Mechbot, a Mobile Robot using Analog Electronics

Project Manual

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1 Lab 1: Assembling Mechbot

In this lab you will do the basic mechanical assembly of the robot. You will also bring the motor and battery connections out to terminal strips for connection to the protoboards, and test the basic operation of the robot.

1.1 Mechanical Assembly of Baseplate

An overall 3-view of the robot is shown in figure1.

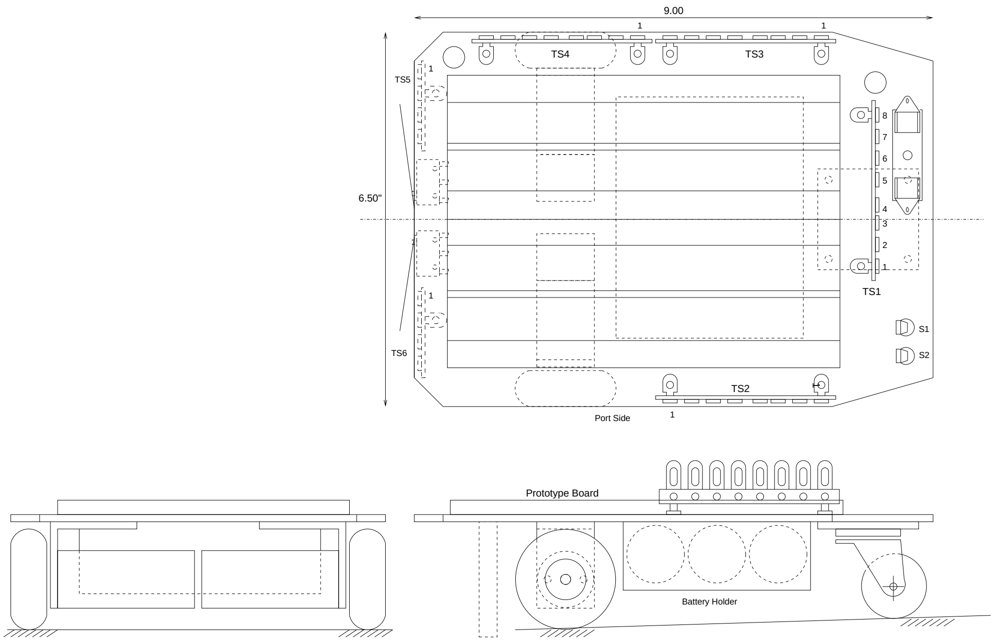

Figure 1: Robot Three View

Identify the following parts on the three-view and in your kit:

- Baseplate
- DC motors (2)
- Motor mounting bracket (2)
- Castoring wheel
- Hexagonal standoffs (4)
- Rubber-tired wheels (2)
- Wheel collars (2)
- Terminal strips, 8-way (4)
- Terminal strips, 4-way (2)

- Microswitches (bumper switches)
- Fuse holder
- Battery holder

Carefully note which parts live on the top of the baseplate, and which attach to the underside. The function of most parts is fairly evident. The standoffs have two purposes:

- When bolted to the underside of the baseplate, they lift the wheels off the ground so that the bot is a stable surface to work on and so that the wheels can rotate when testing the motors.
- When bolted to the topside of the baseplate, they can be used to support a *mezzanine* layer that can mount various sensors and additional electronics.

Parts which are in the drawing but you must supply:

- Power switches (2)
- Protoboards (2)

These assembly steps do not have to be in sequence. Do whichever steps you have the parts and tools to do. A template of the baseplate layout is shown in figure 5 on page 9. You can cut this out and use it as a guide to position parts and drill holes. **The template drawing is approximate. Do not rely on the accuracy of the template drawing. Check your parts fit before drilling any holes.**

Use the 'Fastener Schedule' table on page 10 to identify the various nuts and bolts and their functions.

1. **Trim Baseplate** Use a fine-toothed saw (such as a razor saw hacksaw) or a razor knife (Stanley knife, NT Cutter) to trim the corners off the plastic baseplate, per the template drawing.
2. **Motor Brackets** Find the two motor-mount mechanical **L** brackets. These have sharp edges, so use a file or sandpaper to take off the cutting swarf and round the corners.
3. Use the full-size template of figure 6 on page 6 to lay out the bracket drill holes. The baseplate mounting holes are not critical, but the motor mounting holes are. Check the spacing against the motor itself. After marking the motor mounting holes, carefully transfer the spacing of the holes on the actual motor to a piece of paper and check it against the hole centres on the bracket.
4. Carefully check the position of each motor bracket on the baseplate and drill the two mounting holes. Countersink them from the top.
5. Using the 3mm screws, mount each motor to its angle bracket mount.
6. **Wheel Assembly** Glue the 5/32" shaft collar to the rubber wheel, according to the following procedure:

   The motor shaft is 5/32" in diameter. Drill out each wheel to the same diameter so that it can fit on the motor shaft. Pass a 5/32 bolt or drill bit through a wheel and then a collar so that the shaft is vertical and the collar is resting on top of the wheel. Use the hot-glue gun to lay down a circle of glue around the collar so that it attaches to the wheel. (Don't get glue into the collar grub screw.) When the glue sets (in about 30 seconds or so), mount the wheel on a motor shaft and tighten using the allen key.
7. Using 4, 6-32 x 1/2" FH bolts, attach 4, 2" threaded standoffs to the baseplate.
8. **Castoring Wheel** Mount the castoring wheel mount to the baseplate, using countersunk flat-head screws.
9. **Bumper Switches** Using 2, 2.6mmx16mm" RH bolts and nuts for each bumper switch, mount each bumper microswitch as shown on the template.

1.2 Electrical Assembly

The electrical system includes the battery power supply, switches, fuse and voltage regulator circuitry.

- **Battery Holder** Use the battery holder to mark 3 mounting holes on the baseplate, along the centre-line of the battery holder. Drill these holes with a 1/8” bit. Countersink the top. Use 3, #4x1/2” FH bolts and nuts to mount the battery holder.
- **Terminal Strips** Mount the terminal strips according to the template diagram, using #6 bolts and #4 bolts and nuts.
- **Fuse Holder** The fuse holder is mounted with a single 6-32x3/4” RH bolt and nut.
- **Protoboard** Most of the surface is occupied by the protoboard. This consists of two Wishboard WB-102-J units joined together. (The Wishboard has projecting tabs that will lock with a neighbouring unit.) The protoboard is a tight fit – it must be centred so that it does not overlap outside the MDF baseplate. If you have only one protoboard, mount it so that one edge runs along the centre-line of the baseplate.
- To mount the protoboard, do **not** use the adhesive surface on the bottom of the protoboard. This will make it impossible to remove without destroying the protoboard. Instead, use 4 small squares of double-sided tape or loops of masking tape.

1.3 Wiring and Testing the Motors

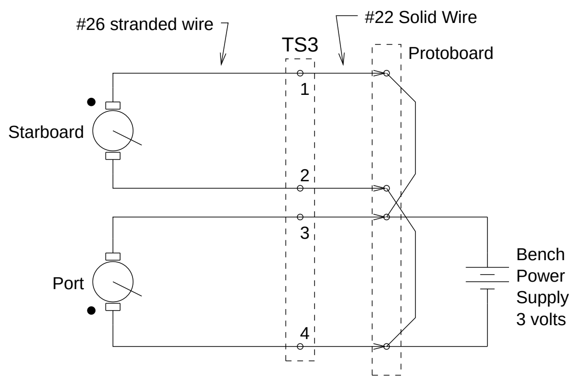

Figure 2: Motor Terminal Wiring

A note on the motor

To take care of the gearmotor -

- Try not operate the motor at more than 12 volts, which is the rated value for these motors.
- Do not back-drive the motor (cause the motor to rotate by turning the robot output wheel). This puts a large strain on the robot output wheel drive shaft and gearbox and may damage it.

- Try not to stall the motor via the robot wheels (by tangling them up in wiring, for example). This puts a large torque on the output shaft and may break it or the motor.

1. Note the names of the terminal strips and how the terminals are numbered, as shown on the three-view of figure 1.
2. According to figure 2, wire up the motors to terminal strip TS3.
   - Use #22 solid wire, preferably a different colour for each of the motor terminals.
   - Strip 1/4” from one end of a one-foot length of wire, tin it with solder so that the strands are held together.
   - Thread this wire end through one of the motor terminals and solder it to the terminal.
   - Repeat this with the second terminal of the motor, using a different colour.
   - Repeat the previous steps for the other motor, so that now you have each motor with two coloured leads attached to it.
   - Twist the four wires together and then thread these leads up through the baseplate cable slot and to the terminals 1-4 of terminal strip TS3.
   - Cut the wires to a suitable length so that they are not tight or too loose to drag on the ground. Using an ohmmeter to determine which wire is which, strip and solder the correct wires to the terminals 1-4 of terminal strip TS3.
3. Now use some #22AWG Solid wire to make jumpers that can plug into the protoboard. For each of the four terminals 1-4 of terminal strip TS3, strip one end of a 2” length of solid #22AWG wire and solder it to the terminal.
4. Strip about 1/4” off the free end of this solid wire so that it can plug into the protoboard.
5. Now the robot motors have been brought to the protoboard, they can be jumpered in parallel as shown in figure 15. Add these jumpers.
6. Connect the parallel motors to a bench power supply of about 3 volts, and check that both motors run. If they run in opposite directions, change the protoboard connection to reverse the wiring to one of the motors.

1.4 Motor Power Supply

The wiring schematic for the robot power supplies is shown in figure 3.

- Motor power is supplied by one battery pack of 6 C-type cells, for a total of 9 volts.
- The batteries are capable of significant output current when short circuited, and might cause melted wiring or a fire. This is protected by a fuse, F1.
- Switch S1 turns motor power on and off.
- Motor power is passed through a noise filter L1, C1, C2, C3. DC motors tend to generate a lot of power-line noise and this can cause electronic circuitry to misbehave. The filter limits the noise to the motor drive circuits.
- A separate ground wire (MGND) is provided for the motor currents to return to the power supply.
- The 9V motor power is also used to run high-current electronic loads, such as the Light Emitting Diodes.

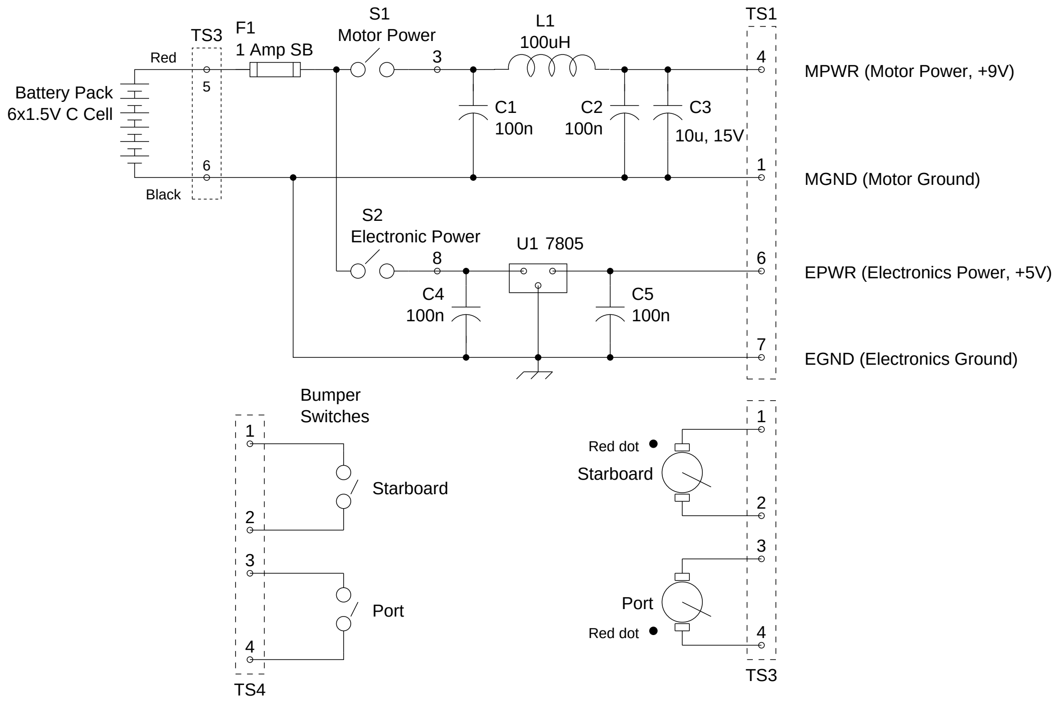

Figure 3: Power Wiring

1.5 Electronics Power Supply

- Switch S2 turns the electronics power on and off.
- The 9 volt battery power is regulated down to 5 volts to power the electronics by U1, a 7805 three-terminal integrated circuit regulator. The dropout voltage of the regulator is 7 volts, so the battery will be useful until it discharges down to this level.
- The regulator is capable of a maximum output current of 1 ampere. The current require by the electronics is expected to be much less than this, probably about 100mA maximum. If significant current is drawn by the electronics circuitry, the regulator will overheat and shut down. It has overtemperature protection circuitry. Consequently, the regulator limits short-circuit current and a fuse is not required.

  Any high-current circuits will be supplied from the 6 volt motor supply, not the regulated 5 volt supply, because a high current on the 5 volt regulated supply would discharge the 9 volt battery quickly and overheat the regulator.

1.6 Wiring the Power Supplies

- Plan where the wires are going to run. (Make a copy of figure 5 and mark it up to guide where the wires will run.) They should be arranged so that they can be grouped into cables, and not run the shortest possible path.

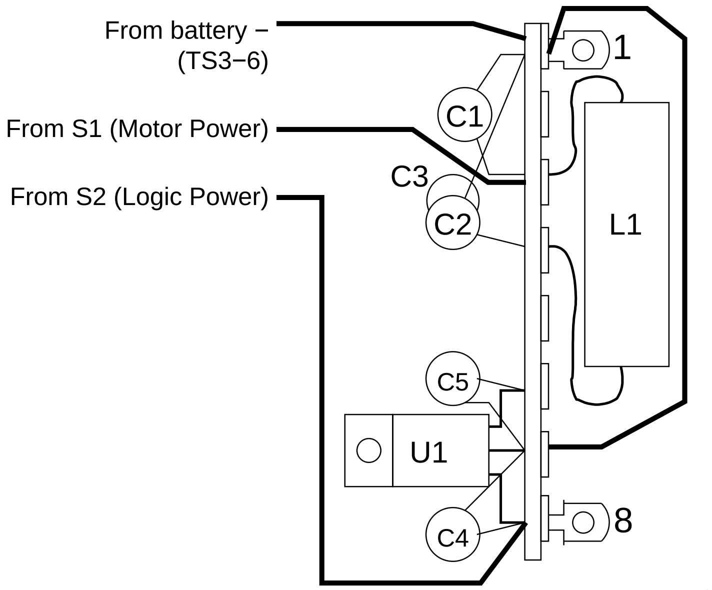

Figure 4: Terminal Strip 1, Detail

- Once the wiring is planned, mount and solder the capacitors onto terminal strip TS1, as shown in figure 4. Use the bottom holes in the terminal strip. The terminals require considerable heat to solder correctly.
- Mount and solder the three-terminal regulator U1 and inductor L1 onto TS1 as shown in figure 4.
- Do a careful visual check of the wiring to ensure that there are no unintended short circuits and that all the solder joints are reliable.
- Use a multimeter on its *continuity* setting, or using an ohmmeter, confirm all the connections on the schematic diagram. (This is called *ringing out* a wiring diagram).
- Install the 6 C cell batteries. Close switch S2. Check that there is 9 volts between terminals 5 and 7 of TS1. Check that there is 5 volts between terminals 6 and 7. Confirm that the polarity is correct in both cases.
- Install the fuse. Close switch S1. Check that there is 9 volts between terminals 3 and 1, and between 4 and 1 of TS1.
- Check these same voltages on the terminal strip TS3.
- Solder #22AWG solid jumper wires onto terminals TS3-1 through TS3-4, TS3-6, TS3-7. These wires should be long enough that they can reach to the protoboard to operate the robot.
- Wire the motors in parallel to a 3 volt supply voltage (TS3-1, TS3-2). This should cause the motors to run.

This completes the power system wiring of the robot.

Polarity Warning

Because this is a prototype device and the wiring is being changed frequently, there is no easy way to prevent the wrong polarity of power supply voltage being applied to electronic circuits. If you apply reverse voltage to an electronic component, it will usually be destroyed. Consequently, **when you are wiring battery power to a circuit check very carefully that the magnitude and polarity are correct before making the final connection**.

It's also a good idea to have spare electronic components, because they are inexpensive and it's almost certain that you will destroy some in the process of developing these circuits.

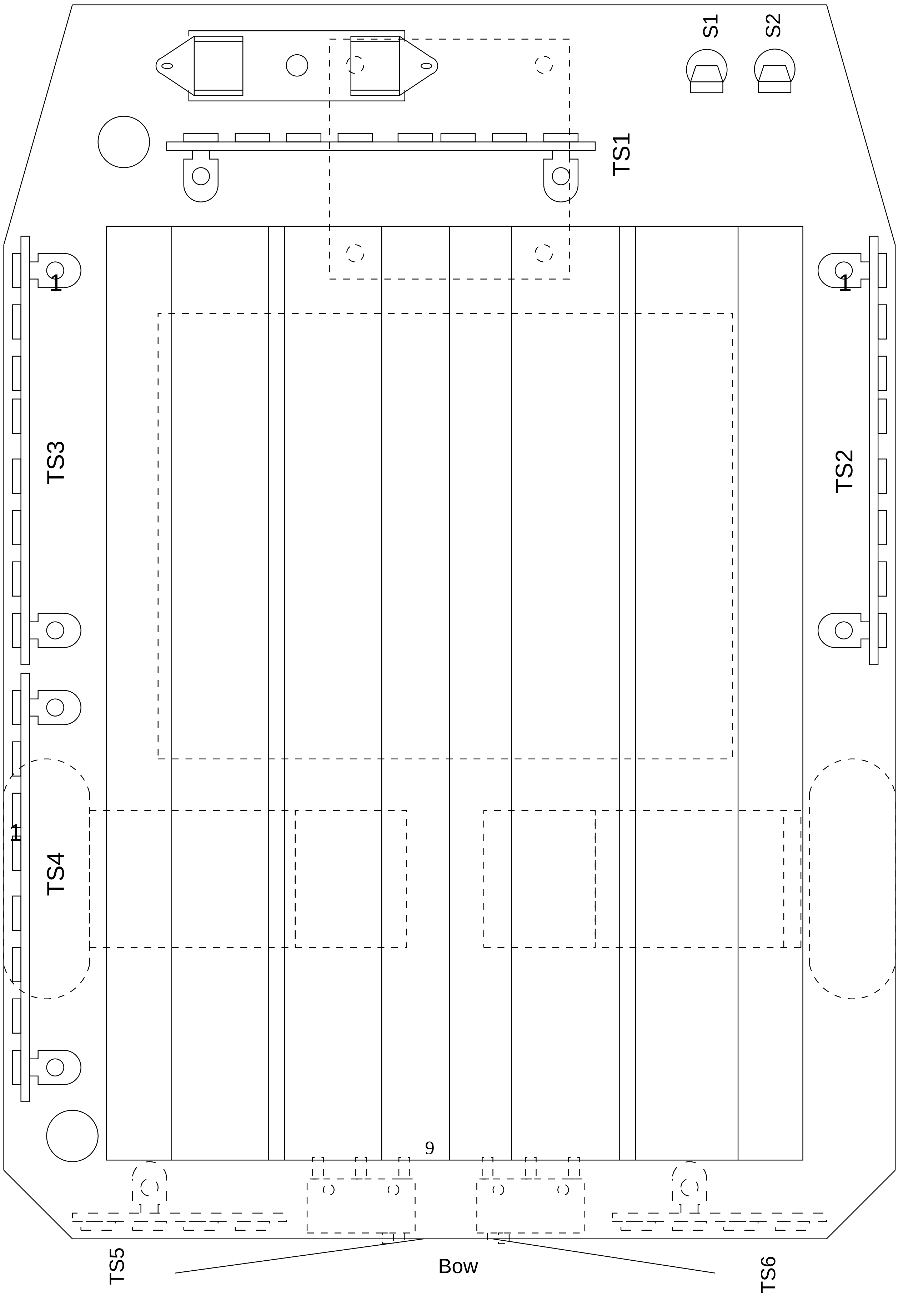

Figure 5: Mechbot Baseplate Template, Full Scale

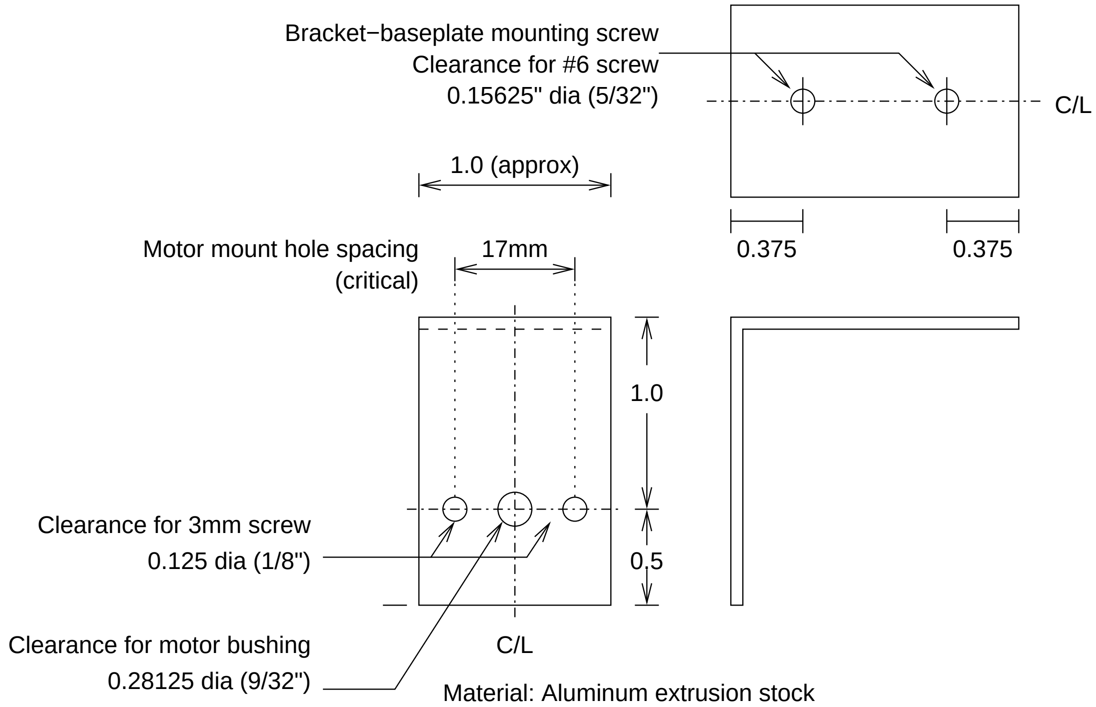

Figure 6: Motor Bracket Template, Full Scale

Fastener Schedule

Description	6-32 1/2 FH	6-32 1/2 RH	6-32 3/4 RH	4-40 1/2 FH	4-40 1/2 RH	3mm 6mm RH	2.6mm 16mm RH	6-32 Nut	4-40 Nut	2.6mm Nut
Standoffs to baseplate		4								
Motor brackets to baseplate	4							4		
Battery holder to baseplate				3					3	
Castor wheel to baseplate	4							4		
Terminal strip to baseplate					7				7	
Fuse holder to baseplate			1					1		
Motor to motor bracket						2				
Microswitch to baseplate							4			4
Totals	8	4	1	3	7	2	4	5	10	4

2 Lab 2: Electronic Circuits

This lab will introduce you to soldering, you will construct test leads that will be useful throughout the lab, and you will build and test some electronic circuits that are useful in the robot design.

2.1 Parts required

Qty	Designation	Description
1	-	Protoboard with power busses: Wishboard WB-102-J
1	R7	470 ohms
1	R33	10k ohms
2	C16, C17	100n
1	D11	Light emitting diode
1	Q1	NPN transistor, 2N4401
1	U1	74HC14 hex schmitt trigger
1	C7	2u2 capacitor
1	R32	470k resistor
1	D5	Small signal diode, 1N914B
-	-	#22AWG solide hookup wire, 2 metres
-	-	Miniature screwdriver

2.2 Construction of Test Leads

Construct 4 test leads as follows.

Each test lead consists of a banana jack on one end, a 3 foot length of test wire, and a ’grabber’ on the other, as shown in figure 7.

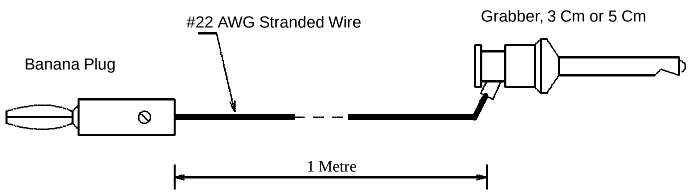

Figure 7: Test Lead

1. The red banana plug, red wire, and red grabber go together.
2. The black banana plug, black wire, and black grabber go together.
3. (Usually, you use red for positive or signal, and black for ground when connecting to a circuit.)
4. Your lab supervisor will identify these parts and guide you through the construction.
5. Strip off 1cm of insulation off each end of the test lead wires.
6. Tin the bare copper wire on each of the 8 bare ends.
7. To mount the wire in a banana jack, use a small screwdriver to loosen the screw on the banana jack, insert the tinned wire, tighten the screw.

8. Disassemble a grabber by pulling the cap off. Feed the test lead through the side hole of the cap. Hook it into the brass tab in the other part of the grabber and solder it there. Remount the cap. Do this with all four grabbers.

9. Now test your leads for continuity and verify that they are functional.

These leads can now be used to connect to the power supply or voltmeter. With an adaptor or BNC cable, they can be used to connect to the oscilloscope or function generator.

2.3 RC Circuits

The following circuits will be used in the robot control circuitry. Here, you are learning the circuits and to wire and take measurements.

Your instructor will brief you on the use of the protoboard, which is used t construct these various circuits.

Your waveform diagrams must include scale factors, labels on the axes, and the zero reference indication.

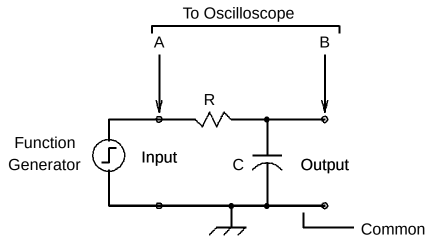

Figure 8: RC Low Pass Circuit

2.3.1 RC Low Pass Circuit

1. Choose R=22k, C=100nF.

2. Adjust the function generator to produce a 5 volt waveform with the minimum value at zero volts and frequency 50 Hz. Connect this to the input of the circuit. Using the oscilloscope, carefully record on squared paper the input and output waveforms.

3. Both the function generator ground and the oscilloscope ground must connect to the common 'ground' in this circuit.

4. Determine the time-constant of this network and compare with the calculated value.

5. Replace the resistor with a value of 470Ω. Change the function generator to 2KHz. Repeat the measurement and calculation. (You will have to change the settings on the scope.) What effect does the change in resistor cause?

2.3.2 RC High Pass Circuit

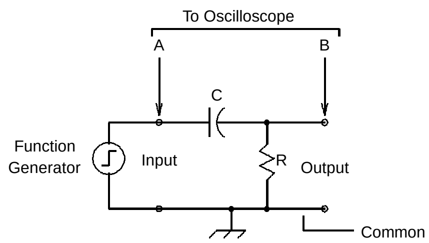

Figure 9: RC High Pass Circuit

1. Choose R=22k, C=100nF
2. Reset the function generator to 50 Hz and wire this circuit. Measure and record the input and output waveforms. Carefully note where the zero voltage line is on the input and output.
3. Change the resistor to 470Ω and the frequency to 2KHz, and repeat the measurement. What effect does the change in resistor cause?

2.3.3 Clipping Circuit

- Place a small signal diode across the resistor. What effect does this have on the waveform? Record the input and output waverforms.
- Reverse the diode. What effect does this have on the waveform?

2.3.4 Schmitt Trigger

The schmitt trigger is an integrated circuit which is used to ’threshold’ a signal. When the input is above the upper threshold, the output switches low. When the input is below the lower threshold, the output switches high. Low and high are zero and +5 volts respectively.

There are 6 schmitt triggers in one IC package in the 74HC14. Figure 10 shows the 14 pin Integrated Circuit package and the pin connections to the schmitt triggers. Notice that V_{dd} must be connected to +5 volts and V_{ss} must be connected to ground for the circuit to function.

We’ll use one of the schmitt triggers.

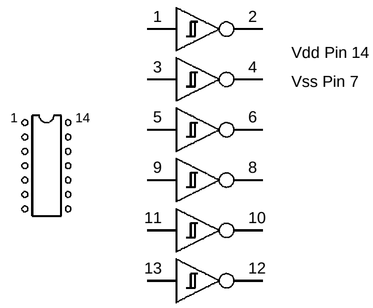

Figure 10: Hex Schmitt Trigger

1. Wire up the integrated circuit to a source of 5 volts (pin 14) and ground (pin 7). Connect a 100nF capacitor across the power supply leads (pin 14 to pin 7) at the IC. (This prevents the device from misbehaving, and it must always be there.)
2. Check that the function generator is producing a waveform between 0 and 5 volts. Switch it to triangle output and connect the function generator signal to the input of the schmitt trigger, pin 1.
3. Carefully check your wiring and then apply power. Connect trace A of the scope to the input signal and trace B to the output of the schmitt trigger, pin 2 of the IC. Using both traces of the oscilloscope, carefully compare the input and output and output waveforms.
4. Note and record the input thresholds that correspond to the output switch points.
5. Switch the function generator to square wave and compare the polarity of the input and output waveform. Verify that the schmitt trigger is an ’inverting’ device. How could you re-invert the waveform?

2.3.5 Fast Oscillator

1. Wire up the circuit according to figure 11, with R=220kΩ, C=100nF.
2. Connect scope trace A to the input of the schmitt trigger and trace B to the output, as shown in figure 11.
3. Carefully check your wiring. Power up the circuit.
4. Record the waveforms at the input and output of the schmitt trigger.

Explain why the waveforms are the shape that they are.

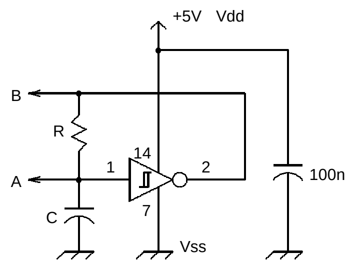

Figure 11: Schmitt Trigger Oscillator

2.3.6 Slow Oscillator

Now we will slow down the oscillator circuit by increasing R and C.

1. Depending on what resistors and capacitors you have, modify the circuit of figure 11 with a resistor and capacitor combination that has a time constant around one second, eg, 1MΩ with 1μF, or 470k with 2u2.

   You have to remove the scope lead from the input of the schmitt (connection **A**) because the scope 1M resistance is low enough to stop the oscillator from working.
2. Power on the circuit and observe the output waveform. Carefully copy down the waveform with scale factors.

2.3.7 LED circuit

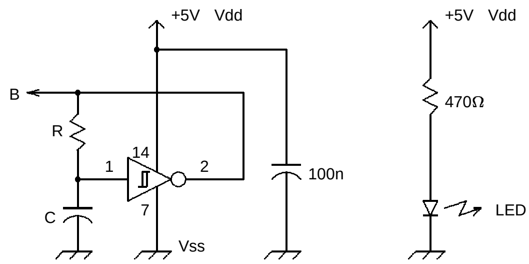

Figure 12: Adding an LED

1. Without removing the oscillator circuit, connect up the LED circuit as shown in figure 12.
2. Power on and the LED should illuminate. (If it doesn't, reverse it, you have it in backwards.)
3. Measure the voltage drop across the LED. Calculate the current through the LED.

2.3.8 LED Oscillator

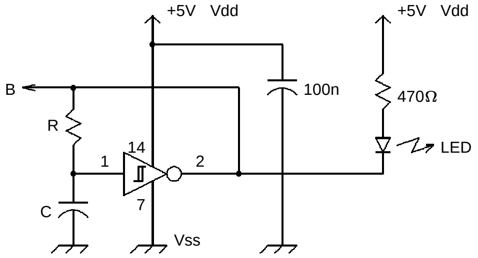

Figure 13: LED Oscillator

1. Power off the circuit.
2. Remove the cathode connection of the LED from ground and connect it to the output of the schmitt trigger oscillator, pin 2 of the IC, as shown in figure 13.
3. Power on the circuit. The LED should flash at about a 1Hz rate.

Measure and record the output voltage of the oscillator circuit at pin 2 of the IC.

2.3.9 Transistor Amplifier

(#9) The transistor can function as a current amplifier. If we want to drive more current through the LED than the integrated circuit can deliver, we add a transistor amplifier[1].

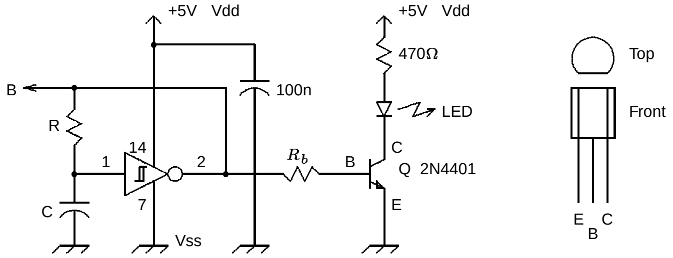

Figure 14: LED Oscillator with Transistor

Wire up the transistor amplifier circuit shown in figure 14 and verify that the LED flashes as before. (The value of R_b is not critical, and 470kΩ or something similar will work.)

Measure and record the output voltage of the oscillator circuit at pin 2 of the IC. Compare it with the value recorded for the previous circuit. Is there any difference?

[1] The theory behind this circuit will be explained in the lecture.

3 Lab3: Directional Control

In this lab you will add basic electronic circuitry to control the direction of the motors.

For reference, the wiring schematic for the existing robot power supplies is shown in figure 46 on page 58.

3.1 Testing the Motors

1. Mount the 4 standoffs so that the bot wheels are raised off the bench.

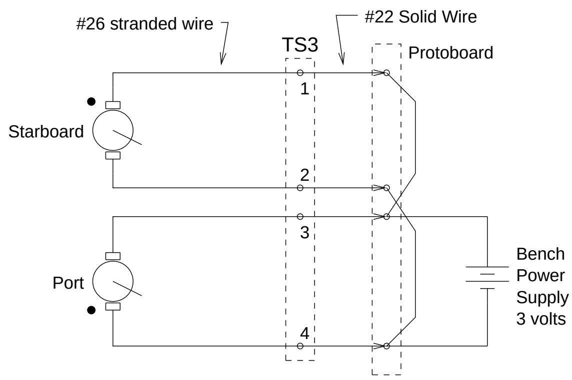

Figure 15: Motor Terminal Wiring

2. Your motors should be wired to the terminal strip TS3 as shown in figures **??** and 15. Connect their jumpers into the protoboard, connect the corresponding terminals together, and power both motors from the bench power supply set to about 1.5 volts.

   The motors should both run in a forward direction. If that's not the case, modify the wiring to the motors until they do.

3. Check the motors one at a time. Verify that the starboard motor runs forward when power is connected to pins TS3-1 and TS3-2, with TS3-1 positive.

4. Verify that the port motor runs forward when power is connected to pins TS3-3 and TS3-4, with TS3-3 positive.

3.2 The Motor Control Integrated Circuit

Luckily for us, much of the motor control circuitry is built into one integrated circuit, the L293D.

The L293D contains two *driver pairs*. Each driver pair can operate one motor. In our application, one driver is connected to each motor terminal and the electronics arranged so that the output of one driver is at the positive supply voltage when the other is at ground, and vice versa. So when `OUT1` is at Vcc and `OUT2` is at ground, the motor runs in one direction. When `OUT1` is at ground and `OUT2` is at Vcc, the motor runs in the opposite direction.

The basic connections are shown in figure 16 and the equivalent circuit in figure 17.

In addition, each pair of outputs is controlled by an *enable* signal which enables and disables both outputs simultaneously. (Outputs are enabled when the enable signal is `HIGH`).

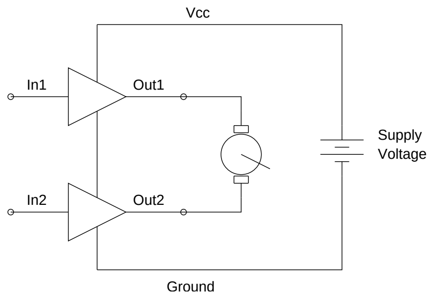

Figure 16: Motor Driver Connections

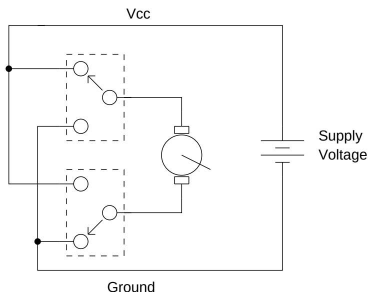

Figure 17: Motor Driver Equivalent Circuit

The enable signal is useful for shutting of a motor entirely or *duty-cycle modulating* the output voltage. If the motor is enabled and disabled at a rapid rate, the average output voltage establishes the motor speed. So if the duty cycle is 50% (equal enable and disable times) then the motor will run at half speed.

3.3 *Motor Forward* Circuit

The circuit shown in figure 18 will run the starboard motor in the forward direction. Notice that `IN1` is connected to Vcc and `IN2` to ground. This will make the top of the motor positive and the bottom zero volts, so the motor rotates forward.

The enable pin `ENABLE1` must also be connected to Vcc for the drivers to be enabled.

Connect up the circuit shown in figure 18. Notice the following points:

- Locate the L293 on the protoboard near the motor terminal strip TS4, with pin 1 of the IC toward the bow of the vehicle.
- The circuits are going to get progressively more complicated from here on, so it is very important to be systematic and check your wiring carefully. I strongly recommend that one person wire the circuit and the other person check the completed wiring, crossing off each wire on the schematic as it is checked.
- If you get power reversed to the integrated circuit, you will destroy it in a few seconds. Carefully check power supply polarity before powering on the circuit.
- Pin 8 is the motor power input and pin 16 is the logic power input. For the moment, they are the same voltage but we might use different voltages in the future.

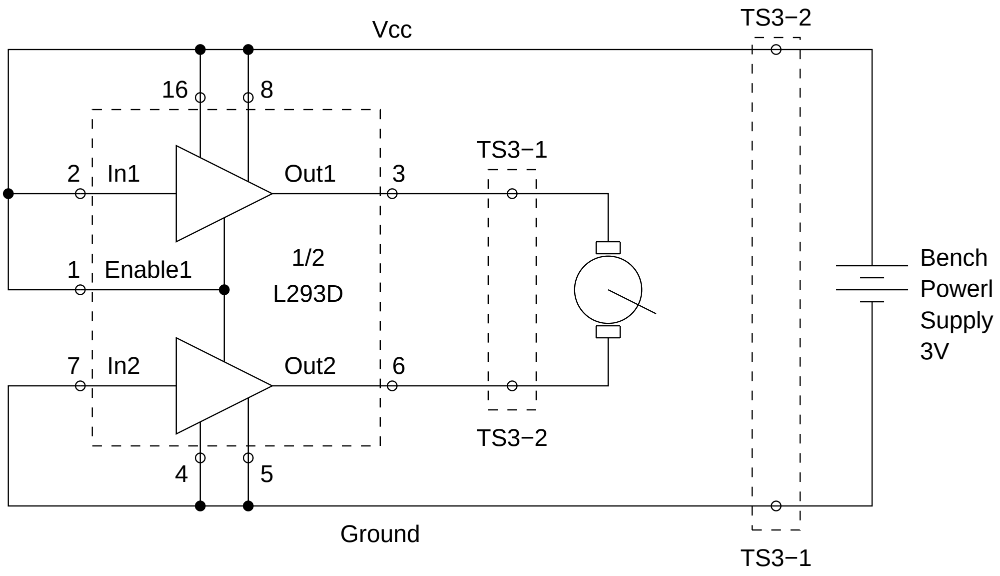

Figure 18: Basic Driver, Forward

- Pins 4,5,12 and 13 are all connected together and are the ground pin. For our purposes it is sufficient to ground pins 4 and 5.

When you have carefully checked the circuit, power on the bench supply and bring it up to about 3 volts. The motor should run forward.

Measure and record the power supply voltage and the motor voltage. Note the difference between these two voltages.

3.4 *Motor Reverse* Circuit

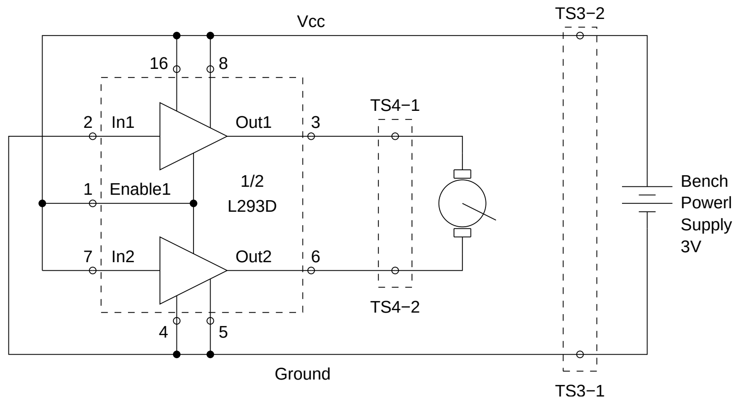

Figure 19: Basic Driver, Reverse

With a small change, the motor can be made to run in reverse. Reverse the voltages on the input pins 2 and 7, so that pin 7 is now at Vcc and pin 2 is at ground, as shown in figure 19.

Power on and check that the motor now runs in reverse.

3.5 Motor Control By Switches

Now we will enhance the circuit so that two pushbuttons can control the direction of the motors. (Direction control could be done with two DPDT switches wired between the power supply and the motors, but this method is more flexible and allows the use of simpler SPST switches.)

The circuit diagram for this part of the lab exercise is shown in figure 20.

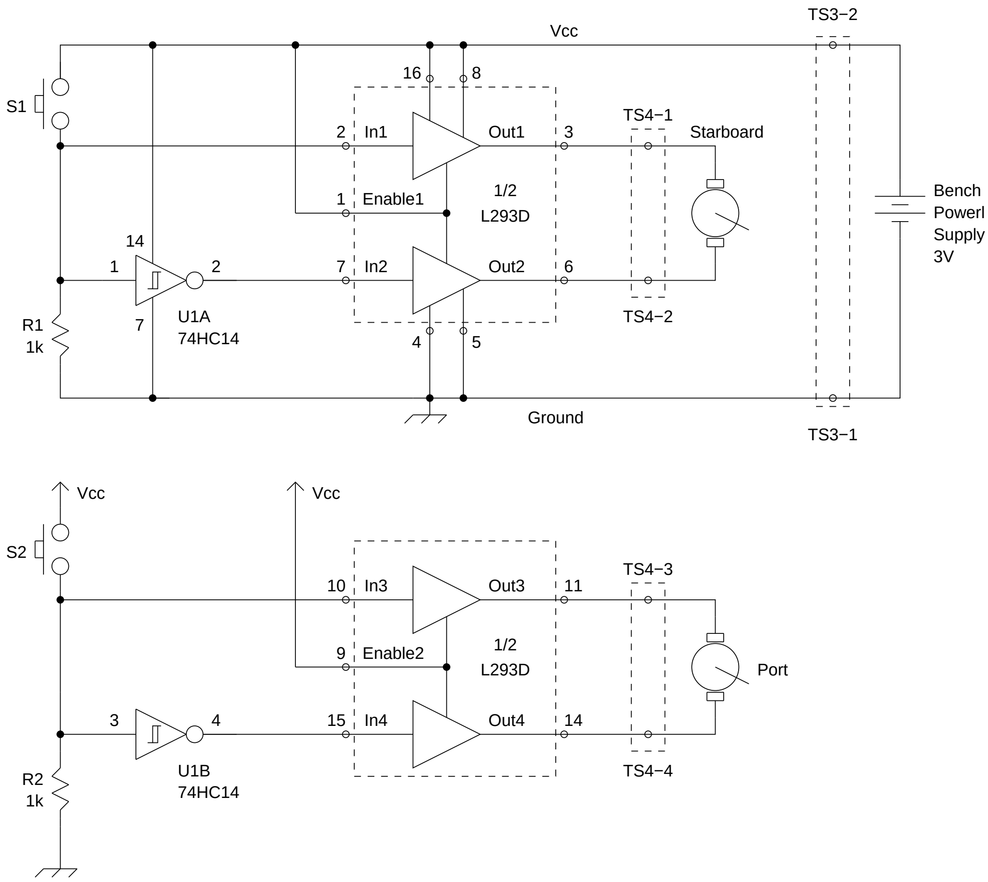

Figure 20: Button Direction Control

When a pushbutton is released (open circuit), the motor will run in reverse. When the pushbutton is actuated (closed circuit), the motor will run forward.

The resistors establish that the input voltage to the schmitt trigger inverters is zero volts when the switches are open-circuit. Otherwise, those wires are *floating* and their voltage is undefined.

The inverters ensure that the inputs to the L293 are opposite polarity for each motor. When a switch is open, the upper input to the L293 and the input to the inverter are zero volts. Consequently, the inverter output is Vcc volts, which is fed into the lower input of the L293. When the switch is closed, the upper input to the L293 and the input to the inverter are Vcc volts. The inverter output is Vcc volts, which is fed into the lower input of the L293.

Notice that the power supply connections only need to be shown once for each integrated circuit.

1. Place the 74HC14 on the protoboard near the L293 and pointed in the same direction.

2. Carefully complete the wiring in figure 20, crossing it off as it is checked. Leave out the pushbutton wiring to start with.

3. When you are confident the wiring is correct, power on the circuit at about 1.5 volts. Both motors should run backwards.

4. Solder solid wires onto the terminals of the pushbuttons and add the pushbuttons to the circuit. Power on the circuit. When the buttons are released, the motors should run in reverse. When the buttons are actuated, the motors should run forward.

5. Demonstrate the operational circuit to your lab supervisor to get credit for the lab.

4 Lab 4: Bump and Turn

In this lab you will install electronic circuitry that controls *bump-and-turn* behaviour. The robot normally proceeds forward. When the robot bumps into an obstacle, it backs up, makes a backing turn, and then resumes travelling forward.

4.1 Theory

The basic circuit for bump-and-turn control is shown in figure 21.

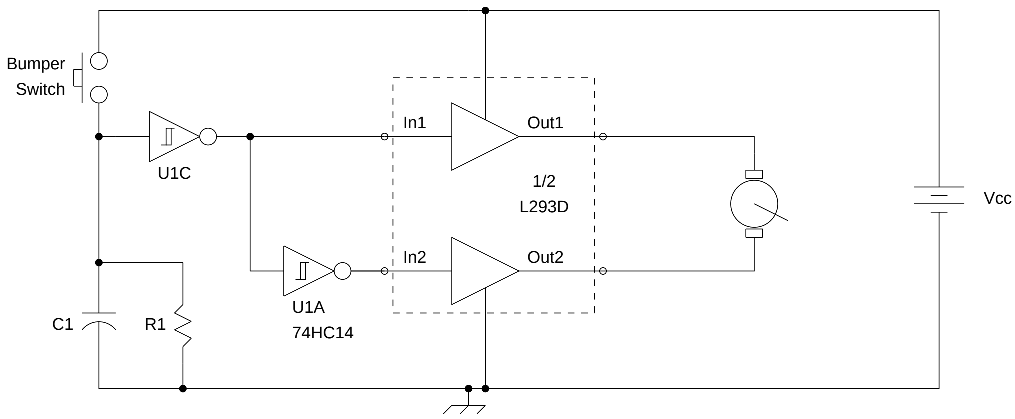

Figure 21: Bump-and-Turn Concept

Initially, the robot is running forward. When a bumper switch closes, the inputs to the motor control IC reverse for a short period to back the robot. The backing interval is different for the two motors, so one motor will continue backing while the other one resumes driving forward. This causes the robot to rotate in place for the brief interval the motors are running in opposite directions. Then both motors resume running forward.

Consider the starboard section of the L283 motor control, IC2. When its inputs are $\frac{H}{L}$, the motor drives forward. When the inputs reverse, $\frac{L}{H}$, the motor reverses.

So we need some way of reversing the motor control inputs for a backing delay of one or two seconds.

Step by step, the sequence of events is as follows:

- The capacitor C1 is normally discharged to zero volts through the resistors R1. Consequently the input voltage for the Schmitt trigger U1C is below threshold and treated as a logic `low`. The output of U1C is consequently logic `high`. This is further inverted by U1A to produce another logic `low` signal. So the inputs to the motor control IC are $\frac{H}{L}$ and the robot is moving forward.

- When a bumper switch closes, the capacitor charges up rapidly to the supply voltage Vcc. This makes the input of U1C a logic `high`, so that the inputs to the motor control IC are now $\frac{L}{H}$. The motor reverses, backing away from the obstacle.

- The bumper switch opens, so capacitor C1 now begins to discharge through resistor R1. When the capacitor discharges to below the threshold of Schmitt trigger U1C, it sees this as a logic `low` signal. Consequently, the inputs to the motor control IC revert to $\frac{H}{L}$ and the robot is again moving forward.

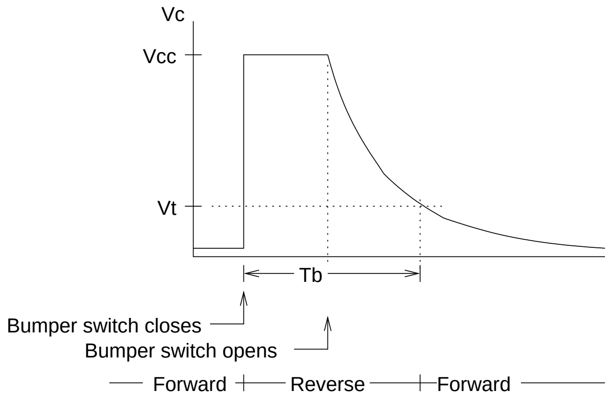

Figure 22: Capacitor Voltage

Now we need to relate the discharge time of the capacitor-resistor network R1-C1 to the required backing interval. The waveform of voltage across the capacitor is shown in figure 22.

The discharge curve of the capacitor is an exponential with the equation

$$V_c = V_{cc}\epsilon^{-\frac{t}{RC}} \tag{1}$$

where V_c is the voltage across the capacitor and V_{cc} is the supply voltage. The product RC is known as the *time-constant* of the circuit.

The negative threshold of the Schmitt Trigger is about 1.6 volts with a 5 volt power supply. Substituting these values for V_c and V_{cc} in equation 1, take the natural log of both sides and we have

$$\begin{aligned} \ln\frac{1.6}{5} &= -\frac{t}{RC} \\ &= 1.14 \\ t &= 1.14RC \end{aligned}$$

So the backup interval will terminate when the elapsed time is equal to 1.14 time-constants after the bumper switch opens. If we want a backup interval about 1 second, then we would make the time-constant RC equal to 1.14. Since this isn't critical, to make the math simple, we'll round the time-constant value off to 1 second. For example, we could choose $R = 100k\Omega$ and $C = 10\mu$F.

4.2 Bump-and-Turn Circuit

The complete bump-and-turn circuit is shown in figure 23.

There are two bumper switches which are wired in parallel so that either one can trigger the backing-turn routine.

The outputs of the switches are fed through diodes D1 and D2 to the timing capacitors C1 and C2. Because the capacitors discharge at different rates, the diodes are necessary to ensure that the capacitor with the larger voltage cannot discharge into the capacitor with the lower voltage.

The maximum capacitor voltage is Vcc-0.7 volts.

The two backing delays are set to 1 second for the starboard motor and 2 seconds for the port motor. This ensures that the robot backs and then executes a turn before continuing.

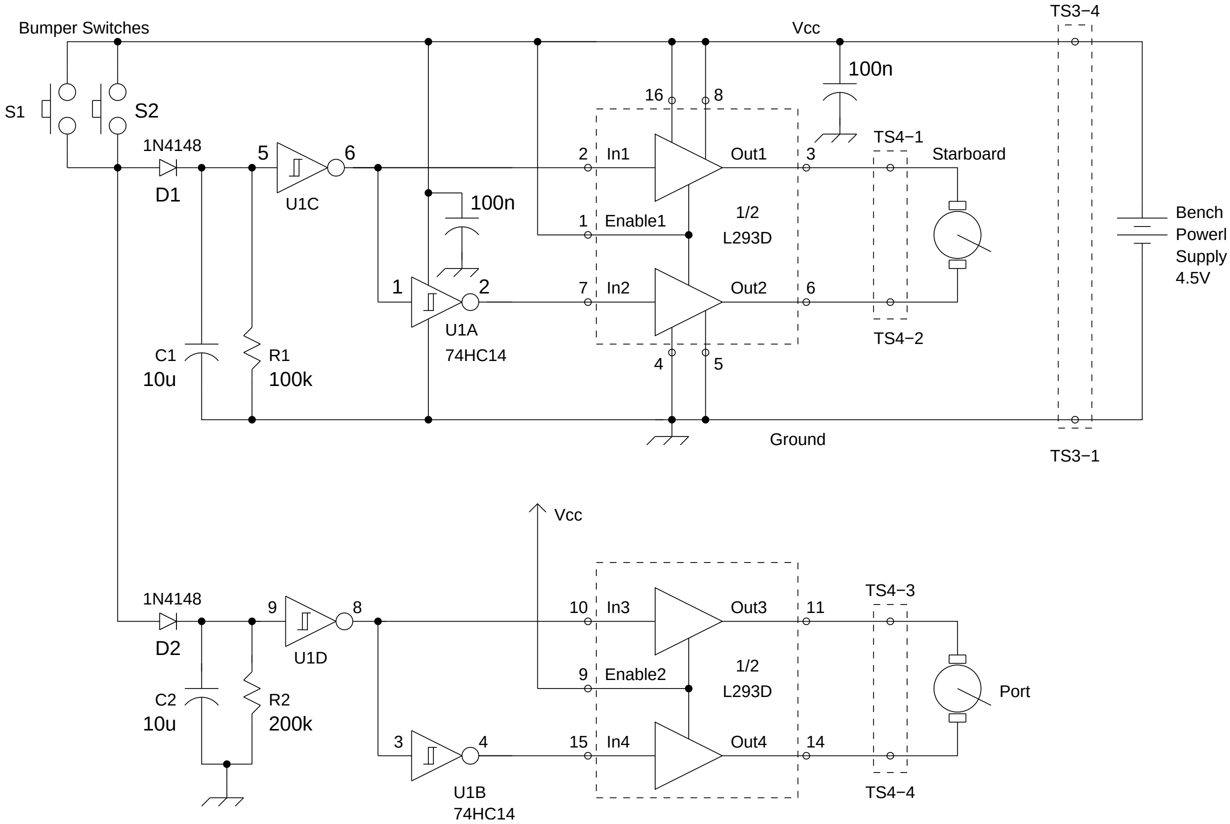

Figure 23: Bump-and-Turn Circuit

4.3 Procedure

1. Mount the robot on its standoffs.
2. If you haven't done so already, wire up the bumper switches to terminal strip TS4 according to figure **??**. Add jumper wires to the same terminals so the switches can be connected into the protoboard. You may have to drill a 1/4 inch hole in the baseplate to provide a path for the switch wiring.
3. Wire up and carefully check the circuit shown in figure 23.
4. Remove the batteries and use test leads to jumper in a lab power supply to terminals TS3-1 and TS3-4.
5. Set the power supply to about 4 volts and test the circuit. When it is first powered on, the robot motors should run forward. Actuating either of the bumpers should cause the motors to reverse for different backing intervals.
6. Optional: Mount a piece of stiff wire to the bumper switch levers so that it forms a loop at the front of the robot, and bumping into this loop will trigger either or both of the bumper switches.

7. Replace the batteries and reassemble the robot. (If you have a jumper lead, you can jumper out one of the batteries. This will reduce the power supply voltage from 6 to 4.5 volts, which is a bit easier on the motors.) Power on and test the robot in operation. Show it to your lab supervisor to get credit for the lab.

5 Lab 5: Bulldozer Steering

In this lab you will install electronic circuitry to steer the robot in *bulldozer* fashion. A speed control is associated with each drive motor. To steer the vehicle, one motor is caused to go faster than the other.

This type of steering is often used in earthmoving equipment and in the *bobcat* machine.

5.1 Motor Speed Control by Pulse Width Modulation

In the previous lab, the motor was operated from continuous DC power. By changing the polarity of the motor voltage, the motor could be made to run in different directions, but it always ran at full speed.

In this lab, we introduce speed control of the motor by *duty-cycle modulation* of the supply voltage. The basic idea is very simple: the motor voltage is switch on and off at a high frequency. In this lab, we'll use a switching frequency of about 1000Hz. The ratio of `ON` time to the total period of the switching waveform is known as the *duty cycle*.

$$\text{Duty Cycle} = \frac{T_{on}}{T} \tag{2}$$

For example, if the time on and time off are equal, the duty cycle is 50%. The pulse waveform in the motor causes pulses of torque, which are then averaged by the mechanical intertia of the motor and the inductance of the motor windings. Consequently, the average voltage across the motor is proportional to duty cycle. As the average motor voltage changes, so does the motor speed.

This scheme is feasible with modern electronic devices that are able to switch at high frequencies. It minimizes the power losses in the driver circuitry. The driver transistors are either full on or full off, so their power dissipation is very low. Put another way, the driver circuit is close to 100% efficient, and the total power losses are minimal. Small power dissipation pays off in a number of ways:

- heat sinks are either not required or very small
- the driver circuitry can be small and light, which reduces cost
- the power supply can be smaller, since it doesn't have to supply electrical losses in the driver circuit
- under battery operation, the battery life is extended

In the mechbot circuit, an L293 integrated circuit contains two output channels, each of which drives one of the DC motors. Each output channel has an *enable* control which enables and disables that output. If the enable control is pulse with a square wave of some duty cycle, then the output power to the motor will have the same duty cycle.

The variable duty cycle waveform is generated by comparing a triangle waveform with some DC level, as shown in figure 24.

As the DC level from the *Speed* potentiometer increases, the op-amp comparator changes state at a higher point in the triangle waveform. This increases the duty cycle at the output of the comparator, which increases the average voltage across the motor, and increases the motor speed.

Some points to notice:

- If the DC voltage from the pot is greater than the maximum value of the triangle wave, the output of the comparator simply stays `HIGH` all the time. Likewise, if the DC voltage from the pot is lower than the minimum value of the triangle wave, the output of the comparator stays `LOW` all the time. Consequently, the voltage from the pot should have the same range as the triangle wave.
- It's not very critical that the triangle wave be completely symmetrical. In fact, it can have the shape of a sawtooth without affecting operation. In our case, the triangle will have slightly curved slopes.
- By reversing the input to the comparator, a larger voltage from the pot reduces the duty cycle.

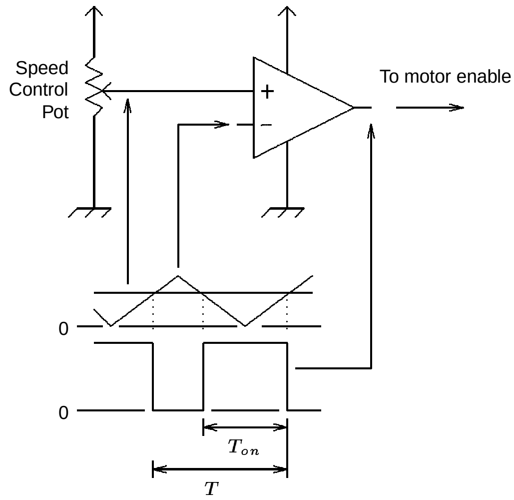

Figure 24: Variable Duty Cycle Generation

5.2 System Block Diagram

With the concept of duty cycle modulation in hand, we can now draw a block diagram of the bulldozer steering system.

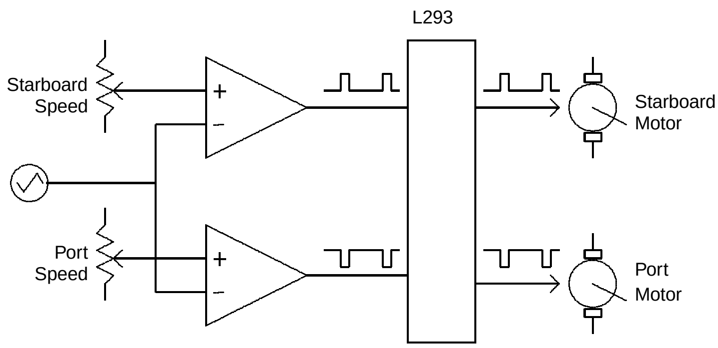

Figure 25: Bulldozer Steering Concept

Any circuitry to control the direction of the motors is additional and not shown in figure 25. In this lab we will simply wire the L293 to drive the motors in a forward direction[2].

5.3 The Triangle Wave Generator

The circuit for a triangle-wave generator is shown in figure 26.

[2]Or you can leave the bump-and-turn circuitry from the previous lab in place. It will still work with the motor speed control circuitry. However, the wiring is then a bit more complicated for troubleshooting.

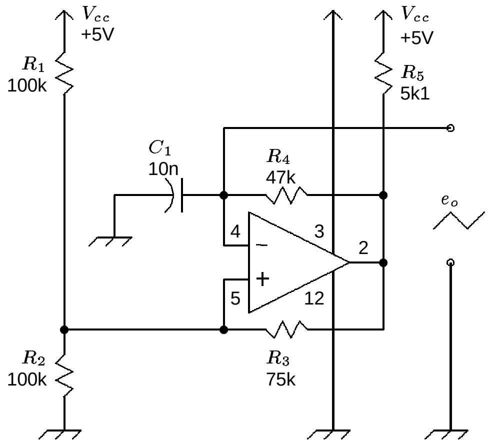

Figure 26: Triangle Wave Oscillator

- The heart of the oscillator is the comparator integrated circuit. The comparator used in this circuit is one of four in the LM339 package. It's very similar to an op-amp in operation, but is optimized to act as a switch rather than a continuous amplifier like the op-amp. In fact, an op-amp can function as a comparator if switching speed is not important.

- There is one important difference between the op-amp and a comparator. The output of the comparator is an *open-collector* circuit, which may be modelled as the switch shown in figure 27. Consequently, there is usually a resistor connected between the output of the comparator and V_{cc}. When the output switch is open, the resistor pulls up the output to V_{cc} volts. When the switch is closed, the output is zero volts. This way, the comparator can be used to switch an output voltage that is different from the voltage supplying the chip. In figure 26 R5 is the pullup resistor. This resistor is generally small compared to the other resistors in the circuit. As a consequence, we can usually regard the comparator as producing either Vcc or zero volts.

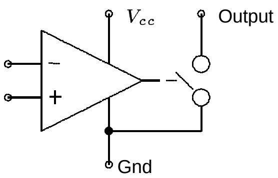

Figure 27: Comparator Equivalent Circuit

- The circuit is basically a Schmitt Trigger with additional parts to make it into an oscillator. The positive feedback is from the output via R3. The values of R1, R2 and R3 determine the trip thresholds for the Schmitt. To see this, thevenize the voltage divider R1 and R2: they become a 2.5 volt source with an internal resistance equal to R1||R2, ie 50kΩ. Then the Schmitt trigger is as shown in figure 28.

- Since this is a positive-feedback circuit, the output V_A will either be at 0V or +5V. Let's assume that it's initially at +5V. Then the voltage at the non-inverting terminal $V+$ of the comparator will be +3.5 volts[3].

[3] The superposition theorem is very handy to prove this.

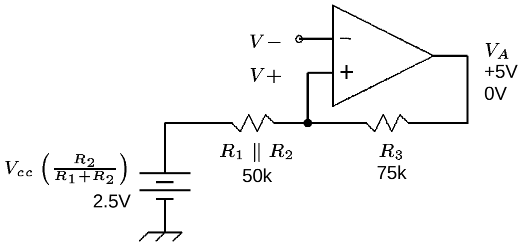

Figure 28: Schmitt Trigger Equivalent Circuit

This sets the upper trip level of the Schmitt trigger at +3.5 volts.

- When the voltage at the inverting terminal exceeds the upper trip level, the comparator will rapidly switch into its other state, with V_A at 0V. This sets the voltage at the non-inverting terminal $V+$ of the comparator to 1.5 volts, so this is the lower trip level of the Schmitt trigger.
- Components R4 and C1 make the Schmitt trigger into an oscillator. When the output is HIGH (+5 volts), capacitor C1 charges through R4 until the voltage at the inverting terminal V- of the comparator reaches the upper trip level of the Schmitt trigger. Then the output switches to zero volts.
- When the output is low, the capacitor C1 discharges down to the lower trip level, and the Schmitt trigger changes state to make the output high again. The resultant waveform is shown in figure 29.

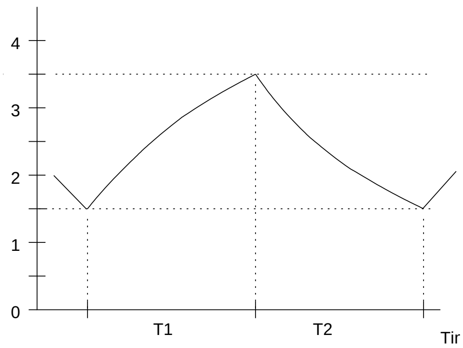

Figure 29: Oscillator Waveform

Timing Interval In order to estimate the frequency of this waveform, we need to calculate the time intervals T1 and T2. During T1, the voltage across the charging resistor R4 is changing continuously and the capacitor is charging exponentially. However, a rough estimate of the charging current can be obtained by using the *average* voltage across R4, which is 2.5 volts. Then

$$\begin{aligned} I_c &\approx \frac{V_{R4}}{R4} \\ &= \frac{2.5}{47000} \\ &= 53\mu\text{A} \end{aligned}$$

From the equation for a capacitor

$$Q = CV \tag{3}$$

then

$$\begin{aligned} I_c &= \frac{dQ}{dt} \\ &= C\frac{dV_c}{dt} \end{aligned}$$

In our case, we're assuming a straight line so *dt* becomes ΔT. Rearranging, we have:

$$\begin{aligned} \Delta T &= \frac{dQ}{dt} \\ &= C\frac{\Delta V_c}{I_c} \end{aligned}$$

Since T_1 is equal to ΔT, we have:

$$\begin{aligned} T_1 &= C\frac{\Delta V_c}{I_c} \\ &= 10 \times 10^{-9}\frac{2.0}{53\mu\text{A}} \\ &= 377\mu\text{sec} \end{aligned}$$

By a similar reasoning process, T_2 is found to be the same value, so the overall period of the waveform is 754μsec, which gives a frequency around 1.3KHz.

Choosing the Trip Levels Why did we choose the trip levels at 1.5 and 3.5 volts? If you read the datasheet for the LM339 comparator, it specifies that the *common-mode input voltage* range is from 0 to Vcc-1.5 volts. So the input terminals are limited to between zero and 3.5 volts when Vcc is equal to 5 volts. It's good practice to make the triangle wave as large as possible, so that noise signals have as little influence as possible. If the Schmitt trigger trip levels are symmetrical, an upper trip level of 3.5 volts implies a lower level of 1.5 volts, with a hysterysis band of 2 volts.

5.4 Design Notes

The complete bulldozer steering circuit is shown in figure 30 on page 33.

A sign of a skilled engineer is that they are able to modify a circuit design to suit components that they have on hand. You may have all the parts that you need for this circuit on hand if you modify the circuit as described below.

- The values of the pullup resistors R5, R9, R13 (shown in the schematic as 5k1) are not critical. Any value between 1k0 and 10k will work just as well.
- The absolute values of R1, R2 and R3 are not terribly critical as long as their relative values are kept the same. For example, 120k, 120k and 91k would also work.
- The values of the oscillator timing components are not critical, as long as the oscillator frequency is somewhere in the range of 1kHz to 10KHz.

- The potentiometers are R7 and R11. The other resistors in each divider chain should be chosen so that the maximum output of a pot is about 3.5 volts and the minimum value is 1.5 volts, in order to match with the oscillator triangle waveform amplitude. So the values of R6,R8,R10,R12 will depend on R7 and R11. (I had pots that were 25K so I used 20k for the fixed resistors.)
- Motor noise affects the operation of the circuit to some extent. Capacitor C2 was added to reduce the effect of motor noise on the power supply lines. Any large electrolytic (ie, polarized) capacitor will help here.
- Capacitor C3 is standard for integrated circuits and should be placed close to U2. Likewise, C4 should be placed close to U1.
- Complete the design and obtain any required parts before coming to the lab.

5.5 Construction Notes

Potentiometer Controls

You will need to mount the two potentiometers R7,R11 in such a way that they can be operated easily to steer the robot. One possible mounting scheme is shown in figure 31 on page 34.

The pots are mounted on metal brackets which are in turn fixed to a wooden base. Plastic knobs are fixed on the two pot shafts and levers glued to the knobs. This is more complicated than absolutely necessary, and any arrangement you can work with is satisfactory.

Potentiometer Wiring

Somehow, the potentiometers R7,R11 need to be attached to 6 lengths of wire that allow the robot to be steered from a distance and plug into the protoboard. There are various ways that it can be done:

- Solder 6 lengths of 26AWG stranded wire (available in the lab) to the terminals of the pots. Twist the wires together or use plastic cable ties to bundle them together. Get a 6-way screw or solder terminal strip from Supremetronics or Active Surplus, and attach that to the other end of the cable. Attach 6 short pieces of 22AWG solid wire to the terminal strip, and plug those wires into the protoboard. Of course, you have to keep track of which wire is which.
- Get a length of flat ribbon cable from Supreme or Active Surplus. (Get the kind that is multi-coloured and can be split into individual conductors. There is also a grey flat cable that is not easy to split.) Split the ribbon cable into two pieces each of 3 conductors. Separate, strip and solder the wires at one end and attach them to the pot terminals.

  Obtain a plug strip at Supremetronic. Cut off two, three-prong pieces. Attach the 2, 3 way plug strips to the other end of the ribbon cable, as shown in figure 32 on page 34. Notice that the long pins fit into the protoboard and the short pins attach to the wires. The plugs will fit directly into a protoboard.

  Wiring of the plugs takes some care in soldering. Tin the plug terminals by melting some solder onto them. Strip the wires back about 1/8 inch. Tin the bare wires. For each wire, hold it against the plug terminal and touch it with the soldering iron so that the solder on the plug terminal and wire melt. Immediately take away the soldering iron, and the new solder joint should hold the wire. Be careful that stray strands of the wire do not short against and adjacent wire or terminal.

  This takes some care, because too much heat will melt the plastic base of the plug and/or the insulation on the ribbon cable. But the results are very attractive and neat once you get the hang of it.

Wiring Prep

1. Remove any batteries.
2. Place the bot on standoffs.
3. Connect TS2-1 and TS2-4 to a DC power supply of about 6 volts.
4. Remove the bump-and-turn switches and associated circuitry, but leave U1 and the motor connections on the board.
5. Connect the wires at the input to U1 that set the direction of the motors.
6. Connect the enable pins of U1 up to Vcc via resistors R9, R13.
7. Power on and check that the motors run forward.

Oscillator

1. Connect up the oscillator circuit (by itself) as shown in figures 26 and 30.
2. Power up the system and check with the oscilloscope that the oscillator is producing a square wave at pin U2-2 and a triangle wave at pin U2-4.
3. Carefully record the waveform of the triangle wave, noting the frequency and the amplitude. **Remember, the scope has to be on DC coupling, zeroed and calibrated for this measurement.**

Speed Pots

1. Connect the speed potentiometers and their associated resistors as shown in figure 30.
2. Connect a digital voltmeter or oscilloscope channel between the wiper of one pot and ground.
3. Power on and check that the voltage wiper of the pot varies from 1.5 volts to 3.5 volts as you rotate the pot.
4. The wiring of the pot should be such that increasing the pot rotation (whatever that means to you, usually forward for a lever or clockwise for a knob) increases the output voltage. If that is not the case, reverse the connections to the end terminals of the pot. However you wire the pots, they should both do the same thing, ie, rotation in the same direction should increase output voltage.
5. Check the other pot output voltage and confirm it is correct.

Complete Wiring

1. Wire comparators U2B and U2C as shown in the circuit of figure 30. Make sure each comparator is wired to its respective output pullup resistor (R9, R13), but disconnect the output of the comparators from the motor driver inputs on U1.
2. Connect up an oscilloscope to monitor the output waveform of U2B (on pin 1). Power on the system. Adjust R7 and you should see a variable duty cycle waveform. If not, troubleshoot the wiring.
   - Check that the triangle wave is appearing on U2 pin 6.
   - Check that the amplitude and frequency of the triangle wave are correct.

- Check that the output voltage of the pot is appearing on U2 pin 7.
- Move the pot and verify that the voltage changes to the correct limits.

3. Repeat with the other channel and verify that a variable duty cycle waveform appears there as well.
4. Power off and complete any missing wiring.
5. This is it: carefully check all of your wiring against figure 30, crossing off connections on the circuit diagram as you go.
6. Power up the circuit and you should be able to speed control the motors with the potentiometers. You will probably hear a high-pitched whistling noise from the circuit. This is is normal, it's the sound of the motors vibrating at the pulse modulation frequency.
7. Demonstrate the working circuit to your lab supervisor to get credit for Lab 6.
8. If you wish, you can put 4 D cell batteries in B1 and B2, and then drive the robot under control of the steering pots.

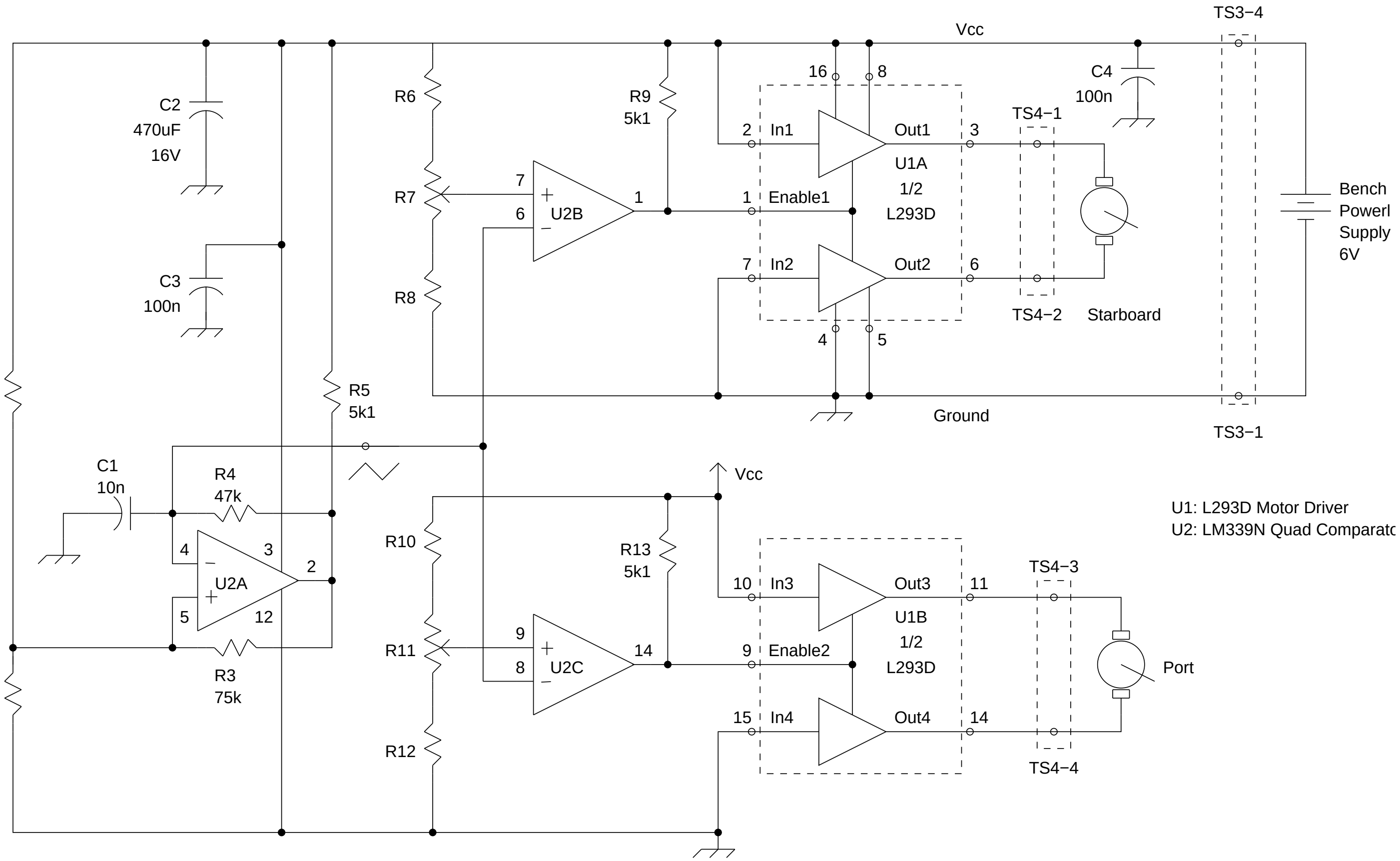

Figure 30: Bulldozer Steering Circuit

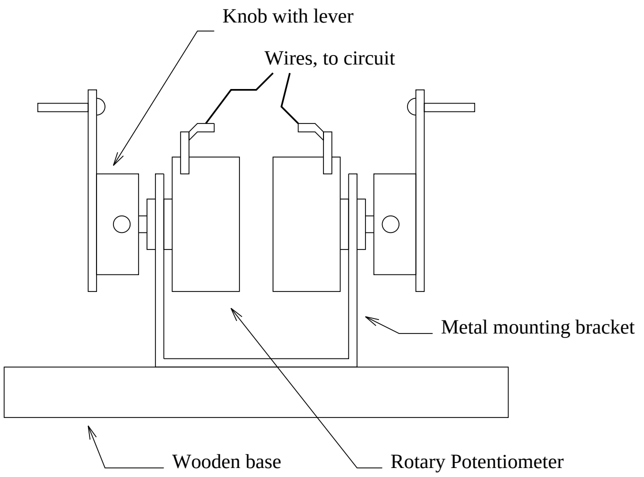

Figure 31: Mounting the Pots

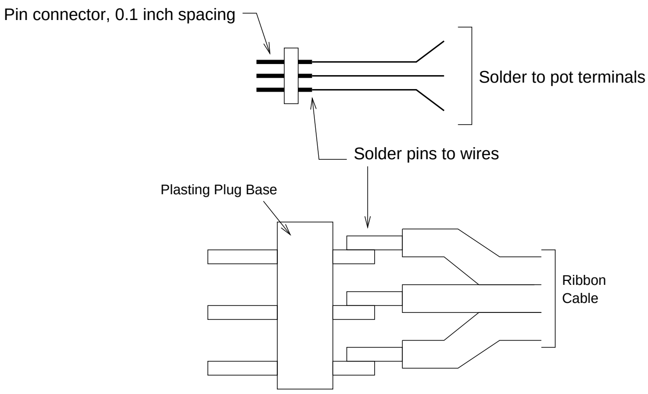

Figure 32: Wiring the Pot Plugs

6 Lab 6: Separated Speed and Steering

In the previous lab, steering was by two controls, one for each wheel. This works and is used in some vehicles, but it takes some getting used to because the steering and speed functions are combined in each control. It's not as easy to operate as a separate steering wheel and throttle combination. In this lab you will install electronic circuitry provides separate steering and speed controls.

6.1 Theory

To begin with, we need a concept to describe how the steering and throttle controls affect motor speed. Figure 33 shows how this might work.

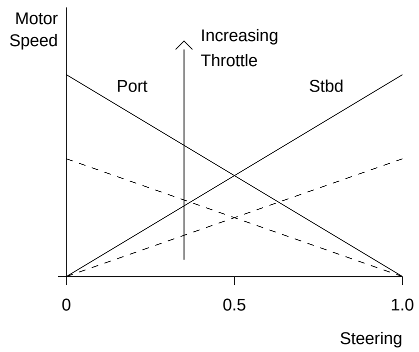

Figure 33: Steering Functions

As the steering control is moved from one side to another, one motor speeds up while the other slows down. When the steering control is centred, the motor speeds are equal.

As the throttle is increased, the relative speeds of the two motors stay the same but the magnitude increases.

Let's assume that the throttle setting can be represented by a variable T that can vary from 0 to 1, and the steering setting is a variable S with the same range. Then the equations for the motor speeds are given by:

$$\begin{aligned}\omega_s &= TSK_m \\ \omega_p &= T(1-S)K_m\end{aligned}$$

where K_m is some constant for the motors.

Obviously, we will need to multiply the throttle and steering signals together. Fortunately, two cascaded potentiometers generate a voltage that is proportional to the product of their settings[4] (the *setting* being a number between 0 and 1), figure 34.

For example, suppose the settings of the two pots are

$$\begin{aligned}K_1 &= 0.5 \\ K_2 &= 0.25\end{aligned}$$

Then the output voltage E_2 in figure 34 is given by

$$E_2 = K_2 E_1$$

[4]This ignores the loading effect of R2 on R1, which is a problem if the pots have the same resistance. It's approximately correct for R2 much larger resistance than R1, or completely true if there is a buffer amplifier between the two pots.

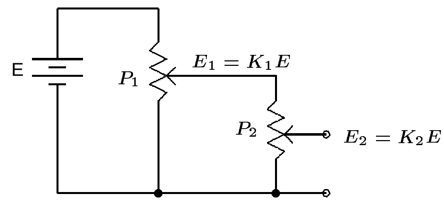

Figure 34: Pot Multiplcation

$$
\begin{aligned}
&= K_2(K_1E) \\
&= (0.25)(0.5)E \\
&= 0.125E
\end{aligned}
$$

That is, the output voltage is proportional to the products of the two pot settings.

Obviously, this only works for numbers that are in the range of 0 to 1. However, if we put amplifiers of fixed gain $\times 10$ in the circuit, then we could multiply by numbers in the range 0 to 10. However, there is a practical limit to the product of these two numbers, given by the system supply voltages. If the supply voltage is 15 volts, you cannot multiply 10×8 and get 80 volts.

The Complementary Voltage

Fortunately, as the voltage across the bottom half of a pot decreases, the voltage across the upper half increases. So if we have a signal S across the lower part of the pot, we have $(1 - S)$ across the upper part, figure 35.

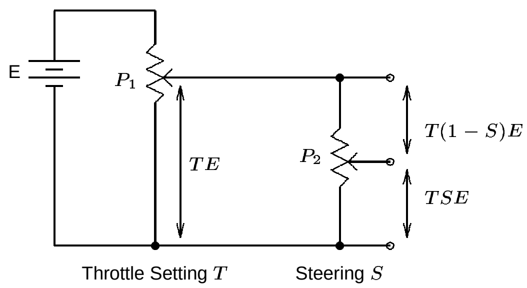

Figure 35: Generating (1-S)

Consequently, we will use the two control signals TSE and $T(1 - S)E$ to set the speeds of the two motors. This is easily done. The control signals set the threshold into the PWM comparators, with a triangle wave into the other input of the comparator. Then as the control signals increase, the motor speed will increase.

Electronic Details

We have a few more details to take care of for a complete circuit.

- To avoid the loading effect of pot P2 on P1, we need a unity-gain buffer between them.

- We need some way of extracting the signal $T(1-S)E$ so that it can be used as a speed control signal into a comparator. This can be done with a differential amplifier, which effectively subtracts the voltage at the wiper of the pot from the voltage at the top of the pot.
- The control signals must act over the same range as the PWM triangle wave. The output voltage of the tri-wave generator from the previous lab ranges from 3.5 to 1.5 volts for a total swing of 2 volts.

  The control signals will run from 0 up to the E volts shown in figure 35. If we pick E equal to 2 volts, then we can do a direct comparison between the 2 volt tri-wave and the 2 volt control signals. However, either we need to translate the control signals up to the $1.5, 3.5$ volt range of the tri-wave generator, or we need to translate the output of the tri-wave generator down into the $0, 2$ volt range of the control signals. The former approach requires two op-amp translator circuits, the latter requires only one op-amp, so that's the method chosen here.

Translator Circuit

We can allow the translation to be inverting, because the inverted triangle waveform is no different than the non-inverted form. This turns out to be convenient.

A suitable amplifier circuit to provide the require translation is shown in figure 36.

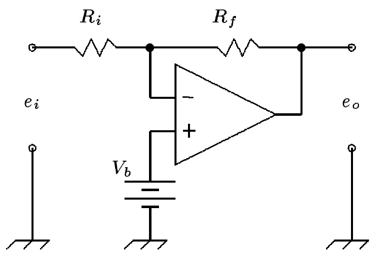

Figure 36: Level Translator Circuit

The see-saw diagram of figure 37 helps us design this particular circuit.

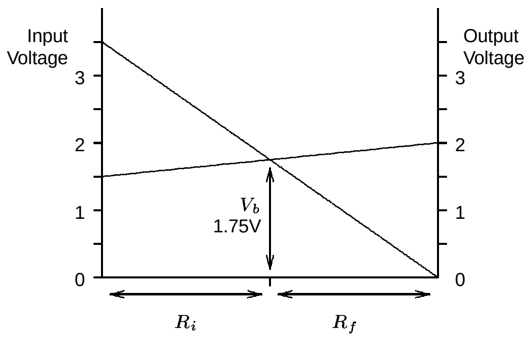

Figure 37: Level Translator, Seesaw Diagram

Reading off the diagram, $R_f = R_i$ and $V_b = 1.75$ volts. The bias voltage can be derived from V_{cc} by a voltage divider.

The seesaw diagram is for a translator that converts +3.5 volts to zero volts, and +1.5 volts to 2 volts. The intersection of these two traces defines the offset voltage and the ratio of Rf to Ri.

6.2 Steering Circuit

The complete steering circuit is shown in the schematic diagram of figure 38.

Notes on the schematic:

- Resistor R11 will depend on the value of your potentiometer R12. Choose a value that will put about 2.5 volts (Vcc/2) volts across the pot, R12.
- The differential amplifier resistors R14, R15, R16, R17 are not critical as long as they are equal. Anything from 50k to 200k should work.
- Resistors R7, R8 are not critical as long as they are equal.

6.3 Commissioning the Circuit

This is a complicated circuit, so it should be started up in sections. A suggested sequence is as follows:

Wiring Prep

1. Remove any batteries.
2. Place the bot on standoffs.
3. Connect TS2-1 and TS2-4 to a DC power supply of about 6 volts.
4. Remove the speed pots and associated circuitry, but leave U1, U2 and the motor connections on the board.
5. Power on and check that the motors run forward.

Oscillator

6. Check that the oscillator circuit is still wired correctly. Power on and check the triangle waveform at U2-4.
7. Add U3 to the circuit board. Connect pins 4 and 11 to Vcc and Gnd.
8. Wire up the resistors associated with the level shifter, U3C.

Level Shifter

9. Check the voltage at pin U3-10, which should be about 1.75 volts.
10. Check that the output of the level shifter (U3-8) is a triangle wave operating between 0 and +2 volts.

Throttle Pot

11. Connect the throttle pot (R11). Check that the voltage at the wiper of the pot varies between 0 and +2.5 volts as R11 is adjusted.

12. Connect the buffer U3A to the pot. Check that the output at U3-1 varies between 0 and +2.5 volts as R11 is adjusted.

Steering Pot

13. Connect the steering pot R12. With the throttle pot R11 at maximum, check that the voltage at the wiper of R12 varies between 0 and +2.5 volts as R12 is adjusted.

14. Connect up the differential amplifier U3B and its associated resistors.

15. Connect the oscilloscope channel A to the wiper of pot R12. Connect the oscilloscope channel B to the output of U3B at U3-7. With the throttle pot R11 at maximum, the voltages seen on channel A and B should move in opposite directions between approximately 0 and 2 volts as the steering pot R12 is adjusted.

Complete Circuit

16. Connect the steering control signals to the inputs of the comparators at U2-7 and U2-9.

17. Recheck the entire circuit against the schematic of figure 38.

18. Power up the circuit. Advance the *throttle* control until one or more motors are running. Move the *steering* control. One motor should speed up and the other should slow down as you adjust steering. Both motors should speed up or slow down if you adjust throttle.

19. Demonstrate the circuit to your lab supervisor to get credit for this lab.

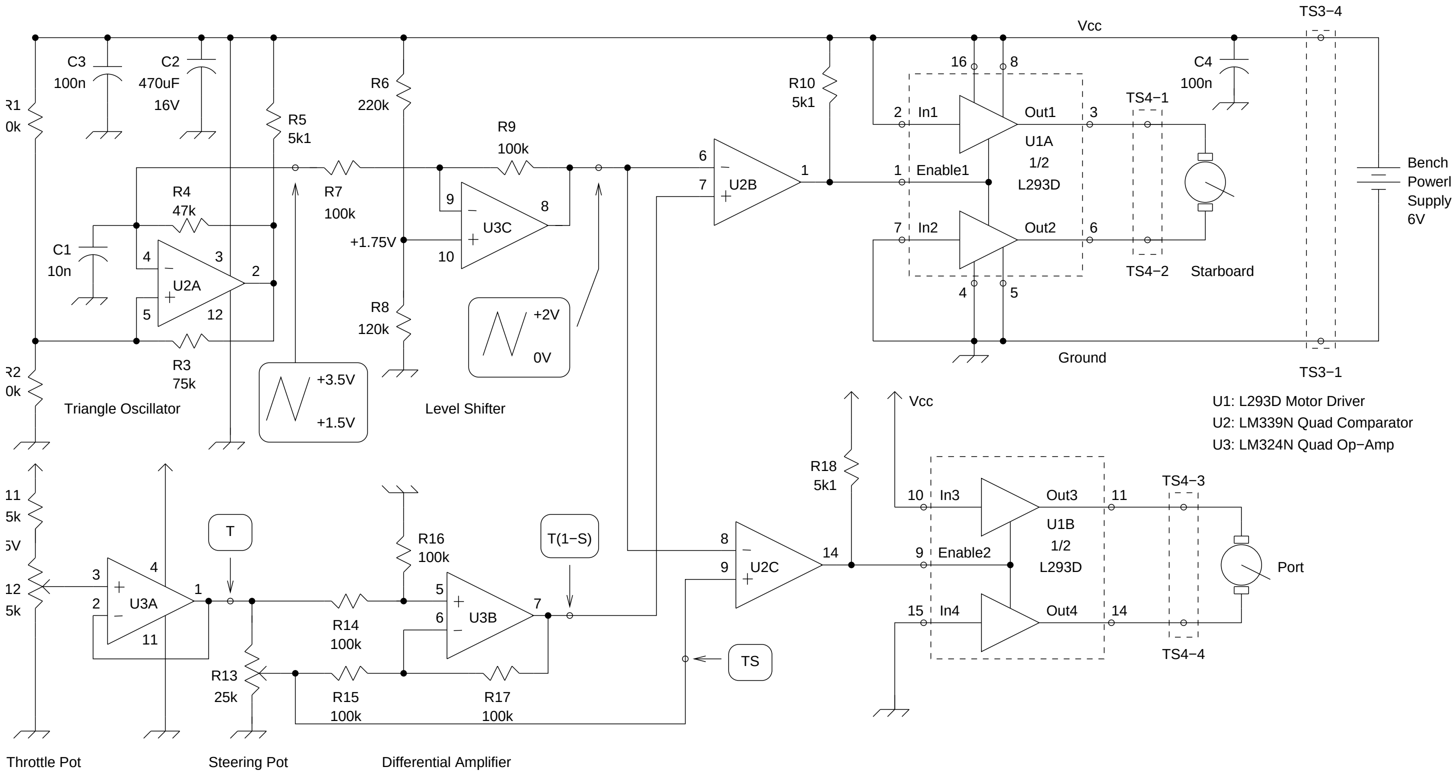

Figure 38: Steering Circuit

7 Lab 7: Line Tracker

In this lab, the mobile robot will sense a black line on a white background and track the line. In order for the line-tracking to work reliably, the robot speed must be relatively slow, so the motors cannot be operated at full voltage. Consequently, there will need to be a motor speed control.

The line sensors will be CdS (Cadmium Sulphide) photocells. The CdS cell decreases resistance in the presence of light. The area under the photocell is illuminated with a high-intensity LED and 'viewed' with a photocell. Then the resistance of the cell increases whenever it is over a black line. This change in resistance is translated into an electrical that reverses one of the motors, which redirects the robot back over the line.

The adjustment of the line detection circuitry is quite critical, and we will list ways that the sensitivity of the line-detection circuit can be improved.

7.1 The Line Sensor

The line sensor consists of a high-intensity LED to illuminate the area under the photoresistor, and the photoresistor in a voltage divider circuit.

Two of these circuits are required, one on each front (bow) corner of the robot.

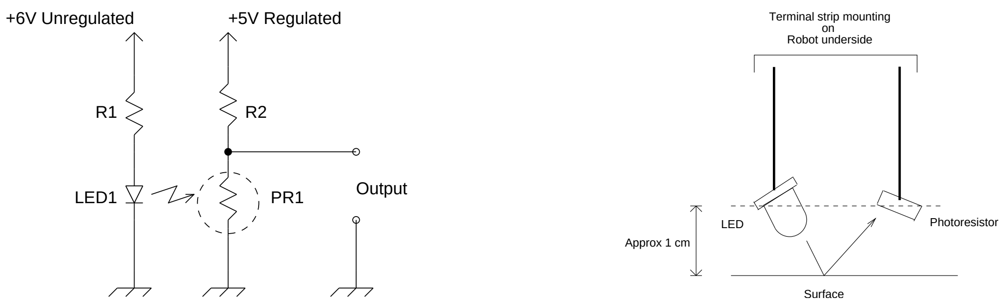

Figure 39: Photodetector Circuit

The as the resistance of the photocell changes, the output voltage changes. (You should be able to write a formula for the output voltage in terms of R2 and PR1).

As indicated in figure 39, the circuit should be operated from two different power supplies. For the LED, voltage regulation is not terribly critical, but it needs a fair amount of current. If it were operated from the 5 volt regulated supply, the LEDs would quickly discharge the 9 volt battery from which the 5 volts regulated is derived. So the LEDs should be operated from the 6 volt motor supply voltage.

On the other hand, the voltage divider output is directly proportional to its power supply, so this should be regulated.

The LED resistor R1 should be designed so that the LED current is about 20mA. This is a reasonable compromise between power consumption and brightness.

The LED *must* be a high-intensity red LED. Generally, these LEDs are packaged in a clear package and produce a narrow beam of red light. The appearance of the beam is visually almost too bright to look at.

The photoresistor is available from Supremetronic. The exact type is not critical, because you will design the circuit to suit whatever you have.

7.2 Designing and Testing the Line Sensor

1. Having designed the LED circuit and obtained the calculated resistor for R1, set up that circuit on the protoboard. Power it up from 6 volts and check that it works.

2. Shine the LED illumination on a surface and check for the illumination area. Ideally, this should be about 1cm diameter or less at a distance of 1cm from the LED.

3. Plug the photoresistor into the protoboard so that it and the LED are at about the same level. Illuminate the LED.

   The *test surface* is white cardboard or paper with a piece of black electrical tape attached to it. This represents the driving surface and its line.

   Place the test surface in the view of both the LED. While measuring the resistance of the photoresistor, move the test surface so that the photoresistor sees the red illumination on a white surface and then on the black electrical tape. Note down the two resistances that correspond to light and dark. Typical values might be 1500Ω for light and 3000Ω for dark. The main issue is not the absolute value of the resistances, but the *change* in resistance between light and dark target areas.

   You will need to get the LED and the photoresistor as close together as possible. It may also help to shade any ambient illumination from the room.

4. Once you have the photoresistor values for light and dark targets, you can choose the resistance R2. This should be a value roughly equal to the average of the two photocell resistances. For example, if the photocell resistances are 3000 and 1500Ω, then a suitable value for R2 would be about 2200Ω. In this case, anything in the range of 1000 to 4000Ω would also work satisfactorily.

5. Add R2 and the 5V power to the photoresistor side of the detector circuit. Power on the circuit, connect a voltmeter to the point labelled *Output* and test it again with the test surface. Record the voltage change between light and dark targets.

   For the circuit to work as a line follower, the larger the variation in voltage the more reliable the circuit will be. A variation of 1 volt or more is quite good, 250mv or less is marginal. Once you have a circuit that you think is reliable, carefully record the schematic and circuit values.

6. Now you can mount the LED and detectors on the front of your robot. Mount two, three-terminal tag-strips at the front corners of the robot. Then solder the LED and photoresistor to the tag strip. The cathode of the LED and one terminal of the photoresistor) use one terminal of the strip. The anode of the LED and the other terminal of the photoresistor use the remaining two terminals of the terminal strip. Bring wired connections from these terminal strips back to the top of the robot to another terminal strip, where they can be plugged into the protoboard.

   It is **really** important to get the LED and the photoresistor close to the working surface. They have a range of about 1cm maximum. More than that, and the reliability is going to be very poor.

7. Wire up both detectors, the LEDs to the 6 volt unregulated supply and the photoresistor divider circuit to the regulated 5 volt supply. Monitor the output of the photoresistor divider and test the robot over the white background and black tape. You should still get a substantial change in voltage between the two of them.

   If the voltage change is not large enough, try shielding the area from ambient light and/or moving the LED and photoresistor closer to the working surface.

7.3 The Steering Circuit

The complete line-following circuit is shown in figure 40.

The circuit consists of two main sub-sections: the basic speed control circuit is U2A and U2B, the line detector and motor control is U2C, U2D and U1A through U1D.

Speed Control

- U2A is a triangle-wave oscillator that produces a triangle wave running between about 1.5 and 3.5 volts.
- The triangle wave is compared with a DC level in U2B. The output of U2B is a pulse waveform, the duty cycle of which controls the speed of the robot. As the duty cycle is decreased, the robot runs at a slower speed.
- The DC level is established at the wiper of the speed control pot R7. As the pot wiper is increased, the duty cycle decreases at the output of U2B.
- The value of resistor R7 is not critical.
- Resistors R6 and R7 are not strictly necessary. In fact, if you use a 10 turn pot for R7, you can probably adjust the speed quite nicely without them. However, if you use a one-turn pot for R7, the region over which the pot has any effect will be very small (1.5 to 3.5 volts out of a total range of 0 to 5 volts). If you want to improve on that, choose resistors R6 and R7 so that 3.5 volts appears at the top of R7 and 1.5 volts at the bottom of R7. You'll need to measure the resistance of R7 and then calculate R6 and R8.

Line Detection

Consider first the starboard line-detector circuit.

- In addition to the line sensor photoresistor discussed earlier, there is a comparator U2C and a diode-RC network.
- The purpose of the comparator is to generate a high (+5V) or low (0V) signal depending on whether the line sensor signal is above or below a threshold voltage.
- The threshold voltage is set by R12 and must be adjusted individually for each photoresistor arrangement.
- When the photoresistor is over a dark surface, its resistance increases, and this appears at the non-inverting input to the comparator. If this voltage is above the voltage at the inverting input, the output of the comparator goes high. This then causes the motor on that side to reverse, steering the robot so that it tends to track down the line.
- In some cases, the line detector may be on the edge of the line and the output of the comparator may fluctuate rapidly between its high and low states. This is hard on the motor and motor driver, so a diode and RC circuit prevents these fluctuations. The first time the output of U2C goes high, it charges the capacitor through diode D1. Then, if the output of U2C drops low again, the diode prevents the capacitor from discharging back through U2C. The capacitor must discharge through the resistor R14, which means it must be above the high threshold of the schmitt trigger U1C for some period of time. In effect, this ensures that every time the motor is reversed, it must reverse for at least some minimum period of time.

7.4 Suggested Sequence of Construction and Debugging

Get the oscillator going

1. Wire up the oscillator U2A. Power it on and use the oscilloscope to check that there is a triangle wave at U2A-3.

Add duty cycle speed control

2. Wire up the comparator U2B and the speed control pot R7. Connect the output of U2B to the enable pins on the L293 motor controller chip so that you have speed control.
3. So that the motor control chip has direction signals, temporarily wire pins U1A-2 and U1B-10 to the positive supply, and temporarily wire pins U1A-2 and U1B-10 to ground.
4. Power on and use the oscilloscope to check that the duty cycle of the pulse waveform at U2B-1 changes as you vary R7.
5. You should be able to control motor speed control by varying R7.

Wire up the Line Detectors

6. Wire up the starboard line detector to U2C as shown on the schematic. Check that the output of U2C at pin 14 goes High (+5 V) when the detector is over black tape, and low when it is over white background. Ideally, the voltage at the wiper of R12 should be set so that it is half-way between the ’dark’ and ’light’ voltages from the sensor circuit.
7. Repeat for the port detector and U2D.
8. Wire up the Schmitt Trigger circuits U1A, B, C and D.
9. Power on the circuit, and it should be possible to control the motors by moving the test card under the line detectors.
10. Turn the robot loose on the test track and see if it can track the line. When this is working, demonstrate it to your instructor to receive a mark for Lab 8.

7.5 Parts List

Resistors	
R1	100k
R2	100k
R3	75K
R4	47k
R5	5k1
R6	Calculated
R7	Choose
R8	Calculated
R9	5k1
R10	Calculated
R11	Calculated
R12	Choose
R13	5k1
R14	22k
R15	Calculated
R16	Calculated
R17	Choose
R18	5k1
R19	22k
Capacitors:	
C1	100n
C2	470u (or 1000uF)
C3	100n
C4	100n
C5	100n
C6	10u
C7	10u
Integrated Circuits:	
U1	L293D
U2	LM339N
U3	74HC14
Miscellaneous:	
PR1	Photoresistor
PR2	Photoresistor
LED1	High Intensity Red LED
LED2	High Intensity Red LED
D1	1N4148
D2	1N4148

7.6 Alternative Motor Control Method

In this design, when a photodetector senses a dark area, it reverses the motor on that side to swing the bow of the vehicle away from the dark area. That may be a bit extreme – going from forward to reverse is hard on the mechanics and electronics.

Alternatively, the motors could be programmed to run forward all the time and simply stop when they detect a dark area. When the corresponding motor stops, the other motor will drive that side vehicle of the vehicle forward, rotating it away from the dark area.

This is actually simpler to implement. The direction inputs on the L293 driver are hard-wired so that the motors always run forward. Then the sensor outputs are connected to the L293 *enable* pins so that when a sensor goes dark the appropriate motor stops. You should be able to work out the circuitry for this. Hint: you can eliminate U3 entirely if you change the inputs on the comparators U2C and U2D.

7.7 Extending the Dwell Time

If you find that there is too much *chatter* on the motor control signals, that is, that the motors are being driven backwards and forwards in rapid succession, you should increase the time constant of the network at the output of the comparator. At this point, you should be able to calculate an appropriate size for the delay capacitor and its discharge resistor, for a given delay, such as 1 second.

7.8 Improving the Photodetectors

With a bit of an increase in complexity, the sensitivity of the detectors may be substantially improved. The basic idea focusses on the voltage divider formed by a fixed resistor and the photoresistor. If the fixed resistor is replaced by a *constant current source*, then a given change in the resistance of the photoresistor will result in a much larger change in voltage out of the divider.

First, we'll compare the two circuits and then we'll look at a practical circuit. Refer to figure 41 on page 48.

The leftmost circuit in figure 41 is the original circuit. Assuming a fixed resistance of 2200Ω in the upper part of the divider and a photoresistor that varies between 1500Ω and 3000Ω, the output voltage will swing between 2.02 and 2.88 volts, for a change of 0.86 volts.

Now consider the middle circuit. In this case, a 1 mA current generator drives current through the photoresistor. Then for the same resistance values as before, its voltage will change between 1.5 volts and 3.0 volts, for a change of 1.5 volts. This is a factor of 2 improvement in sensitivity!

The constant current generator is shown in the rightmost part of figure 41. It requires 2 PNP transistors and a resistor. The transistors are arranged in a configuration known as a *current mirror*. Current flows down through the leftmost transistor, setting up a voltage across it approximately equal to 0.6 volts. This voltage appears across the base-emitter junction of the rightmost transistor. Since the transistors are similar, the same current will flow through the rightmost transistor and out its collector into the photoresistor. It turns out that the voltage at the collector of a transistor has no effect on its current (within the limitations of saturation and cutoff), so this is an effective constant current generator.

The resistor values shown in figure 41 are for the assumed values of photoresistance. If your photoresistor has different parameters, the circuit must be modified to generate a suitable current value so that the sensor output voltage is always somewhere between 0V and 5V. You would do this by changing the 4300Ω resistor to some other value.

A second, identical circuit, is required for the other photoresistor.

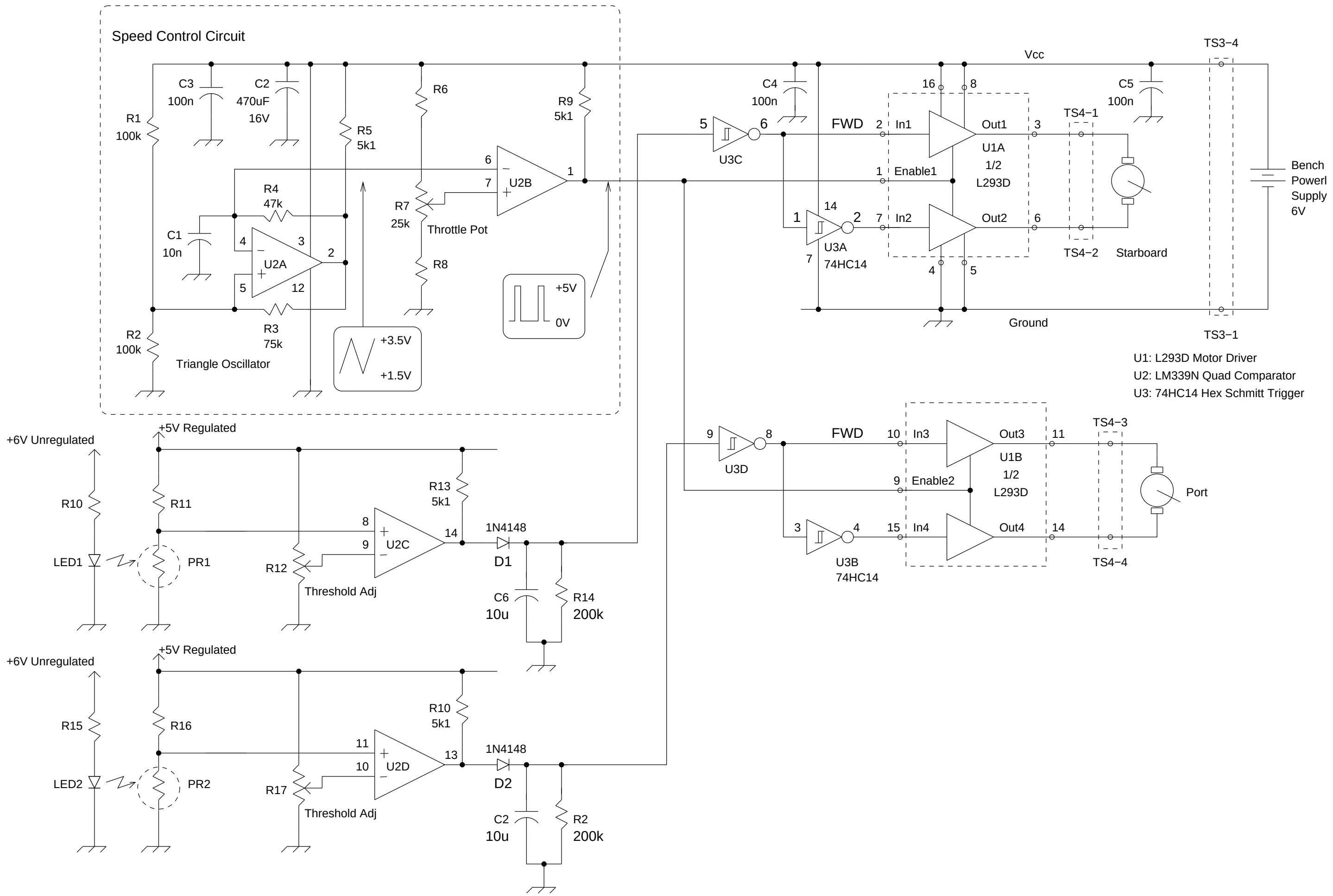

Figure 40: Line-Follower Circuit

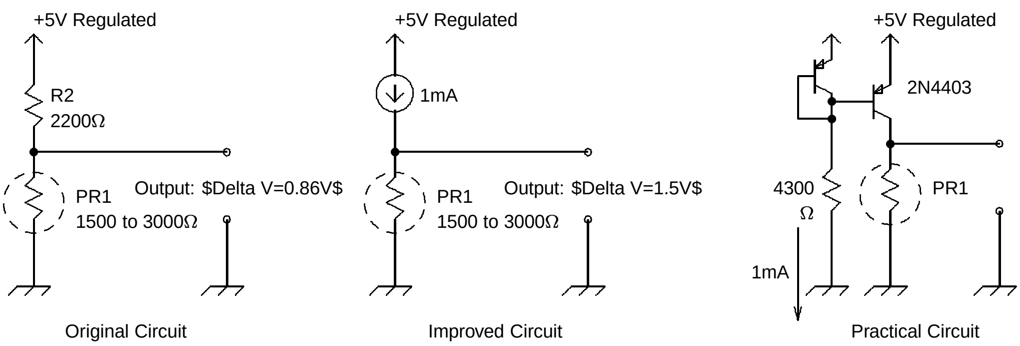

Figure 41: Improved Photodetector Circuit

8 Project: Sumo Competition Robot

This project is the culmination of the EES612 Electronics Lab. The Mechbot platform is equipped with circuitry that enables it to participate in a Sumo robot wrestling competition (lightweight autonomous class).

Two robots are placed in a circular ring area. They move about in the ring, detecting the edge of the ring and backing away from it. If they sense another robot, they move toward that robot and try to push it out of the ring, without falling out themselves.

8.1 Robot Behaviours

The Sumo robot has the following behaviours:

- The motors normally operate at a low speed (*cruise* mode). They operate open-loop but with individual speed adjustment. Then when both motors are operating, the robot speed adjustment ensures that the robot drives approximately in a straight line.
- Two object detectors face forward at the front of the robot. When either object detector senses an object, the robot assumes that object is another robot. It moves the opposite moter into high speed (*engage* mode). The effect is to rotate the robot so that the other detector and/or whiskers can detect the object. When the second detector detects the robot, both motors are then in engage mode and the robot drives into the obstacle and tries to push it out of the ring.
- Two microswitches (*whiskers*) are located at the front of the robot. When a whisker is triggered (ie, the switch is closed), the corresponding motor goes into high speed. The effect is to ensure that the motors stay in high speed mode as long as the robot is pushing the opponent.
- There are two edge detectors in the front corners of the robot. When either of these detects th black line that defines the edge of the ring, it throws both of the motors into reverse. A time delay circuit runs one motor in reverse longer than the other, so the robot does a *back and turn* manoevre away from the edge. The direction of the back-and-turn depends on which edge detector was triggered. The edge detector circuitry works regardless of the motor speed, so even if the motor is in high-speed mode, it will back away from edges.
- The robot is powered by a large 6 volt battery for the motors and LEDs, and a small 9 volt battery for the electronics.

8.2 Edge Detection Subsystem

A block diagram of the edge detection and back-and-turn concept is shown in figure 42.

The two photoresistive cells PR1 and PR2 are placed at the front corners of the robot. The photoresistive cells are normally over a light-coloured area. Then the voltage into comparators U1 and U2 is below the voltage set by the potentiometer P1, and the output of the comparators is low.

When a photoresistive cell is over a dark area, its resistance increases and the output voltage from its voltage divider also increases. If this voltage is above the voltage set at the threshold pot P1, then the comparator produces a high voltage.

This voltage triggers two time delays, shown on diagram as 0.2 seconds and 0.5 seconds. These delays are the backup times for the two motors when the robot detects an edge.

A pair of diodes for each motor act as a logical OR gate. For example, when the Port detector is triggered, this causes the port motor to back for 0.2 seconds and the starboard motor for 0.5 seconds. The net effect is to back

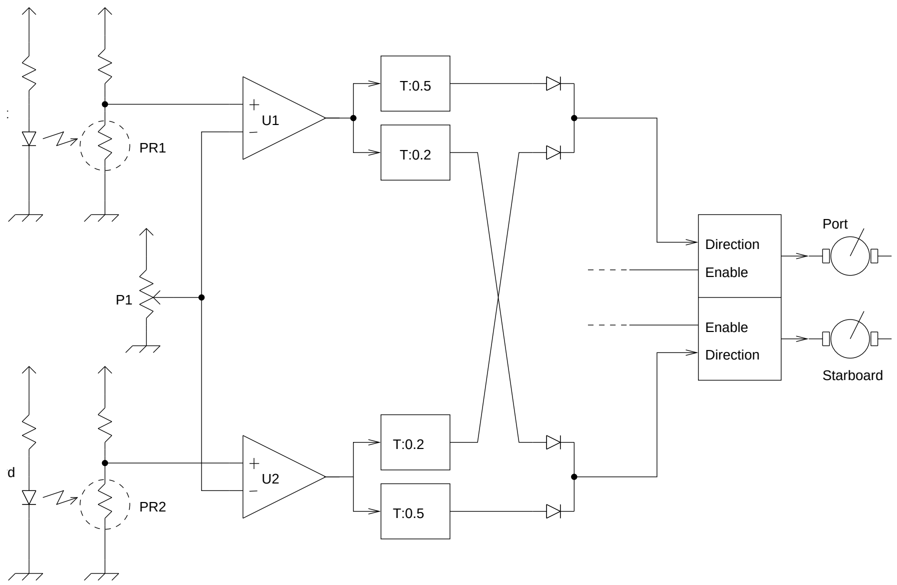

Figure 42: Edge Detection, Back and Turn Concept

the robot away from the edge, but longer on the side that did not detect the edge. This tends to rotate the robot more toward the centre of the field.

The circuitry for the edge detector is shown in figure 44 on page 56.

Notes on the circuit:

- The robot includes a *DIP switch* [5] which may be used to enable and disable robot functions. If these switches are opened, then the edge detector is disabled, which is useful when debugging other functions.

- Each of the four delay networks consists of a leftmost diode, resistor capacitor and rightmost diode. The leftmost diodes act as a one-way gate for edge detection signals. When the output of a comparator goes high, it rapidly charges the capacitor. When the robot starts backing up, the edge detection signal will disappear, and the output of the comparator will immediately go low. The leftmost diode prevents the capacitor from discharging back through the output of the comparator.

  The rightmost diode creates a logical OR gate so that, for example, either the Port or Starboard edge detector can trigger the Starboard motor.

  The time delay is approximately equal to the product of the timing resistance and capacitance, and you may wish to adjust these later. can trigger a motor.

  The outputs from the time delay circuits drive Schmitt trigger inverters that produce the signals to operate the L293 motor driver. The *enable* pins on the L293 are not shown as connected in this schematic because they are operated from a different circuit.

8.3 Object Detector and Speed Control

The circuitry for detecting another robot, the *object detector*, is shown in figure 43.

[5] DIP stands for *dual-inline package*, so this is a switch with the same footprint as a 16-pin integrated circuit.

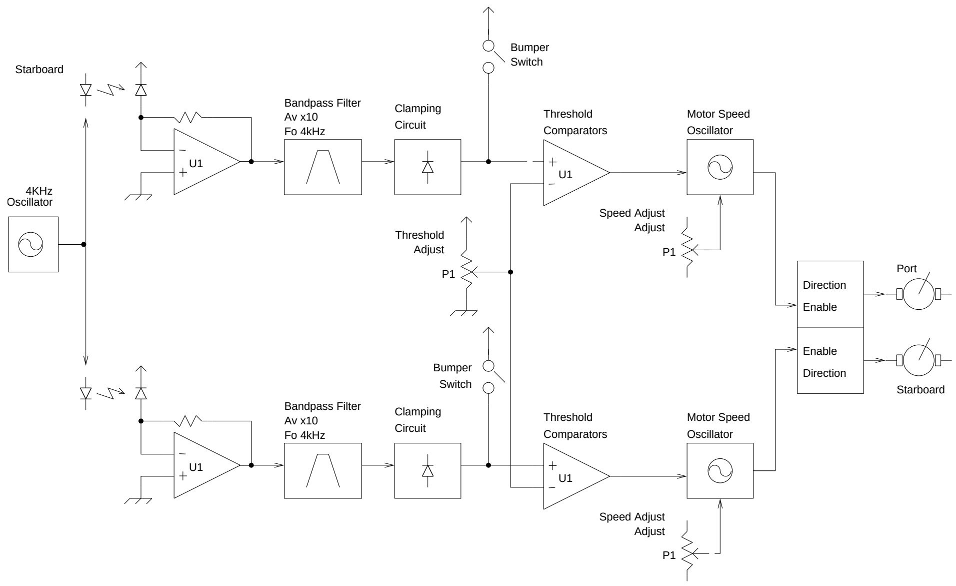

Figure 43: Object Detector Concept

Two infared LED emitters, one on each side at the front of the robot, are driven from a 4KHz oscillator so that their light beams (which are invisible because they are infared radiation) are chopped at a frequency of 4KHz. The detector is design to respond to this 4KHz signal and ignore other illumination such as sunlight or 120Hz from fluorescent lamps.

There are two detector channels, so we'll just describe one of them. The reflected infared illumination is detected by an infared photodiode, and amplified in a *transresistance* amplifier. This is an op-amp circuit that converts the current from the photodiode into an AC voltage at 4KHz.

This signal, along with any other spurious signals, is fed into a 4KHz *bandpass filter*. The filter amplifies a signal with a frequency at around 4KHz and rejects frequencies at 120Hz and (ambient light).

The output of the bandpass filter is an AC signal of unknown amplitude riding on a DC level. The next function is a *clamping circuit*, which fixes the lower level of the 4KHz waveform at around zero volts. Then as the signal changes in strength, it grows upward from the zero volt level.

The clamped signal is fed into a *threshold detector*, which compares the level of the signal with a fixed level from the *threshold adjust* potentiometer. If the signal exceeds the threshold level, the comparator will produce a 4KHz train of pulses at 5 volts amplitude.

Each motor has a *speed adjust* circuit so that the two motors can be adjusted to run at the same, low speed. When an object is detected, the signal into the speed adjust circuits puts them into full speed mode, so the robot closes at maximum speed and pushes the other robot with maximum torque.

When this robot touches the other robot, it should actuate either or both the bumper switches. As long as the bumper switch is closed, that simulates an object detected signal and keeps the robot in high speed mode. The switch artificially pulls up the comparator input to create this signal.

8.4 Object Detector Circuit

The complete object detector circuit is shown in figure 45 on page 57.

- U4A is the 4KHz oscillator which drives the infared emitters LED3 and LED4.
- U5A and U5C are the transresistance amplifiers that convert the photodiode current to a voltage.
- U5B is the bandpass filter for one channel, U5D for the other channel.
- The clamp circuit on the upper channel is C13 and D9. These devices behave as a half wave rectifier that charges up the right plate of C13 to the peak value of the signal voltage. The result is that AC voltages rest on the zero volt baseline.
- U6A is an op-amp schmitt trigger with positive feedback via R21 and R20. The threshold voltage is set at the inverting input pin.
- Switch S1A allows the object detector to be disabled during debugging sessions.
- Schmitt trigger U4A, P3, diodes D11 and 12, and C17 form an oscillator which generates the motor drive waveform. The duty cycle can be adjusted by changing P3.
- When an object signal is generated, that turns on Q2, which then forces the input of the schmitt trigger U4B to ground. This forces the output of U4B to a high state, which puts the motor into full output.
- The other channel operation is identical.

8.5 Construction and Testing Hints

Edge Detector

- This is a big circuit and there are many opportunities for wiring mistakes. You will have to test each section independently. Fortunately, that's not difficult to do.
- We suggest that you put the edge detector circuit on one protoboard and the object detector on the other protoboard. No IC parts are shared, so this should be possible.
- You should have enough experience debugging the line-follower circuit to be able to debug the edge detector circuit. Disable the object detector (using the DIP switch) and then test it independently. Keep in mind that you may have to adjust the fixed resistor in the photoresistor divider. Once you get it working, you can replace the fixed resistor with a constant current source if you wish to increase the detector sensitivity.
- Verify that your robot will detect the edge of the ring and back away from it.

Object Detector

- Wire up the circuit.
- Mount the two infared LED emitters at the front of the robot, next to its corresponding photodiode, so that they are both looking forward at the height of another robot.
- Check that the 4kHz oscillator is producing a square wave at U4A-2. Verify that it is the correct frequency.
- Place a white target in front of the robot so that the emitted radiation is reflected back into the photodiode detectors. You should see a strong AC signal at the output of U5B-7.
- Check that the clamp circuit is functioning correctly.

- Check that the schmitt trigger U6A changes state when the input signal exceeds the threshold set by P2.
- Check that the reception of a signal changes the motor speed output from a pulse waveform to a pure DC level at +5 volts.
- Repeat these tests for the other channel and fix any problems.

8.6 Milestones and Marks

This project will be treated as three labs. You will get credit for each of:

- Demonstrate the edge detector circuit working
- Demonstrate the object detector circuit working
- Show the completed robot functioning as a sumo wrestling robot.

8.7 Parts List

Resistors	
R1	470
R2	470
R3	4k7
R4	4k7
R5	4k7
R6	4k7
R7	22k
R8	47k
R9	47k
R10	22k
R11	240k
R12	4k7
R13	100
R14	470k
R15	470k
R16	47k
R17	47k
R18	470k
R19	470k
R20	47k
R21	470k
R22	4k7
R23	470k
R24	4k7
Potentiometers	
P1 10k, 10T, screwdriver adjust	
P2 10k, 10T, screwdriver adjust	
P3 10k, 10T, screwdriver adjust	
Capacitors:	
C1	100n
C2	10u
C3	10u
C4	10u
C5	10u
C6	100n
C7	100n
C7A	470u (or 1000uF)
C8	22n
C9	10u
C10	22n
C11	47n
C12	47n
C13	220n
C14	220n
C15	220n
C16	100n
C17	10n
C18	10n

Diodes	
D1	1N4148
D2	1N4148
D3	1N4148
D4	1N4148
D5	1N4148
D6	1N4148
D7	1N4148
D8	1N4148
D9	1N4148
D10	1N4148
D11	1N4148
D12	1N4148
D13	1N4148
D14	1N4148
Integrated Circuits:	
U1	LM339N Quad Comparator
U2	74HC14 Hex Schmitt Trigger
U3	L293D Motor Driver
U4	74HC14 Hex Schmitt Trigger
U5	LM324 Quad Op Amp
U6	LM324 Quad Op Amp
Miscellaneous:	
PR1	Photoresistor
PR2	Photoresistor
LED1	High Intensity Red LED
LED2	High Intensity Red LED
LED3	Infared emitting diode
LED4	Infared emitting diode
PD1	Infared photodiode
PD2	Infared photodiode
S1	8 way DIP switch
S2	Microswitch
S3	Microswitch

8.8 Acknowledgements

The design of the robot presented here was inspired by *Basey*, an analog-guided robot by Andrew O'Malley. The detail design and concept verification was done by Devin Ostrom.

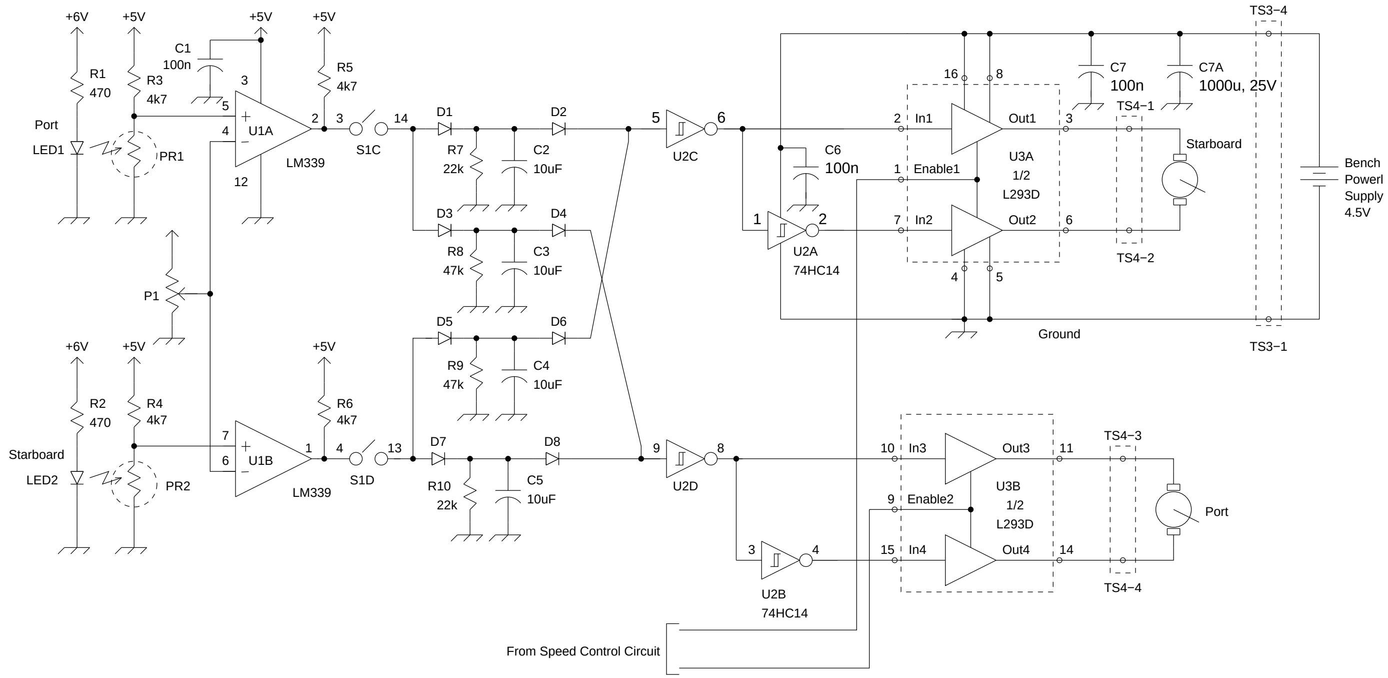

Figure 44: Edge Detection Circuit

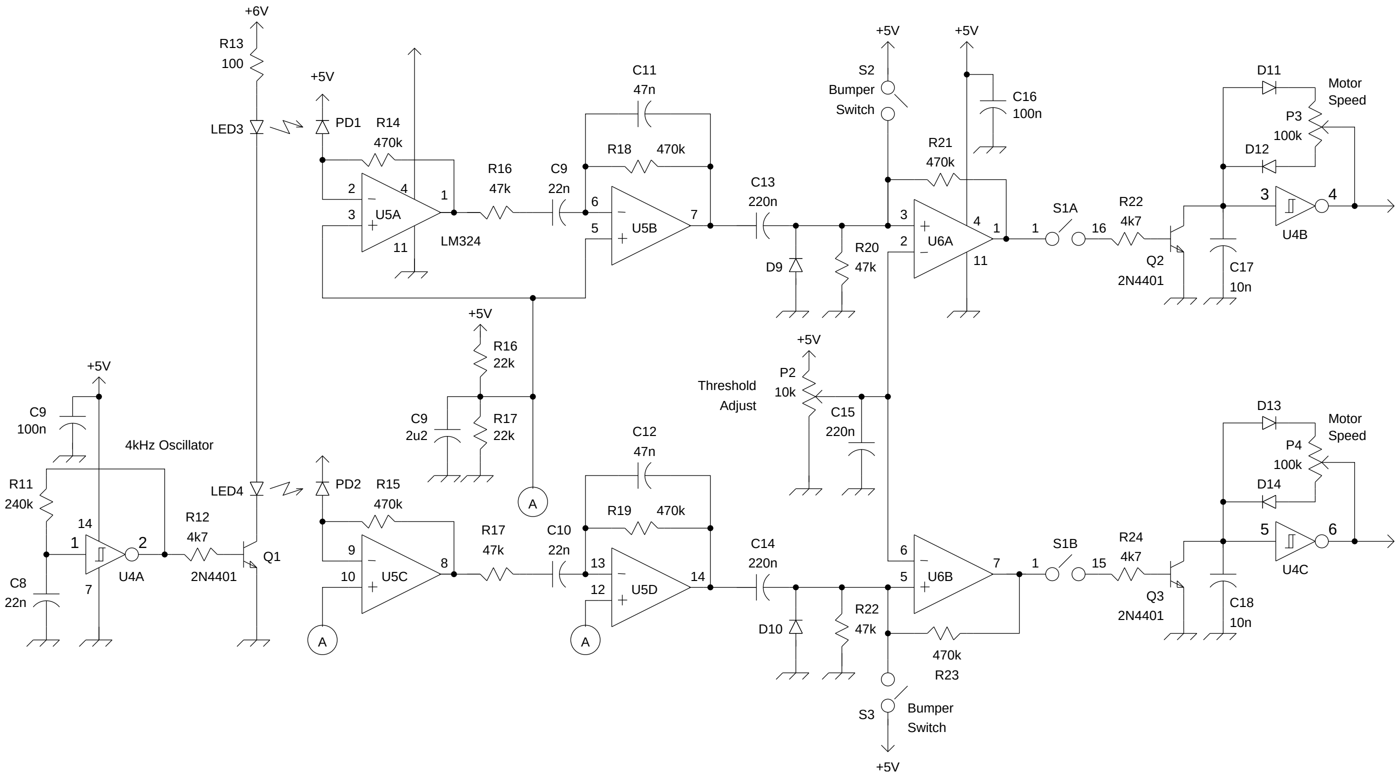

Figure 45: Object Detector Circuit

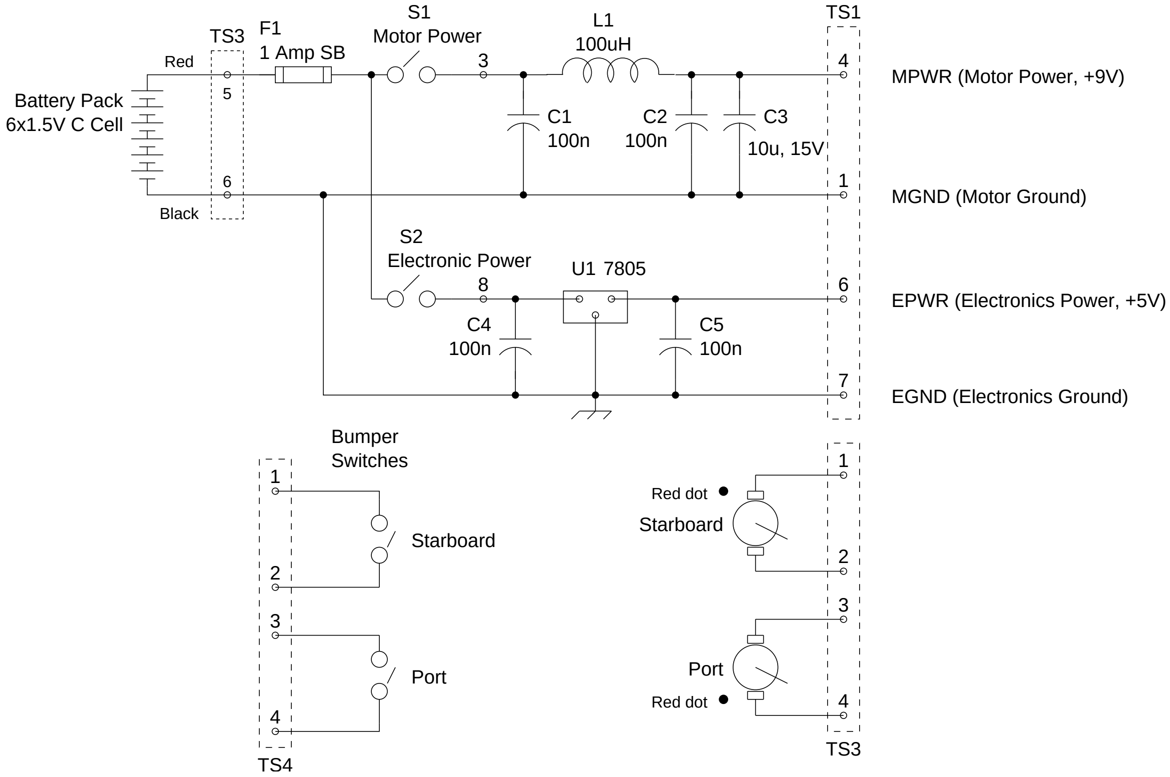

Figure 46: Power Supply Wiring