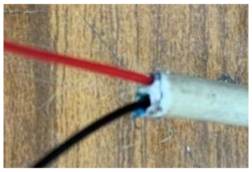


When pin 1 is an open circuit, Opto 1 is off. With no current flowing through Opto 1's output, Q3 is off, so the red LED, D1, is dark. While pin 1 pulls to near ground, current flows through Opto 1, which turns on Q3. This causes current to flow from the CNC interface circuit and through D1. The red LED lights.

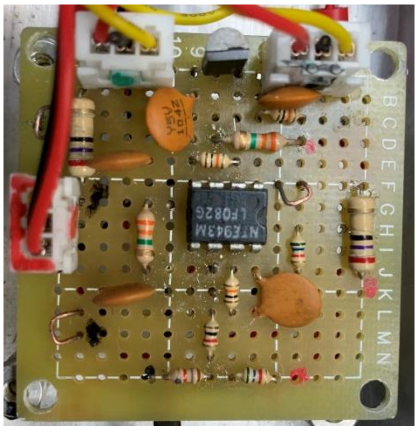
Opto 2 is on whenever 5V is present. It drives the probe detect signal from the CNC interface.

See Appendix I for details.

Construction Hints



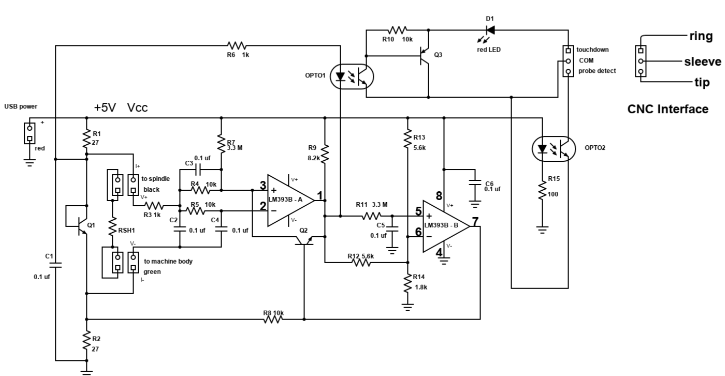
I took a scrap USB cable and cut off the non-USB plug end. Then I removed an inch of the outer insulation and inner shield from the end. I cut off the green and white wires. The red wire connects to +5V, and the black wire connects to ground.



Due to the high speed and sensitivity of the LM393B, the manufacturer does not recommend using a socket.

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

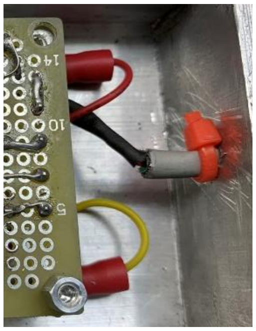
It may seem wasteful to run two wires from the board only to solder them together at the lug of the magnetic clip. This configuration is part of the Kelvin Connection, explained on page 28.



Keep the following close to each other:

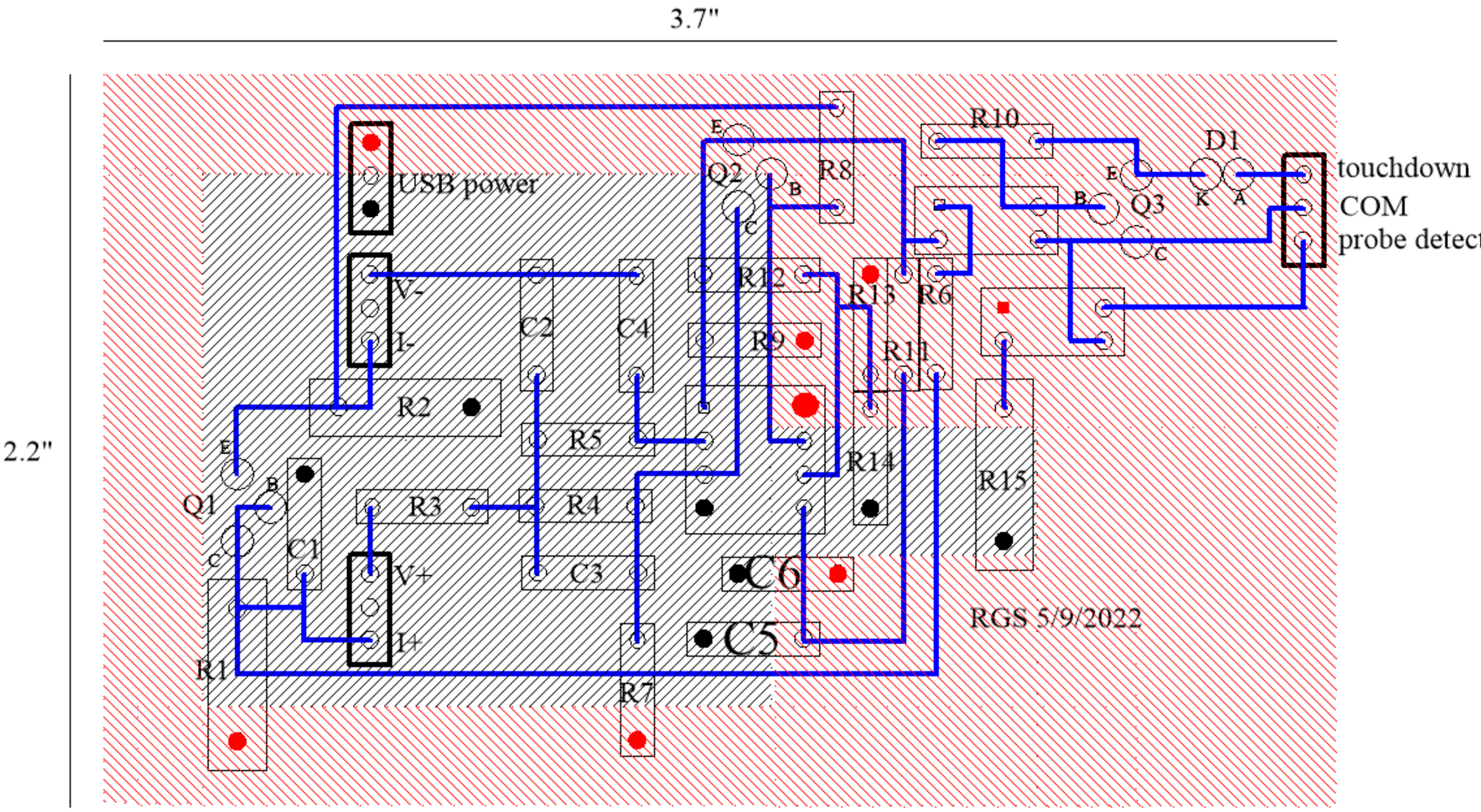
- C3, R4, R7, and pin 3
- C4, R5, and pin 2
- Q2, pins 1, 3, and 7
- C6, pins 8 and 4
- C1, R1, and R2

Keep the components and traces tied to pin 1 as far away as possible from the components and traces tied to pins 2 and 3.



Two wires run from the machine body connector to the enclosure, which rests on the machine's body.

The circuit will falsely trigger if there is poor contact between the bottom of the enclosure and the mill table or lathe ways. Even the slightest movement can cause the circuit to trigger falsely. You can achieve a solid connection by filing and or sanding the bottom of the enclosure flat.

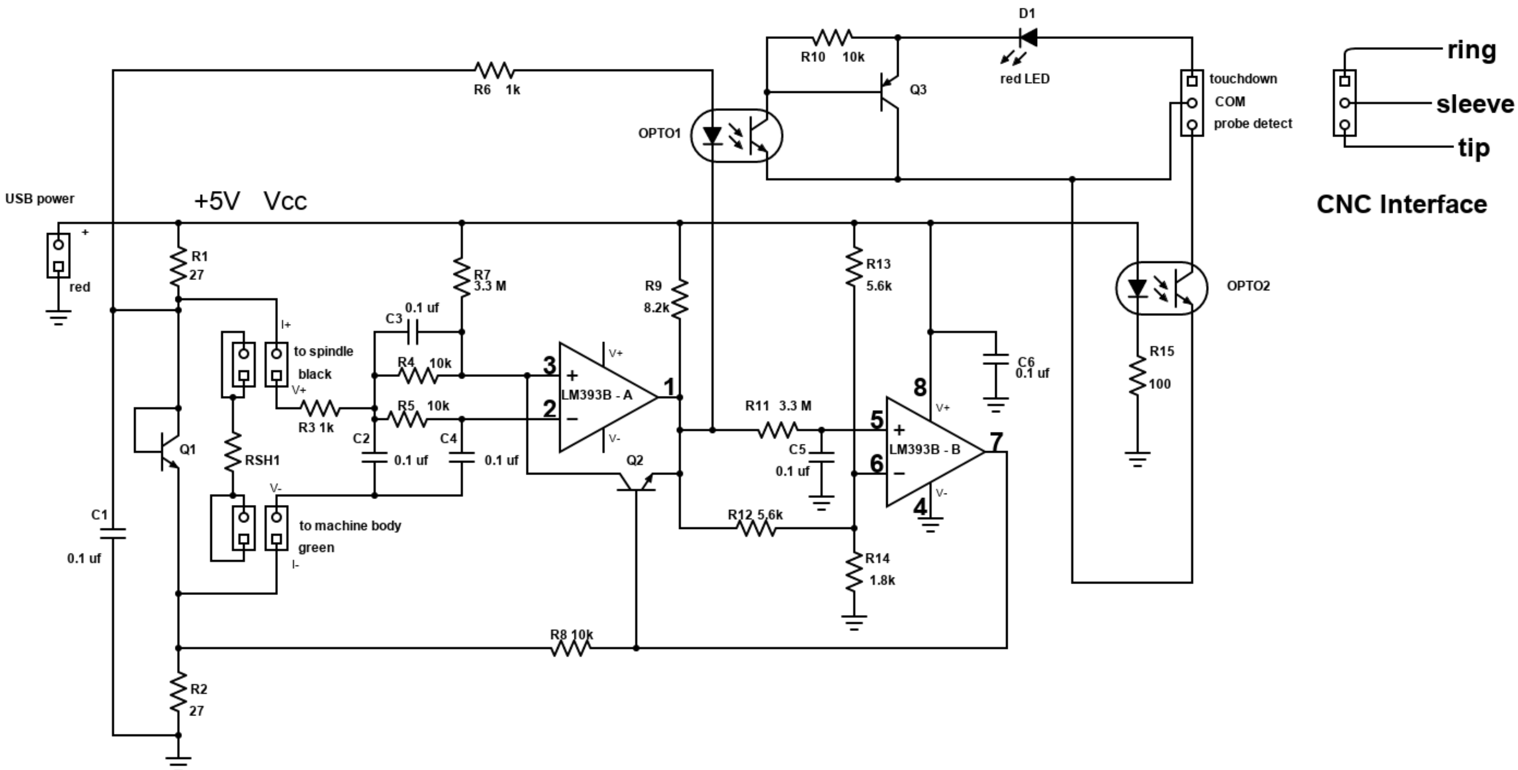


Here is one possible layout for a double-sided board using through-hole devices. The red and black shaded areas are power and ground planes on the top side. All signal traces go on the bottom side. Etch motes around each signal trace and tie the isolated copper to the nearest top side plane. Red dots mean the component lead ties to power while black dots go to ground.

Bench Testing of the Prototype

A change in resistance of more than 94 milliohms causes the LED to turn on for ½ second. Changes less than 73 milliohms were not detected. See Appendix II for details.

Debugging Tips

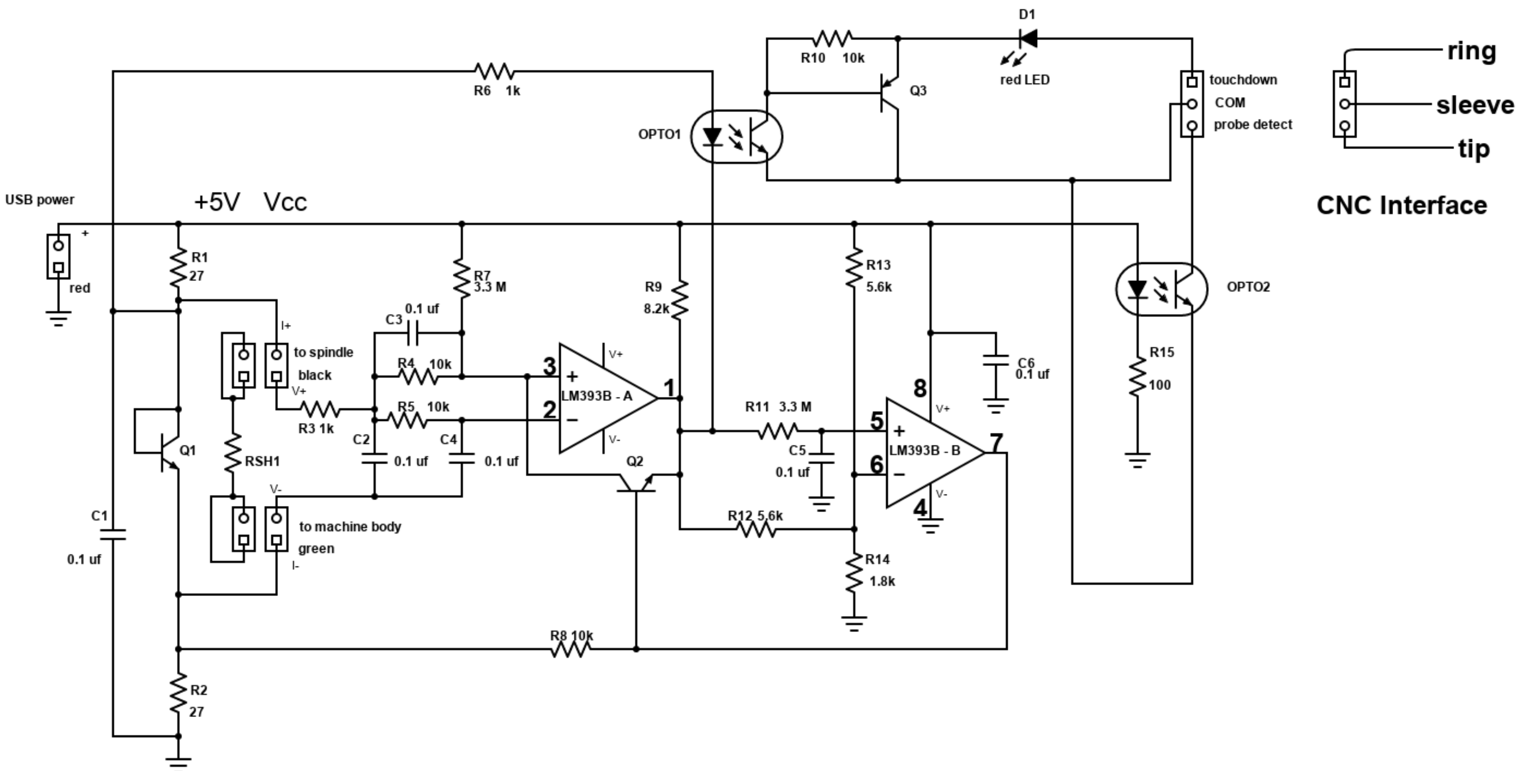


If the circuit does not work correctly, it is best to verify that all resistors are of the correct value and that all components are connected. There is still a chance that extra connections exist. We hopefully will catch them later when measuring voltages. If in doubt, go back to the spec sheets for the active devices to be sure they are right.

R1, R2, and R15 will get warm to the touch. If they are not of the proper wattage, they might overheat and fail.

If R1 seems too hot, measure the voltage on its lower terminal. If it is 0V, you have a short to ground. If R2 seems too hot, measure the voltage on its upper terminal. If it 5V, you have a short to power. If R15 seems too hot, measure the voltage at its top terminal. If it is at 5V, look for a short to power.

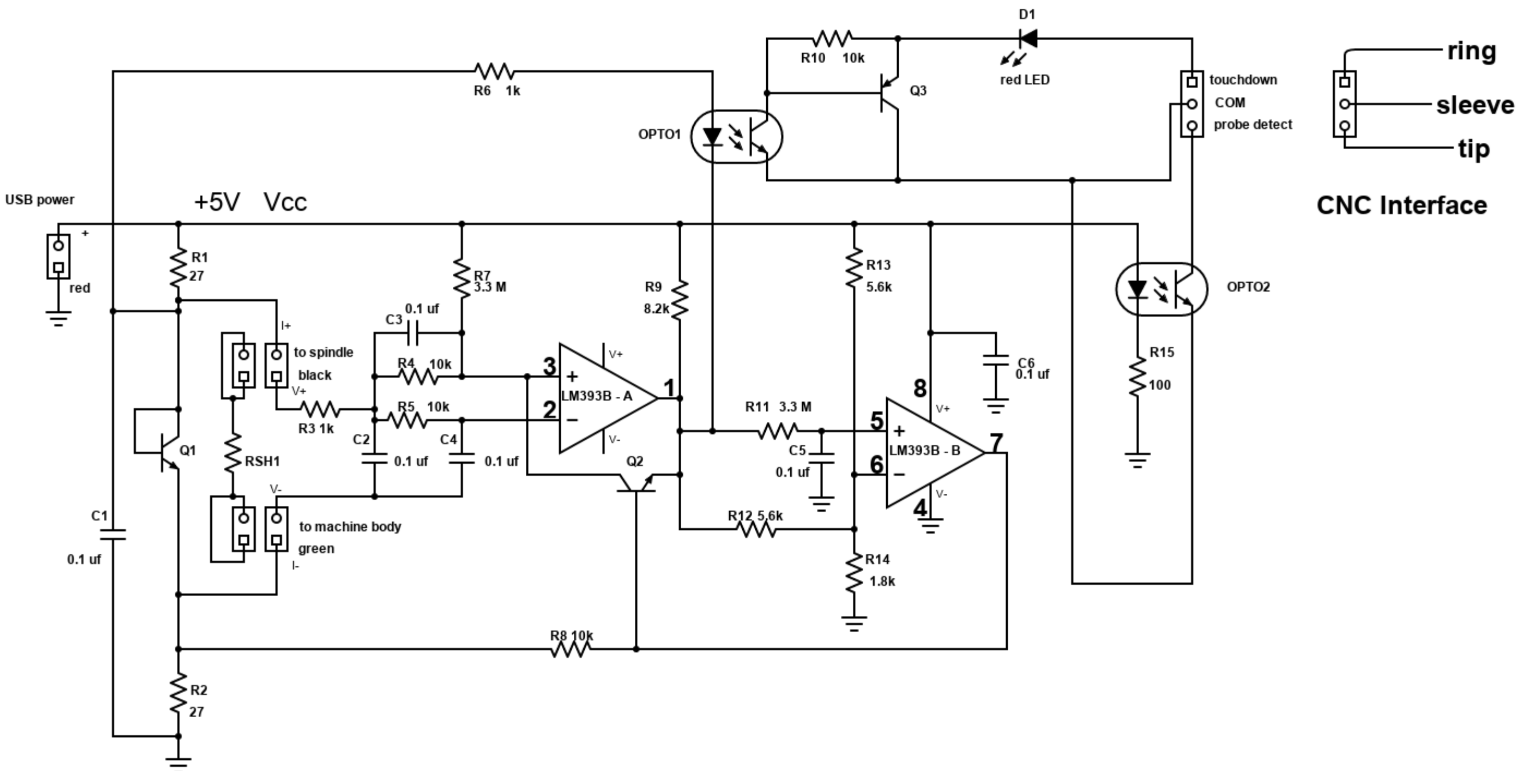
Pay close attention to the stability of the voltages. If they jump around more than in the last digit, you likely have oscillations in the circuit, which means you should not trust your reading. It isn't easy to debug this circuit when it oscillates, even if you use an oscilloscope. Remove Q2 to quiet the circuit down for debugging.



Connect the COM terminal of your voltmeter to circuit ground. Starting on the far left with the magnetic probe isolated from the enclosure, you should see 5V at the top of R1 and 2.85V at the bottom. The top of R2 should be at 2.15V. With the magnetic probe touching the enclosure, the bottom of R1 and the top of R2 should be at 2.5V. If these voltages are more than 10% off, look for extra connections at this point.
With the magnetic probe touching the enclosure, pin 2 and 3 should be at about 2.5V. Measure the voltage at pin 3 relative to pin 2 and expect to see about 7.6 millivolts.

The voltage at pin 1 should be 2.9V. If it is more like 1.2V, verify R9 is connected and of the correct value. If 0V, there is a short to ground. If 0.2V, disconnect pin 1 from the other components on this net. If you then see 2.9V, either the device is defective or pin 3 is not more positive than pin 2 by 7.6 millivolts.

If you see none of these voltages, closely inspect your soldering and look for conductive particles pulling this node to adjacent nodes. I had a tiny solder fleck that caused the voltage to stay around 0.8V but it would drift up and down by 0.4V.



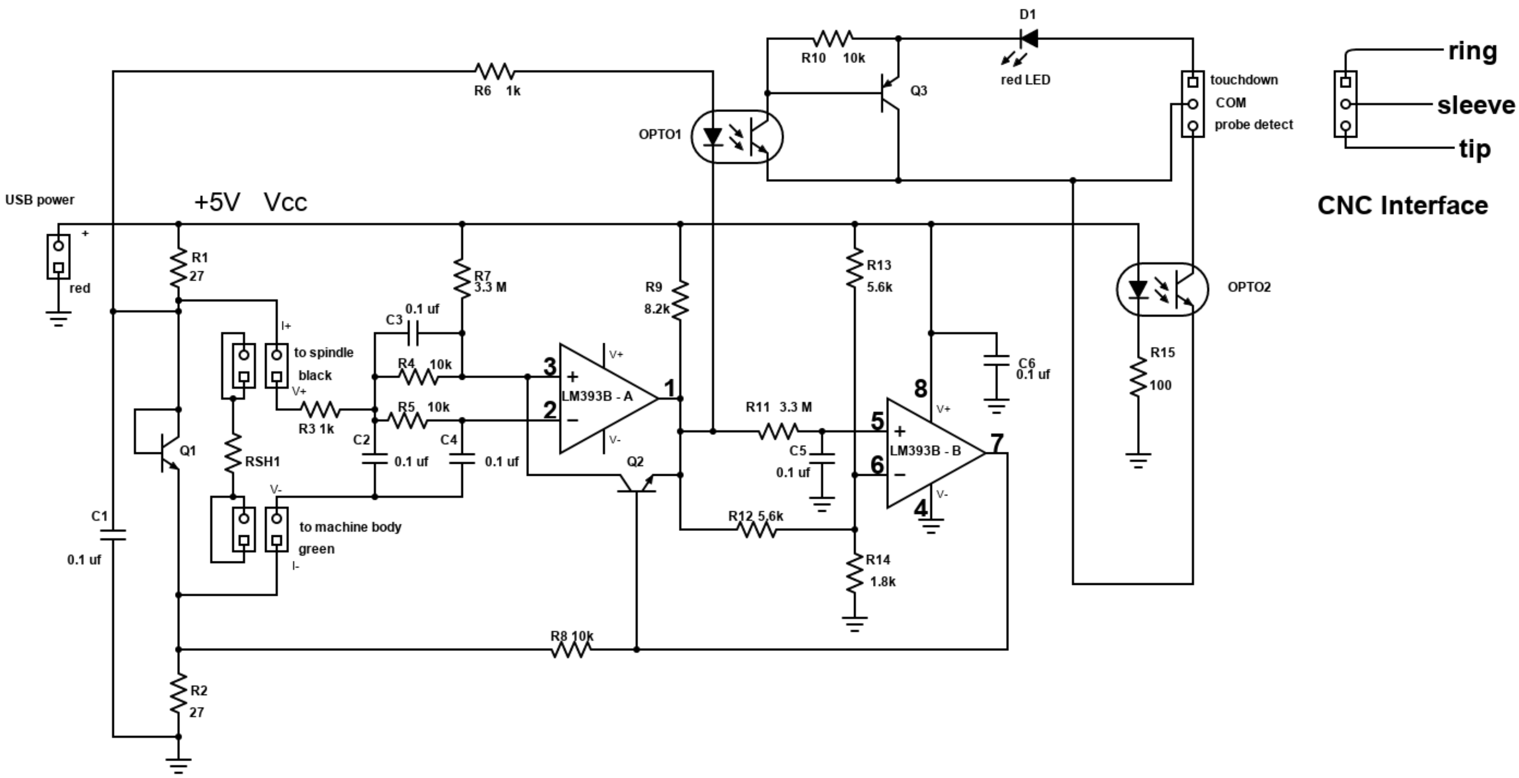
If the voltage at pin 1 is 2.9V, pin 6 should be at 1.6V. If it is not, look for extra connections to R13 and R14.

If all DC voltages are right, but the circuit oscillates when Q2 is reinstalled, you may have a capacitor of the wrong value or only partially connected. Take an extra capacitor and touch it between the appropriate terminals to see if that quiets the circuit down.

If the CNC system does not detect a probe, measure the voltage across the output of opto 2. It should be under 1V. If not, measure the voltage at the top of R15. It should be 4.3V. If not, look for a wiring error with it and opto 2.

If the CNC system does not detect touchdown, ground pin 1 and see if the LED turns on. If it does but the CNC system still does not see touchdown, it is a problem with the wiring to the CNC system or within this system. If the LED remains dark, measure the voltage from COM to touchdown at the CNC interface. It should be 24V for the Centroid Acorn configuration. Check your system specs if you see another voltage.

Short the emitter of Q3 to its collector and see if the LED turns on. If not, look for a break between Q3, the LED, and the CNC system. If it does turn on, remove that



short and short the base of Q3 to its collector. If the LED turns on, Q3 is fine. If not, replace Q3.

With pin 1 grounded, the left side of R6 should be at 5V, and the right side should be around 4V. If both sides are 5V, short the input of the opto and see if the right side of R6 goes to 0. If not, you have a wiring error.

If none of these suggestions help, don’t hesitate to contact me for further tests before you get too frustrated.

Acknowledgment

Thanks to Gregg Kricorissian for making numerous suggestions to this design and document.

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 proper distribution list.

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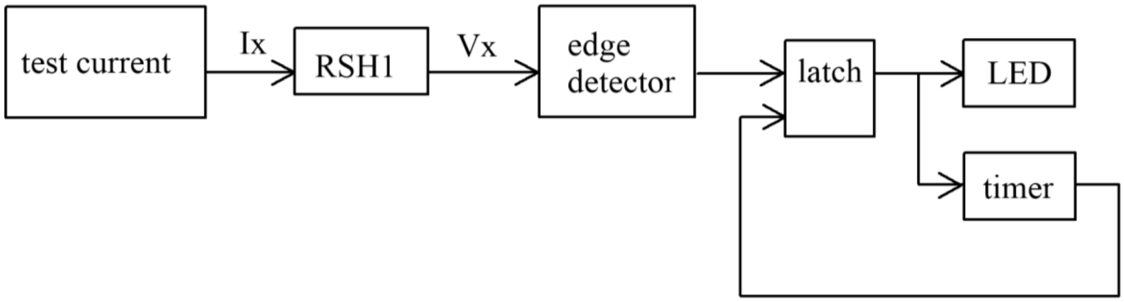
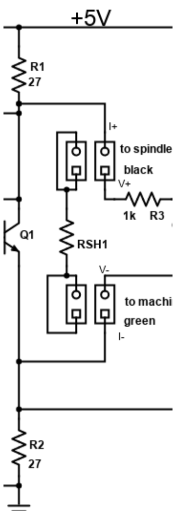
Rick Sparber
Rgsparber.ha@gmail.com
Rick.Sparber.org

Appendix I: Detailed Circuit Description

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



The Resistance Being Measured



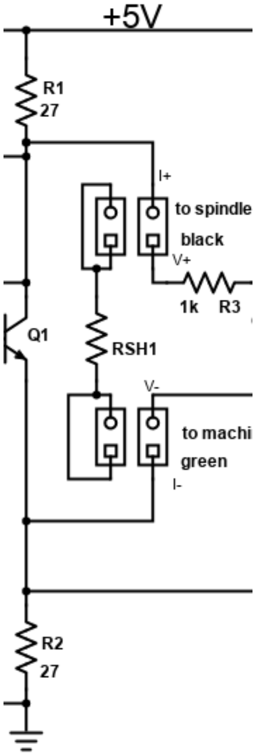
The EEF measured the resistance between the spindle and the body of the machine (see page 6). Before touchdown, this resistance is dominated by the electrical resistance of the spindle bearings[9].

At touchdown on a mill, this resistance is shorted out by the electrical resistance between the part and the machine's body[10]. On a lathe, it is the resistance between part and chuck. This resistance will be less than 0.1 ohms if the part is solidly bedded down. For more details, click here.

I represent this resistance in the schematic as RSH1.

[9] The circuit can tolerate a resistance from 0.15 ohms up to 5 ohms.
[10] The maximum part resistance the circuit can tolerate is 0.15 ohms less than the spindle resistance.

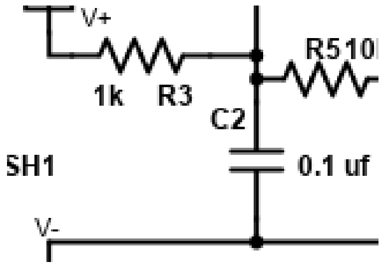
The Kelvin Connection



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 through the top of the black connector and into RSH1. It exits the bottom of RSH1 and into the bottom of the green connector. From there, it flows through R_2 to ground. Small variations in contact resistance have a minimal effect on this test current.

The test voltage connection, V_x, goes to the other side of these connectors. V_+ connects to the top of RSH1 via the bottom of the black connector. V_- connects to the bottom of RSH1 via the top of the green collector. Small variations in contact resistance have no effect on the sensed voltage because the current flowing in this path is near zero.

Machine Noise Suppression

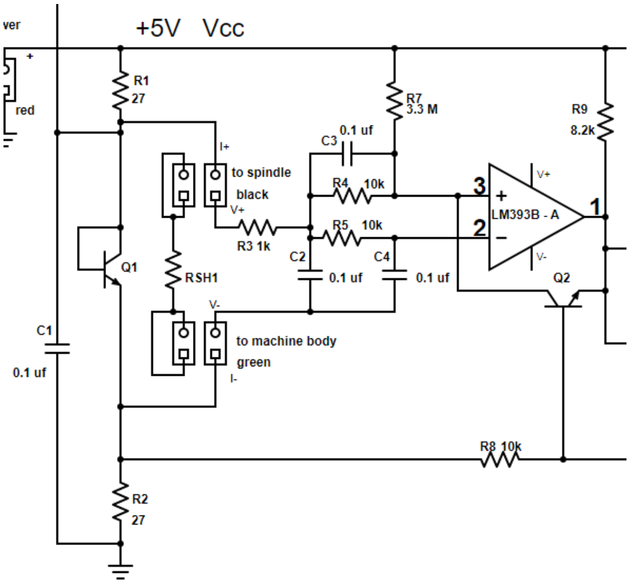


V_x can contain an unknown amount of high frequency noise which can falsely trigger the circuit.

R3 and C2 form a low pass filter (LPF) to reduce this noise without blocking the drop in RSH1. This LPF passes signals below 1.6 kHz, so it does a good job of blocking spikes generated by CNC systems.

It is standard procedure to put a large electrolytic between +5V and ground to suppress low-frequency noise. I have found that the USB power supply is sufficient for this task.

Pre-Touchdown



Our test current, I_x, is set by R_1, R_2, and R_{SH1}. R_{SH1} is $R_{spindle}$ during pre-touchdown.

$$I_x = \frac{V_{cc}}{R_1 + R_2 + R_{spindle}} \qquad (1)$$

But since $R_{spindle}$ is much smaller than $R_1 + R_2$, we can say

$$I_x \approx \frac{V_{cc}}{R_1 + R_2} \qquad (2)$$

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

But $V_x = V_+ - V_-$ so

$$V_+ - V_- = I_x R_{spindle} \qquad (4)$$

Since $R_{spindle}$ is much smaller than R1 and R2, V_+ is close to half of V_{cc}. Also notice that R7 is much larger than R4, which is ten times larger than R3. This means that the voltage across R4 is

$$V_{R4} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4 \right) \qquad (5)$$

Notice that V_{R4} is almost constant and not a strong function of $R_{spindle}$.

There is no current flowing through R5, so there is no voltage drop. Therefore,

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4 \right) \qquad (6)$$

We also have

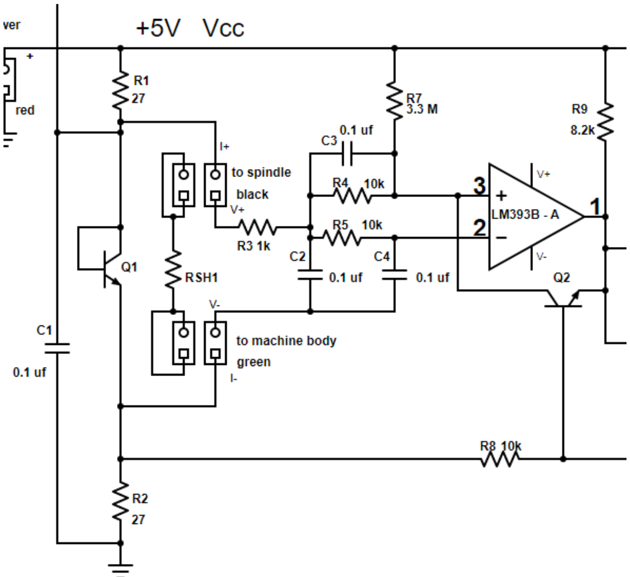
$$V_{R3} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_3 \right) \qquad (7)$$

Which is also almost constant.

Combining (4) and (7) we get

$$V_{C2} = V_{C4} \approx I_x R_{spindle} + \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4 \right) \qquad (8)$$

At Touchdown



RSH1 now approximately[11] equals R_{part}. We can then say

$$V_+ - V_- = I_x R_{part} \qquad (9)$$

(2) is still valid:

$$I_x \approx \frac{V_{cc}}{R_1+R_2} \qquad (2)$$

Since the voltage across a capacitor can't change instantaneously,

$$V_{C4} \approx I_x R_{spindle} + \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) \qquad (8)$$

The drop in V_+ has a minimal effect on I_{R6}, so (5) and (7) are still valid:

$$V_{R4} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) \qquad (5)$$

$$V_{R3} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_3\right) \qquad (7)$$

Because R_3C_2 is ten times smaller than R_4C_3 I will ignore the effect of R_3C_2 and say that pin 3 falls almost instantly from $I_x R_{spindle}$ to $I_x R_{part}$ with respect to V_-. This means that the drop in voltage between V_+ and V_- appears at pin 3. This drop is found from

$$V_+ - V_- = I_x R_{spindle} \qquad (4) \text{ [pre-touchdown]}$$

and

$$V_+ - V_- = I_x R_{part} \qquad (9) \text{ [at touchdown]}$$

So

$$V_{drop} = I_x\left(R_{spindle} - R_{part}\right) \qquad (10)$$

[11] This assumes $R_{part} \ll R_{spindle}$ which I have found to be true. If it is not true, replace R_{part} with $R_{spindle}$ in parallel with R_{part}.

From pre-touchdown:

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) \quad (6)$$

At touchdown, we know $V_{pin\ 3}$ drops by

$$V_{drop} \approx I_x\left(R_{spindle} - R_{part}\right) \qquad (10)$$

So we land at

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - V_{drop}$$

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - I_x\left(R_{spindle} - R_{part}\right) \qquad (11)$$

Pre-touchdown, $V_{pin\ 3} - V_{pin\ 2}$ was > 0V so the output of the comparator is high. This output will go low when $V_{pin\ 3} - V_{pin\ 2}$ < 0. The threshold is, therefore when $V_{pin\ 3} - V_{pin\ 2} = 0$:

$$0 = \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - I_x\left(R_{spindle} - R_{part}\right)$$

$$R_{spindle} - R_{part} = \frac{\left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right)}{I_x}$$

But

$$I_x \approx \frac{V_{cc}}{R_1 + R_2} \qquad (2)$$

So

$$R_{spindle} - R_{part} = \frac{\left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right)}{\left(\frac{V_{cc}}{R_1 + R_2}\right)}$$

$$R_{spindle} - R_{part} = \frac{\left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right)}{\left(\frac{V_{cc}}{R_1+R_2}\right)}$$

$$R_{spindle} - R_{part} = \left(\frac{R_4}{2R_7}\right)(R_1+R_2) \qquad (12)$$

Plugging in nominal values,

$$R_{spindle} - R_{part} = \left(\frac{10k}{6.6M}\right)(54\ ohms)$$

$$R_{spindle} - R_{part} = 81.8\ milliohms$$

Ideally, a drop in resistance of more than 81.8 milliohms will cause the comparator's output to drop to its low state from its high state.

The comparator's input offset voltage, V_{os}, shifts the threshold, as does the tolerance of the resistors. Going back to (11), we can include this imperfection

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - I_x\left(R_{spindle} - R_{part}\right) \qquad (11)$$

The threshold is then

$$\pm V_{os} = \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - I_x\left(R_{spindle} - R_{part}\right)$$

$$\pm V_{os} = \left(\frac{\left[\frac{V_{cc}}{2}\right]}{R_7} R_4\right) - \left(\frac{V_{cc}}{R_1+R_2}\right)\left(R_{spindle} - R_{part}\right)$$

$$R_{spindle} - R_{part} = \left(\frac{R_4}{2R_7} - \frac{\pm V_{os}}{V_{cc}}\right)(R_1+R_2) \qquad (12)$$

Each resistor is ±5%. V_{os} is ± 2.5 mV over the full temperature range. V_{cc} is 5 ± 0.15V.

The absolute worst-case minimum threshold is, therefore

$$R_{spindle} - R_{part} = \left(\frac{9.5k}{6.93M} - \frac{2.5mV}{4.85V}\right)(51.3\ ohms)$$

$$R_{spindle} - R_{part} = 43.9\ milliohms$$

The absolute worst-case maximum threshold is, therefore

$$R_{spindle} - R_{part} = \left(\frac{10.5k}{6.27M} + \frac{2.5mV}{4.85V}\right)(56.7\ ohms)$$

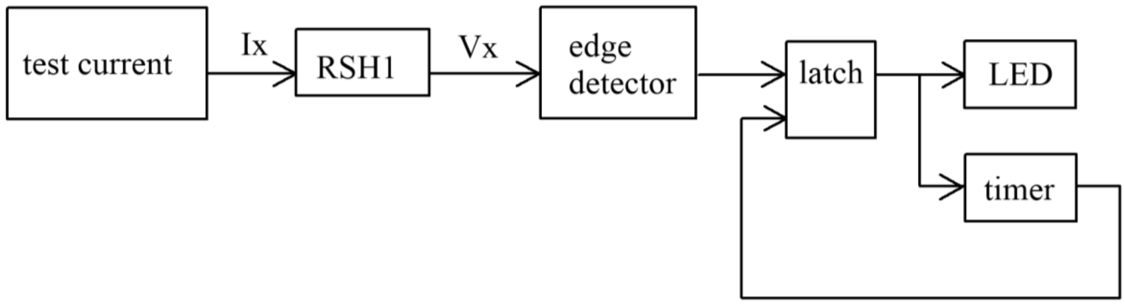
$$R_{spindle} - R_{part} = 124\ milliohms$$

This says that any $R_{spindle} - R_{part}$ greater than 124 milliohms will cause the output of the first comparator, pin 1, to change from an open circuit to near ground.

In the most sensitive worst-case, the circuit still has a positive margin of 43.9 milliohms, so it should not get stuck in the detect state.

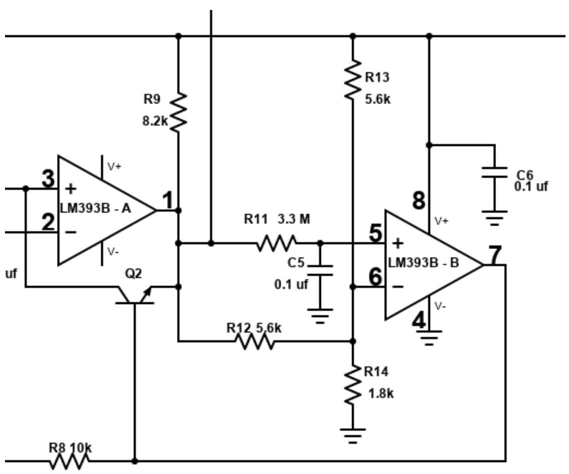
Pre-Touchdown Latch and Timer

This math might have your head spinning, so let's go back to the top.

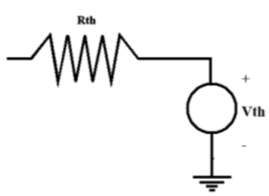


We have calculated the absolute worst-case minimum drop in RSH1 that will cause our edge detector to change state. Pin 1 changes from an open circuit to near ground.

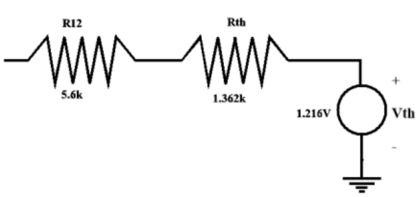
R_9, R12, R13, and R14 set the voltage at pin 1.



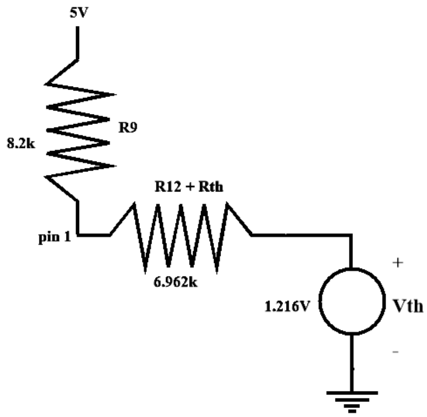
The first step in analyzing this part of the circuit is to Thevenize R13 and R14. With R12 disconnected, the voltage at the top of R14 is $\left(\frac{R14}{R14+R13}\right)(V_{cc}) = \left(\frac{1.8}{1.8+5.6}\right)(5) = 1.216V$. This is the Thevenin equivalent voltage, V_{th}. I then set V_{cc} to its internal resistance and calculated the input resistance of the circuit. This gives me R13 in parallel with R14, which equals 1.362k and is my Thevenin equivalent resistance, R_{th}.



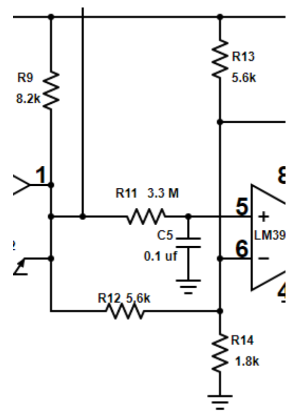
I can now replace R13 and R14 with a 1.362k resistor connected to a 1.216V source tied to ground.



By adding R12 to R_{th}, I have a model of R12, R13, and R14.



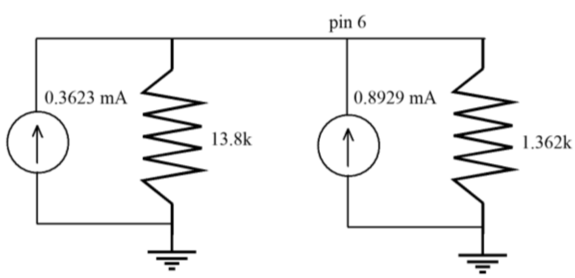
The circuit tied to pin 1 has become a lot more manageable. The current flowing through R9 is $\frac{5V-1.216V}{8.2k+6.962k} = \frac{3.0784V}{15.162k} = 0.2496\, mA$. Pin 1's voltage is then $1.216V + (6.962k \times 0.2496\ mA) = 2.95$V, which is below the recommended limit of $V_{cc} - 2V = 3V$ for pin 5.



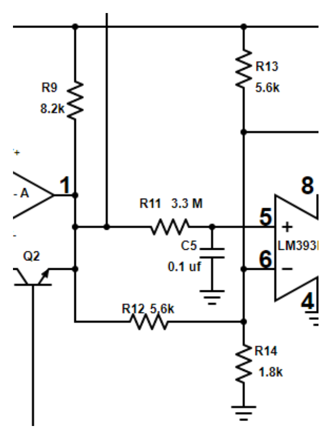
I can now calculate the voltage at pin 6. I take the Norton Equivalent of V_{cc} with R9 plus R12 and the Norton Equivalent of V_{cc} with R13 and R14.

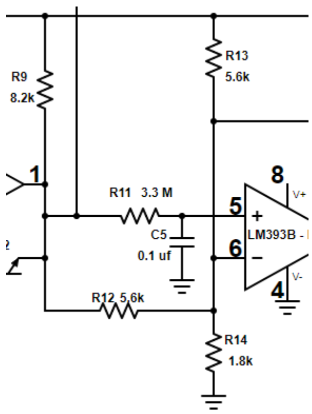
For V_{cc} with R9 plus R12, I have $I_n = \frac{V_{cc}}{R9+R12} = \frac{5V}{8.2k+5.6k} = 0.3623\, mA$. R_n is R9 + R12 so 13.8k.

For V_{cc} with R13 and R14, I have $I_n = \frac{V_{cc}}{R13} = \frac{5V}{5.6k} = 0.8929\, mA$. R_n is R13 in parallel with R14, so 1.362k. I then have:

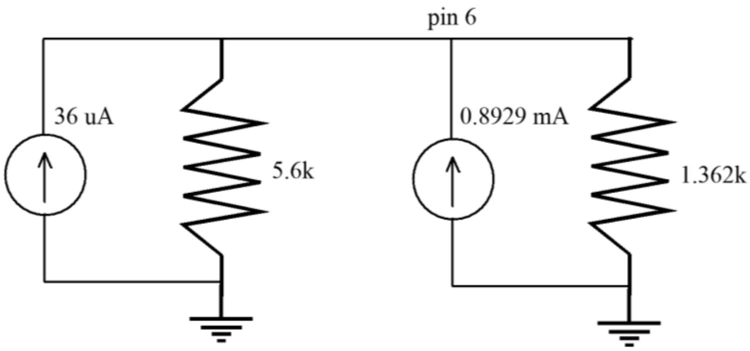


The total current into the pin 6 node is 0.3623 mA + 0.8929 mA = 1.255 mA. The total resistance at this node is the parallel combination of 13.8k and 1.362k, which is 1.240k. This means the voltage at pin 6 is 1.255 mA $\times$ 1.240k = 1.56V when pin 1 is an open circuit.



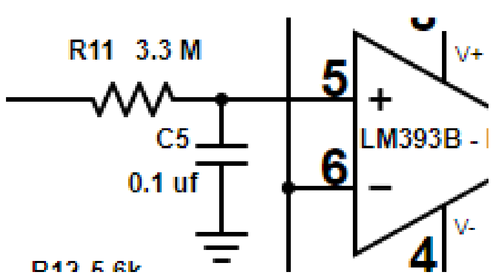


While this is still fresh in my mind, I will calculate pin 6's voltage when pin 1 is low: pin 1 is nominally at 0.2V. This sets the first Norton current to $\frac{0.2V}{5.6k} = 36\ uA$.



The total current into the pin 6 node is 36 uA + 0.8929 mA = 0.9289 mA. The total resistance at this node is the parallel combination of 5.6k and 1.362k, which is 1.0956k. This means the voltage at pin 6 is 0.9289 mA × 1.0956k = 1.02V.

If pin 1 were at 0.55V, the voltage at pin 6 would be 1.09V.

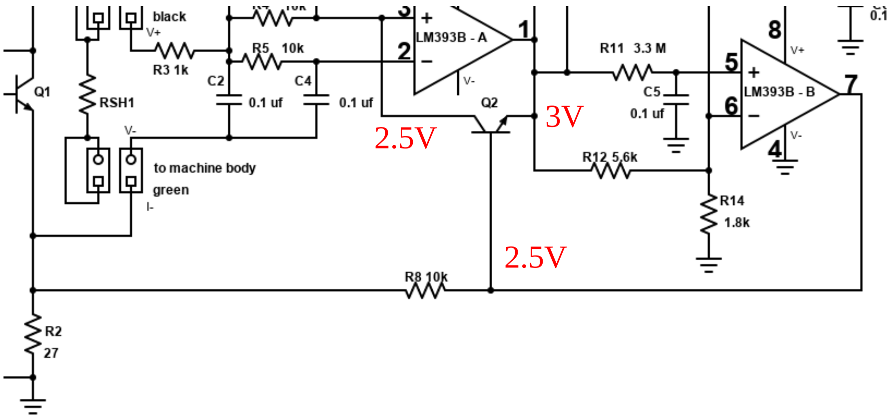


The input bias current out of pin 5 is typically 3.5 nA means that V_{R11} is typically 11.6 mV at room temperature. It can be as high as 50 nA, which yields 165 mV.

The voltage across C5 when pin 1 is open, is typically 2.95V + 11.6 mV = 2.96V but could be as high as 2.95V + 165mV = 3.1V which is within spec[12].

With pin 5 at 3V and pin 6 at 1.6V, the second comparator's output at an open circuit.

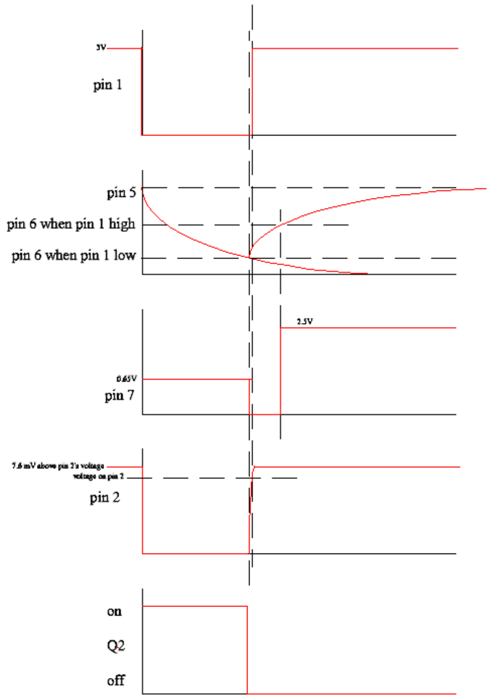
[12] From the spec sheet: "The upper end of the common-mode voltage range is limited by VCC – 2V. However only one input needs to be in the valid common mode range, the other input can go up the maximum VCC level and the comparator provides a proper output state." So while pin 5 can get above Vcc – 2.0V = 3.0V, pin 6 is below 2V.



Q2's collector is around 2.5V, its emitter is at 3V, and pin 7 is an open circuit so Q2's base is at about 2.5V because R8 isn't carrying any current and is tied to the top of R2 which is at about 2.5V. This means Q2 is off.

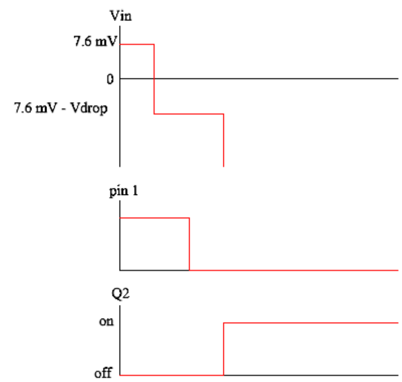
Touchdown Latch and Timer

At touchdown, the edge detector causes pin 1 to change from an open circuit to being low. Pin 1 changes from typically 2.95V to 0.2V. This causes pin 6 to drop from 1.56V down to typically 1.02V. Pin 5 starts at typically 2.96V and discharges to 0.2V. With pin 1 at 0.2V and pin 7 open-circuited, Q2 turns on, and yanks pin 2 down to about 0.3V. This locks pin 1 low.



Pin 7 remains an open circuit until C5 discharges to below typically 1.02V. Then pin 7 changes from an open circuit to near 0V. That turns off Q2 which permits pin 3 to rise. When pin 3 gets above pin 2 due to the near constant voltage drop across R4, the first comparator's output at pin 1 changes from low to an open circuit. The voltage at pin 1 jumps from typically 0.2V to 2.95V. C5 switches from discharging towards 0.2V to charging to 2.95V. But pin 6 jumped from typically 1.02V to 1.56V so pin 5 is still below pin 6. This keeps pin 7 near 0V so keeps Q2 off.

C5 charges until pin 5 is above 1.56V. Then pin 7 changes from near 0V to an open circuit.



A lot is going on at the input of the first comparator. If I expand the time scale, you can see this voltage drop from

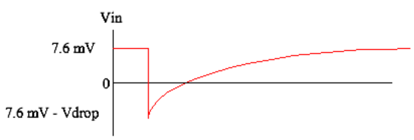
$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{V_{CC}}{2}\right]}{R_7} R_4\right) \quad (6)$$

$$V_{pin\ 3} - V_{pin\ 2} \approx \left(\frac{\left[\frac{5V}{2}\right]}{3.3M} 10k\right)$$

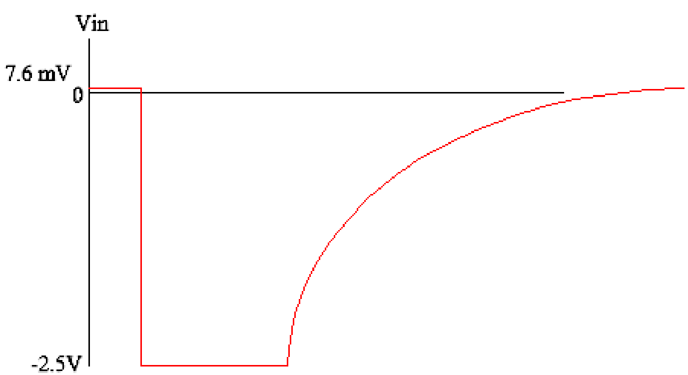
$$V_{pin\ 3} - V_{pin\ 2} \approx 7.6\ mV$$

to 7.6 mV – V_{drop}.

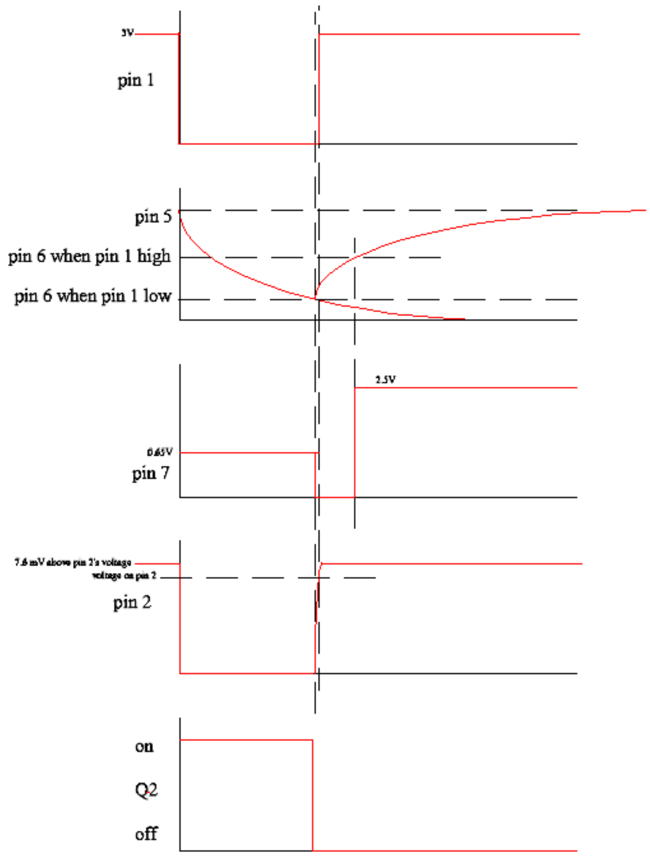
In this timeframe, V_{in} stays constant. Within 1 microsecond, the comparator responds to this drop in input and changes its output from open circuit to near ground. In much less than 1 microsecond, Q2 changes from off to on.



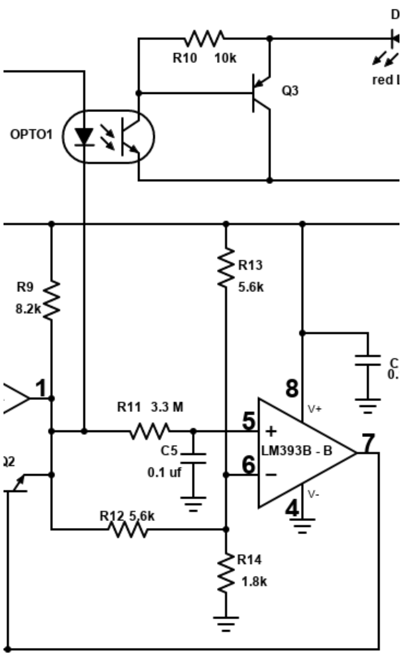
If I expand the vertical axis, we can better see how V_{in} behaves. Without Q2, V_{in} drops from 7.6 mV to 7.6 mV minus the drop voltage. It then takes about 5 milliseconds to return to 7.6 mV.



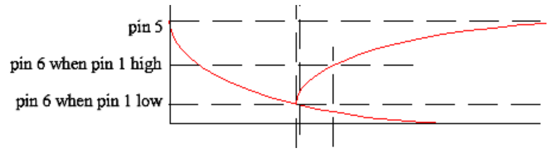
Because of Q2, rather than rising to 7.6 mV, it is yanked down to about -2.5V. When the timer has completed its cycle, V_{in} is released and able to rise again to 7.6 mV. This takes about five milliseconds.



If I did not have the two thresholds for pin 6, Q2 would turn off shortly after pin 1 went high. At this time, V_{in} is still negative, so pin 1 would be driven low again. By keeping Q2 off for more than five milliseconds, we prevent retriggering.



The nominal time constant at pin 5 is 3.3 meg × 0.1 uf = 330 milliseconds.



Pin 5 starts at typically 2.96V and would discharge to 0.2V if pin 1 did not rise:

$$V_{pin\ 5}(t) = (2.76V)\left(e^{\frac{-t}{330\ ms}}\right) + 0.2V$$

To reach 1.02V:

$$1.02\text{V} = (2.76V)\left(e^{\frac{-t}{330\ ms}}\right) + 0.2V$$

so t = 401 milliseconds. This is the time the LED is on.

I was not sure what conditions would give me the worst case time so tried all four:

In the first worst case, pin 1 high is 2.96V and low is 0.55V. This means the threshold is 1.09V

$$1.09\text{V} = (2.41V)\left(e^{\frac{-t}{330\ ms}}\right) + 0.55V$$

so t = 494 milliseconds.

In the second worst case, pin 1 high is 2.96V and low is 0.2V. Pin 6 is 1.02V

$$1.02\text{V} = (2.76V)\left(e^{\frac{-t}{330\ ms}}\right) + 0.2V$$

so t = 401 milliseconds.

In the third worst case, pin 1 high is 3.1V and low is 0.55V. This means the threshold is 1.09V

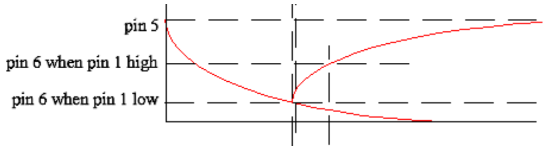
$$1.09\text{V} = (2.55V)\left(e^{\frac{-t}{330\ ms}}\right) + 0.55V$$

so t = 512 milliseconds.

In the forth worst case, pin 1 high is 3.1V and low is 0.2V. Pin 6 is 1.02V

$$1.02\text{V} = (2.90)\left(e^{\frac{-t}{330\ ms}}\right) + 0.2V$$

so t = 416 milliseconds.



Therefore, the time from pin 1 falling until pin 7 falls is between 401 milliseconds and 512 milliseconds with a typical value of 401 milliseconds.

When pin 1 jumps back to its high value, C2 charges. Typically, it heads to 2.96V

$V_{pin\ 5}(t) = (1.94V)\left(1 - e^{\frac{-t}{330\ ms}}\right) + 1.02\text{V}$

To reach 1.56V:

$1.56\text{V} = (1.94V)\left(1 - e^{\frac{-t}{330\ ms}}\right) + 1.02\text{V}$

so t = 108 milliseconds.

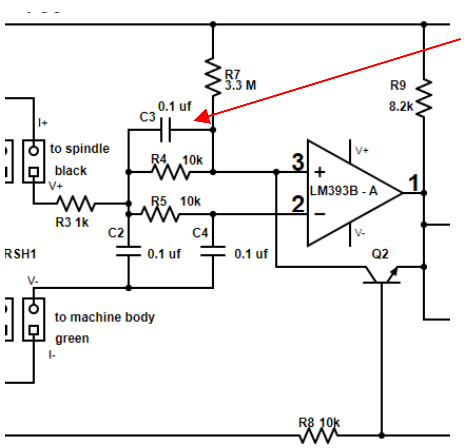
In the worst case, it is heading for 3.1V so will be as its fastest

$1.56\text{V} = (2.01V)\left(1 - e^{\frac{-t}{330\ ms}}\right) + 1.09\text{V}$

so t = 88 milliseconds which is far more than the minimum of 5 milliseconds needed for pin 3 to rise above pin 2.

Preventing Instability

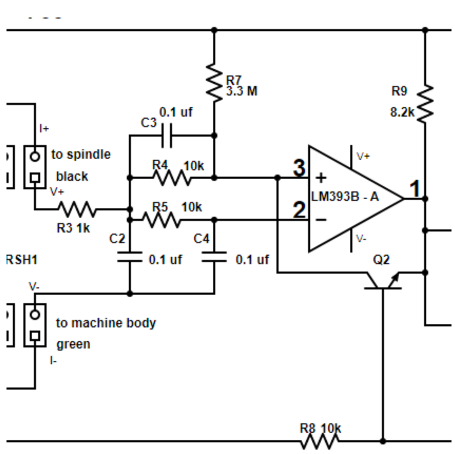
When I used an opamp as a comparator, the circuit ran approximately 1000 times slower so high-speed noise spikes were not a problem. When I changed to a comparator, these spikes caused unwanted state changes.



C3 prevents the circuit from becoming unstable. Here is my best guess as to why it works.

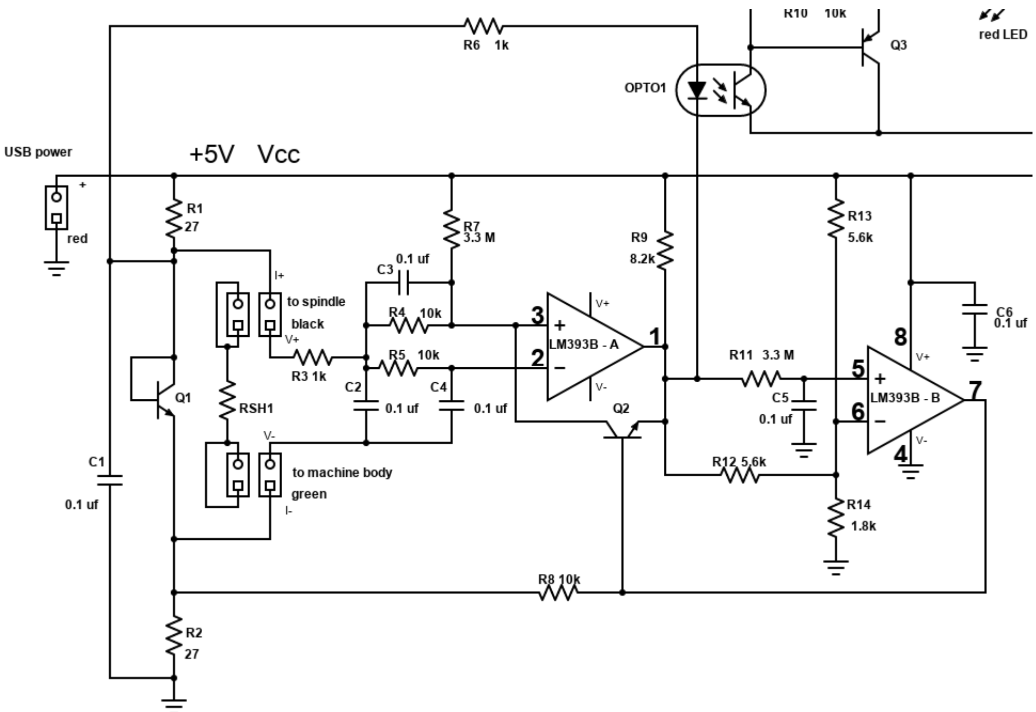
Consider the case of Q2 recently being turned off and the voltage at pin 3 has risen so it is equal to the voltage at pin 2. There is no C3.

Pin 1's volt will rise. This rising edge is coupled back into pin 3 via the parasitic capacitance between the collector and emitter of Q2. This will pull up on pin 3, causing pin 3 to rise more. When pin 1 is done rising, this current through the parasitic capacitance of Q2 will go to zero. This will cause pin 3 to fall back. That causes pin 1 to fall. Now we have a falling edge that is coupled to pin 3 via the parasitic capacitance of Q2. This pulls pin 3 down, causing pin 1 to fall. When pin 1 stops falling, this current through the parasitic capacitance of Q2 will again go to zero. Pin 3 is no longer pulled low so it returns to its higher value. Pin 1 rises. Thus, the cycle repeats forever.



A capacitance on pin 3 forms a capacitor divider with the parasitic capacitance of Q2. This parasitic capacitance is no more than 10 *pf* so I don't need much to swamp it.

C3 couples the drop in voltage at V_+ to pin 3. The larger it is, the better this coupling. Furthermore, I strive to minimize the number of different part values in the circuit. The result is that while a 0.1 *uf* cap is gross overkill for swamping out the parasitic capacitance, it is great for coupling V_+, and is a value that is already being used.



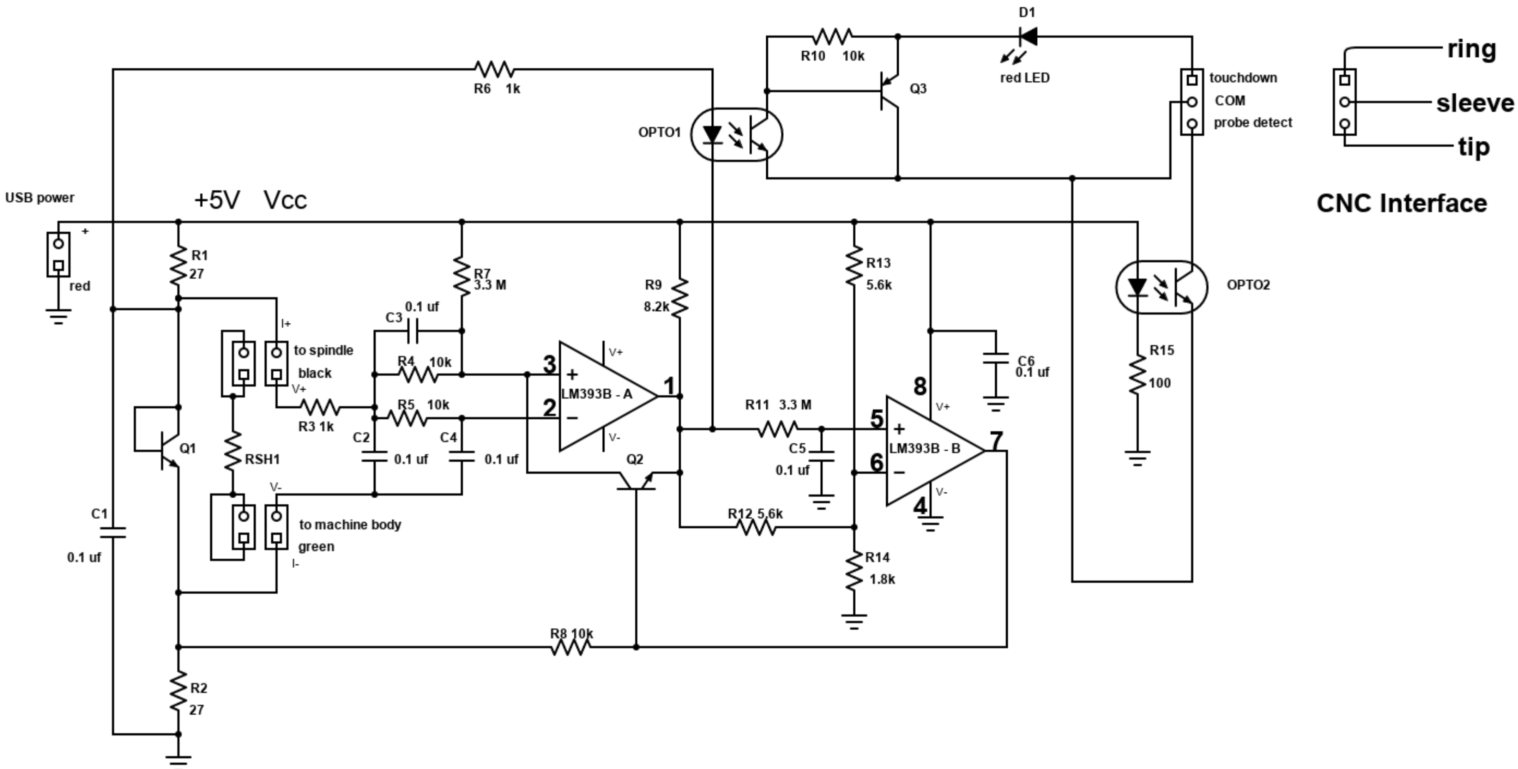
C1 also prevents instability. Here is my best guess as to why it works.

When pin 7 rises, it turns off Q2 to mark the end of the cycle. This causes the comparator to draw a spike of current from V_{cc} causing it to dip low. C6 must help, but it isn’t enough given the sensitivity of the circuit.

Without C1, this spike causes a sudden drop in the current flowing through R1, RSH1, and R2. $V_+ - V_-$ dips low. This appears to the edge detector as a touchdown, causing a new cycle to start.

With C1 present, this spike is adequately attenuated before it reaches the edge detector, so it causes no harm.

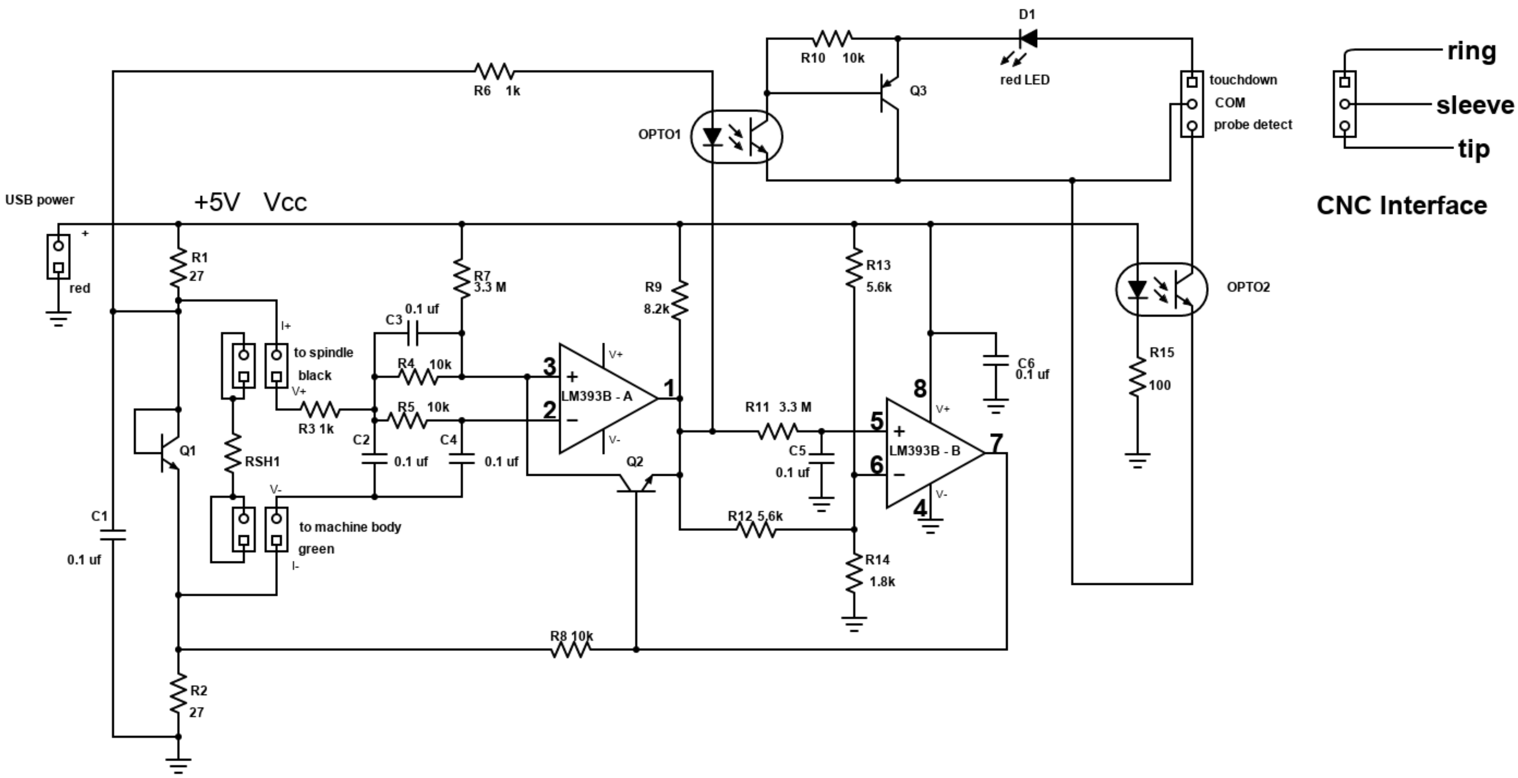
Additional Design Considerations



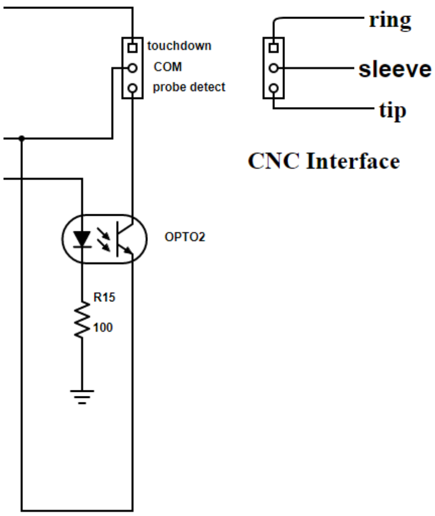
Beyond achieving the desired functionality, I wanted to minimize the parts count and the number of different parts. I was willing to accept a slightly different circuit behavior if it meant fewer different part values. One example is the reasoning behind C3.

Another example is the use of Q1. I only need a diode to prevent the voltage on pin 3 from getting too high when the probe to the spindle is removed. For the same money, I can buy a general-purpose NPN. This lets me reduce my variety of parts by one with no cost penalty.

I chose R7 to give me the most sensitivity to touchdown. I then checked to see what this would give me in the timer where R11 has the same value.



I must sink about 20 mA from the CNC board. The opto has a current transfer ratio (CTR) of at least 50%. The comparator must not sink more than 6 mA. I solved this problem with Q3, which has a minimum gain of 30. R10 prevents noise from turning Q3 on. When pin 1 is at about 3V, the opto has about 0V across its input so it cannot turn on. When pin 1 goes low, opto 1 turns on and pulls the base of Q3 down to near COM. This permits about 20 mA to flow through D1 and turn it on. If the circuit detects touchdown but the current from the CNC interface does not flow, the LED does not flash.



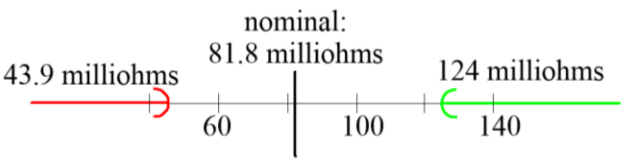
Opto 2 is brute force. I pass about 40 mA through its input to ensure it can pass 20 mA through its output. This requires a ¼ watt resistor for R15, but I have plenty of power from the USB wall wart. It wasn’t worth the cost to add another 10K resistor and PNP as used for the touchdown signal.

Appendix II: Testing Details

Using my Centroid CNC, I will address the EEF's electrical behavior and then look at touchdown accuracy.

Electrical Testing

Threshold

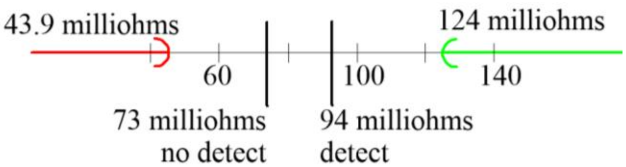


From page 33, we know that the nominal drop threshold is 81.8 milliohms with a guaranteed detect above 124 milliohms and a guaranteed no detect below 43.9 milliohms.

I used a resistor to simulate $R_{spindle}$. The test current was 92.6 mA, and I measured 20.9 mV across it, so the resistor was $\frac{20.9\ mV}{92.6\ mA} = 226$ milliohms.

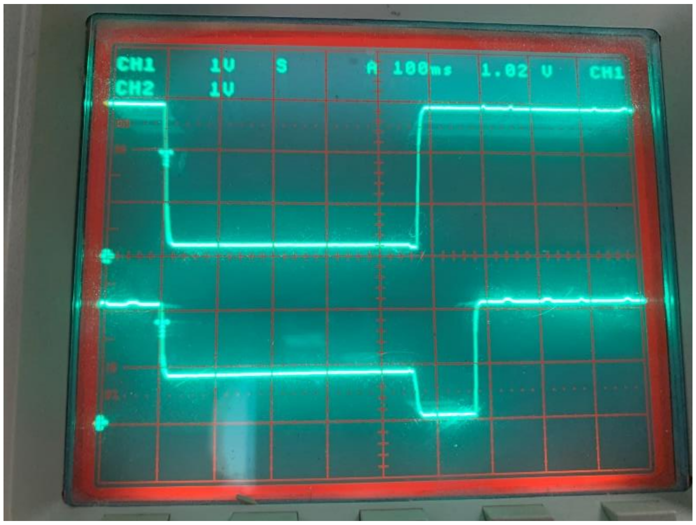
When I shunted it with a 0.47 ohm resistor, the voltage was 14.1 mV, a drop of 6.8 mV. This says the resistance was 152 milliohms, a drop of 74 milliohms. The circuit did not report touchdown.

When I shunted it with 0.47 ohms in parallel with 1 ohm, the voltage dropped by 12.2 mV, a drop of 94 milliohms. The circuit reported touchdown.



These readings are within the predicted range.

Timing



Both channels of the oscilloscope are DC coupled. The circuit is isolated from the mill, so I am able to connect scope ground to circuit ground.[13]

The time base is 100 ms per division. The top trace is monitoring pin 1 and shows it low for 480 milliseconds. From page 43, I predicted pin 1 would be low or 401 to 512 milliseconds.

The bottom trace is monitoring pin 7 and shows the signal near ground for about 100 milliseconds. I predicted 88 to 108 milliseconds.

[13] If the circuit is connected to the machine, scope ground is at the same potential as the machine body. This causes a shift down in the trace by about 2.5V.

Mechanical Testing

You can see in this video that my Centroid CNC system is reading my EEF and moving to the same place each time, as verified with my Starrett finger Dial Test Indicator (DTI). My resolution with this DTI is better than a tenth. I repeated this test ten times and found it landed on 0.0 seven times. It hit 1 tenth once and -1 tenth twice. Throwing away the extremes, I see 0 seven times and -1 tenth once. The average is 0 tenths with a variation of ± 1 tenth using the full data set.

My probe has a measured diameter of 0.7288 inches, so a radius of 0.3644 inches. I installed it, ran four passes, and read a machine position of 5.4488 inches each time. This puts the reference surface at 5.4488 + 0.3644 = 5.8132 inches.

I then installed a Starrett rotating edge finder. With the spindle running at about 600 RPM, I watched for the edge finder to jump along the reference surface to indicate a tenth past touchdown as I advanced a tenth at a time. I then noted the machine position on my CNC display[14]. Before each touchdown, I moved 50 thou away from the surface to ensure no backlash error was present as I fed in. My readings were 5.7125, 5.7124, 5.7124, and 5.7124. The average is 5.7124. Therefore, the surface is at 5.7123 inches plus the radius of the tip, which is 0.09995 inches to get 5.8123 inches.

The EEF said the surface was 9 tenths further than the Starrett rotating edge finder.

I reran the test at a different machine position to see if this was a constant error.

This time I took eleven probe readings. I discarded the maximum and minimum readings and averaged the remaining nine to yield 1.0814, which varied[15] between 1.0813 and 1.0815. This places the reference surface at 1.0814 + 0.3644 =1.4458 inches.

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[14] The display is configured to show tenths.

[15] This much variation was unexpected since I had been seeing no variation. I was having some trouble with the prototype circuit at this time so changed to an alternate EEF that is based on directly reading voltage. This approach is not able to detect fast dips in voltage which are caught by the analog EEF.

I next took ten readings with the rotating edge finder, discarded the two extremes, and averaged the rest to get 1.3445. These readings varied[16] between 1.3444 and 1.3446. This puts touchdown at 1.3444 + 0.09995 = 1.4444 inches.

The EEF said the surface was 14 tenths further than the Starrett rotating edge finder.

Moving to a third position, I repeated the test. I took four readings and they were all the same. My probe said the position was at 6.1257 + 0.3644 = 6.4901 inches. I made four readings with my rotating edge finder, which varied between 6.3889 and 6.3890 with an average of 6.38895. After adding the tip's radius of 0.09995, I calculated a position of 6.4889 inches.

The EEF said the surface was 12 tenths further than the Starrett rotating edge finder.

At a fourth position, the rotating edge finder indicted touchdown at 7.3195 four times and 7.3194 once. The average is 7.3195 so touchdown was at 7.3194, and the reference surface is at 7.3194 + 0.09995 = 7.4194 inches. I read 7.0556 once and 7.0557 twice using my probe and auto touchdown[17]. The average was 7.0557 so the calculated position of the reference surface is at 7.0557 + 0.3644 = 7.4201 inches.

The EEF said the surface was 7 tenths further than the Starrett rotating edge finder.

There is a consistently larger value from the EEF than determined by the rotating edge finder. Given these four data points of 9, 14, 12, and 7 tenths, the mean is 10.5 tenths, and the variation is 3.5 tenths.

[16] As with my EEF readings, I could not explain this variation of ± a tenth.

[17] I wanted to take more readings but on the fourth cycle, the resistance of the spindle dropped to near 0 and I had a crash. In the past, this was due to a bit of swarf around the bearings. The crash moved the reference surface so subsequent cycles were not possible.

As part of calibration, I can subtract 10.5 tenths from the probe's radius. I will be left with the variation of 3.5 tenths.

Given that my display shows four places past the decimal, all readings are ± 1 tenth. This means that my rotating edge finder's position is ± 1 tenth and my probe is also ± 1 tenth.

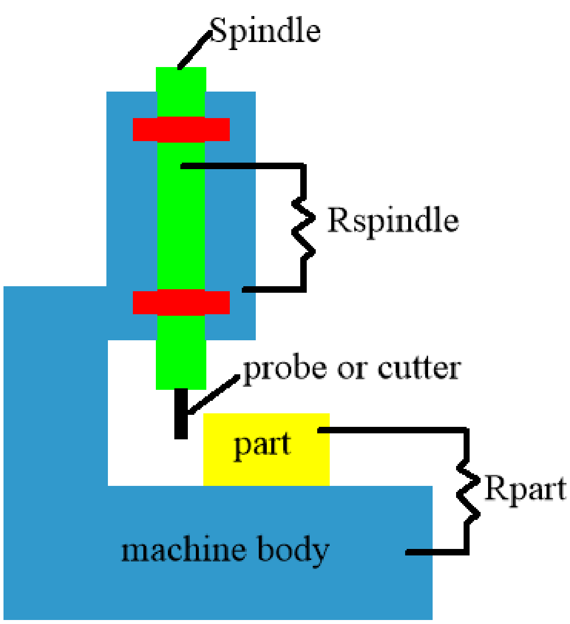
As explained on page 51, the automatic touchdown function is ± 1 tenth. It has no error 70% of the time, so assigning a full tenth of error here is a stretch.

Therefore, the total uncertainty is ± 3 tenths which compares well with the measured variation of 3.5 tenths.

My conclusion is that the probe matches the rotating edge finder after "calibration" within the uncertainty of the system.

Appendix III: Potential Bearing Damage Caused by the EEF

If you do a web search using "arcing on ball bearings," many papers address how arcing on the surface of ball bearings causes damage. Voltage is generated across these bearings, and periodically current conducts, causing arcs. These arcs pit the surface and lead to failure. In all cases, the motor is running, and these arcs occur millions of times. One reference says that damage can result with as little as 6V across the bearings.



With the EEF's enclosure sitting on the machine body, my magnetic probe can have no more than 0.65V on it. I touch it to the spindle, and less than 0.1 amps flows. This current passes through the bearings, which see no more than 0.65V.

At touchdown, the probe contacts the part. This diverts most of the 0.1 amps away from the bearings as the voltage drops to near 0.

If there was going to be arcing, it would be between the magnetic contact and the spindle during setup or at touchdown between probe and part. It would not be within the bearings.

Therefore, I do not believe my EEF can cause damage to my spindle bearings.