Ryerson Polytechnic University

Department of Electrical and Computer Engineering

EES874 Mechatronics

Laboratory Manual

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Contents

List of Figures

1 Overview

As electronic and computer technology develops, it becomes increasingly attractive to enhance the operation and control of vehicles with systems based on this technology. For example, modern automobiles use electronic devices and computers to control the engine, improve its energy efficiency, adjust the ride of the vehicle and brake it to a stop under emergency conditions.

Electronics technology is attractive for these functions because it enables complex rules of operation to be embedded in the machine. For example, the operation of an automobile engine so that it emits few pollutants is a complex function of engine and air temperature, air pressure, speed of the engine. However, an analog or digital computer can compute the required quantities and deliver them to the appropriate places in the engine.

Electronics also permits the *remote operation* of vehicles, and that is what we will use as the basis for these laboratory exercises. As in many real life situations, the ease of operating a vehicle is greatly enhanced with information from the environment and feedback to the vehicle provided by electronic means. Examples of situations that use this type of vehicle include remote controlled mining machinery at the INCO factory in Sudbury, robot manipulators in nuclear reactors and the planetary explorer vehicle currently on Mars.

The focus of this course is a small guided vehicle which is guided by a student operator through an obstacle course. At first, the vehicle is operated by simple electronic switches which turn power on and off to the driving motors, and it will be evident that the vehicle is quite difficult to control.

The vehicle control system will then be progressively enhanced, first with with analog electronic devices and then using a computer. There are two exercises using computer control. In the first case, the computer reads operator controls, processes the signals, and then operates the vehicle. In the final exercise, the computer reads signals from detectors of a path of red reflective tape, and guides the vehicle entirely without operator intervention to a target location.

1.1 Nature of the Lab

This lab is new this year. While the professor and lab technologist have made considerable efforts to plan and debug the lab, there will undoubtably be snags as it proceeds. Students are expected to get the work done, but the lab supervisors will take the newness of the lab into account when enforcing deadlines and assigning marks.

Also as a consequence of the newness of this course, these notes are subject to possible changes as the course progresses.

1.2 What you have to do

Students will identify, purchase, assemble and debug mechanical and electrical components into a functional guided vehicle, according to directions provided these notes. A detailed schedule is shown below.

Lab time is expected to be used for debugging assistance from the lab instructors and for demonstrating functional devices. Construction and preliminary debugging is expected to take place **outside** lab time.

Students are expected to purchase their own parts for the vehicle and its electronic systems. Lists of useful tools and possible suppliers of parts are listed below. We expect that the parts cost for lab supplies will be under $100 total.

Students are required to use their own tools to build the vehicles. At the time of writing, laboratory access hours had not been finalised, but it is expected that soldering irons and electronic test equipment (power supplies, meters and oscilloscopes) will be accessible to students.

The exercises requiring use of a P/C will require programming in QBasic. Some information will be provided in the lab notes, but it will be necessary for students to learn the details of QBasic programming on their own. It is desireable that the student have access to their own P/C or a school lab P/C for this purpose.

1.3 Laboratory Schedule

The laboratory schedule is as follows:

Week	**Topic**	Group A Deadline, Week of	Group B
1	Read lab manual, purchase parts, assemble vehicle.	(no demo)	(no demo)
2-3	Demonstrate basic vehicle operation via motor switches.	19 Jan	26 Jan
4-5	Demonstrate simple analog speed and steering controls.	2 Feb	9 Feb
6-7	Demonstrate combined analog speed control with motor feedback.	16 Feb	2 Mar
-	Study week: catchup	23 Feb	23 Feb
8-9	Demonstrate optical line sensors.	9 Mar	16 Mar
10-11	Interface and program PC to act as sensor display and control panel for vehicle.	23 Mar	30 Mar
12-13	PC control of vehicle: vehicle navigates route autonomously. Public demonstration.	6 Apr	13 Apr

Demonstrations must be completed by the end of the lab period on the due date or they will be considered to be late. Late demonstrations will automatically lose 50% of the possible mark. To avoid a traffic jam at the conclusion of the lab, the instructor will establish a schedule of demo time slots, working backwards in 10 minute intervals from the closing time of the lab. Time slots may be assigned by agreement or lottery.

Students will work in pairs and receive the same mark. Both students in a lab group are expected to understand the operation of circuits, to be able to answer technical questions from the lab supervisor and to keep a diary of what they contribute to the project.

Each lab session will require running the vehicle through an obstacle path or maze within a time limit. Results will be evaluated on the basis of correctness of operation, reliability of the vehicle, effectiveness of operator control, standard of construction and completeness of the lab records.

1.4 Laboratory Record Notebook and Report

Students are expected to maintain a laboratory record notebook. Part of each lab session mark will be based on the neatness and completeness of the lab record. The lab record must contain a listing of what each student contributed to the project (the diary), parts lists, schematic drawings, mechanical sketches and a brief description of results.

It is recommended that the lab record be in the form of a 3-ring notebook to which lab instructions and data sheets can be added.

At the conclusion of the laboratory, students will be required to submit a brief report assessing the effectiveness of the laboratory in terms of things that worked and aspects that were problems and should be improved.

1.5 Laboratory Evaluation

The evaluation for the entire course is:

Laboratory Work	42	%
Term Test	18	%
Final Exam	40	%

Students must obtain a passing grade in both the laboratory work and the lecture material.

The evaluation of the laboratory is based on 6 laboratory demonstrations, each with a weight of 7 marks toward the final grade.

1.6 Contacting Lab Instructors

Professor: Peter Hiscocks
Room: T-321
Phone: 416-979-5000 Ext 6109 (voice mail available)
email: phiscock@ee.ryerson.ca

Lab Supervisor: Jim Koch
Room: T-131-A
Phone: 416-979-5000 Ext 6118 (voice mail available)
email: jkoch@ee.ryerson.ca

Course announcements and hints will be placed in the newsgroup, and questions may be asked as well. The name of the newsgroup:

rye.ee.mechatronics

Within the university, newsgroups are readable by anyone with a computer account. Enter the 'tin' newsreader, yank in (key 'y') all unsubscribed groups, search for the newsgroup (backslash plus the name of the group), subscribe to it (key 's') and yank out (key 'y' again) all unsubscribed groups.

From outside the university, use **telnet** to connect to `ee.ryerson.ca` or `acs.ryerson.ca`, logon and proceed as above.

1.7 Obtaining Electronic Parts

There are a number of electronic part suppliers in the Toronto area. Learning what is available from which supplier is considered to be part of the learning experience for this course.

The two primary shopping areas are

- Queen Street, south side, near the intersection of Beverley Street, between University and Spadina: Active Surplus Annex (home of the Motorized Gorilla) and Supremetronics.
- Victoria Park and Gordon Baker Road (south of Steeles Avenue): Active Electronics, Sayal, Double H, Electrosonic Supply. In a nearby mall is also Toronto Surplus and Scientific, with an extensive collection of electronic equipment.

When searching for electronic parts, a good strategy for saving money is to start at the least expensive sources, purchase what you can, and then work up to the source of last resort (usually Electrosonic Supply). If you are more short of time, you may wish to go directly to Active or Electrosonic Supply.

1.8 An Electronics Tool Kit

It is important that you have decent tools to work with. Poor or inappropriate tools are frustrating to use and can result in damage to the work.

Good tools are expensive, and you may not be able to afford to purchase all of them at one go. However, if you look after them, the tools you purchase for this project will last a very long time. Students may wish to get together with others to collaborate on a shared tool kit.

The tools listed below are a minimum requirement for electronics work.

Fine tipped soldering iron It is preferable that the iron be temperature controlled. Non-temperature controlled irons tend to overheat. An oxide scum develops on the tip, and this impedes soldering. The Weller model WTCPS (Active Electronics, $122) is a suitable temperature controlled iron. It includes a sponge holder and stand, and accepts a variety of different shaped tips.

A non-temperature controlled iron is much less expensive. An iron with a three-wire cord should be obtained, since this ensures that the tip is grounded and is less likely to pose a static hazard to integrated circuit devices. The Weller WP25P (25 watts, $27.93 at Active Electronics) is a good choice. However, you will also need a stand (Weller PH25, $14.65) and sponge.

Sponge A wet sponge is needed for cleaning the soldering iron tip. **Wet it. Use it.** Otherwise the solder joints are not reliable.

Solder Electronic solder is usually a 60% 40% alloy of tin and lead, with a centre core of *flux* which assists cleaning the metals and the soldering process. For electronic work, the flux must be *rosin.* Do not use **acid** core solder, which is available from hardware stores for plumbing and roofing jobs. The acid destroys electrical connections. (Recently, I was told of a so-called repair technician who was found using acid core solder to repair a $150,000 aerial photography camera. Not good.) Multicore M-2, Active Electronics, $2.16 is a suitable solder for electronics work.

Small Side Cutters Xcelite 96-CGV (Electrosonic, $10.11) are suitable. Many *diagonal cutters*, as they are also known, are suitable, but get the smallest ones that you can find, and they are much nicer to use if they are spring loaded. Use them *only* for cutting wire, never bolts.

Needle Nosed Pliers Xcelite 133-CGV (Electrosonic, $12.68) are suitable. Serrated jaws and spring opening are preferable. Again, you should get the absolute smallest pliers you can find. Use them *only* for forming wire leads, never for removing the wheel nuts on your Honda.

Wire strippers Get the Miller 101-S ($5.50 at Electrosonic) or equivalent. A wide variety of ingenious and expensive wire stripping machines are available. Most have great entertainment value but little utility. The Miller 101-S is one of the best and least expensive.

Multimeter In recent years, a wide variety of low-cost multimeters have become available from manufacturers such as Metex and Radio Shack. At a minimum, the multimeter you purchase should include a beeping continuity tester, DC volts, Resistance and AC volts. Additional features which are useful are DC current measurement, transistor beta, and capacitance. Supremetronics on Queen Street has a large selection of inexpensive meters.

If you're purchasing a new multimeter, try to get one that accepts *banana plugs* rather than *tip jacks* on the test leads. (Banana plugs are shown in figure 1 below.) The banana plugs are more common, are used in the Ryerson labs, and are easier to wire.

Troubleshooting Leads It's really handy to be able to attach a voltmeter to some point in the circuit and then make changes and adjustments, watching the effect on the voltmeter. To do this, you need test leads with *wire grabbers* on one end the of the lead, and *banana plugs* on the other end. These *clip leads* are also useful in attaching the oscilloscope to the circuit, or can be used to connect a lab resistor decade box into the circuit under test.

So called *alligator clips* can connected at both ends and used for this, but even the smallest alligator clips are big for the electronic components in use today, so the wire grabbers are preferred. You'll need at least two of the leads shown in figure 1 below. The parts are very inexpensive, and can be purchased at an electronic supply house such as Active Electronics or Supremetronics.

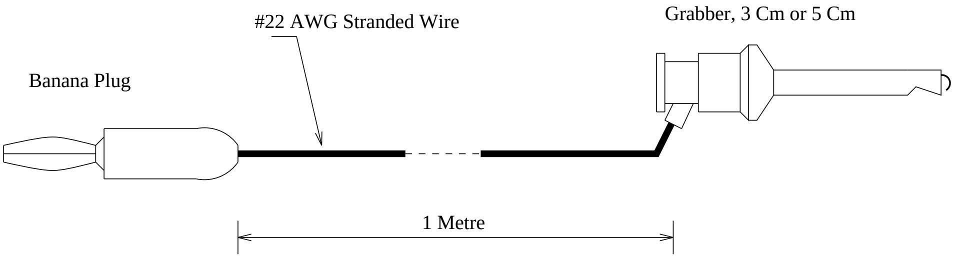


Figure 1: Test Lead

The grabbers come in various sizes: both the 3 cm and 5 cm sizes are useful.

The banana ends may also be plugged into alligator clips, converting a test lead into one with a grabber at one end and an alligator clip at the other.

Solder Sucker If you have to remove components that have been soldered to a printed circuit board, it is difficult to do so without damaging the PC board in the process. The solder sucker tool is a spring loaded vacuum plunger. Melt the solder while holding the tip of the desoldering tool near the solder joint. When the solder melts, trigger the solder sucker, which then vacuums up most of the melted solder. Once solder is vacuumed up from all the pins, the component can usually be removed from the board. My personal favorite of these devices is the EDSYN Soldapullt tool, $24.95 at Electrosonic. There are less expensive versions available, but this one has a nice strong spring and a long throw, which helps.

Vice You will be working on small electronic devices, measuring and soldering wires to them. It's really handy to have some method of holding them in one place while you're working on them. My personal favorite is the *Vacu-Vice*, which weighs about 4 lbs and occupies a base of about 5 inches square. It's claimed that you can stick this thing down to any smooth surface, but I don't use that feature. It's small enough to carry around, but heavy enough that it stays put when you're working with it. Unfortunately, it's pricey: about $70 in the current Electrosonic catalogue. Lenline have a *Free Angle Vice* which is half that price and may do just as well.

Electrical Tape Except in emergencies, don't use it. Even electricians don't use the stuff in permanent installations. It hides mistakes, makes things gooey, and eventually unravels or degenerates into a sticky mass. Ugh. If you wish to insulate connections, use heat-shrinkable tubing, preferably the transparent version so you can see if a connection has come appart.

1.9 Readings

Electronic Concepts and Applications, Boctor, Ghorab, Hiscocks, Holmes, Ryff
West Publishing Company, 1996
This is the assigned textbook for the course.

Mobile Robots: Inspiration to Implementation, Jones and Flynn
A.K.Peters Publishing, 1993
A classic textbook on mobile robots of the type we will be using. Available by special order from most book stores.

Practical Robotics, Bill Davies
Werd Technology Inc, 1997
A wealth of useful information on electronics and mechanical devices for this type of project. Available from CPIC Technical Books, 905-670-1252.

The ARRL Handbook for Radio Amateurs
American Radio Relay League
Newington, CT 06111, USA
(Available in the Ryerson library or from Electrosonic Supply, $34.97)

Exercise 1: Basic Vehicle Operation

In this exercise, each student team will construct a motorized vehicle and drive it though the lab obstacle course using switches connected to the vehicle motors.

As long as the vehicle meets the requirements listed below, it will be accepted.

1.1 Vehicle Requirements

Prebuilt, Kit or Scratchbuilt The vehicle may be obtained off the shelf (and modified, if necessary), built from a kit, or built from parts to the builders own design.

Size The size of the vehicle should not exceed 20 cm width and 30 cm in length. **Excessively large vehicles may be disqualified, at the discretion of the instructor.**

Drive System The vehicle should steer by differentially driving the wheels or treads on the two sides of the vehicle. Each drive should use one small DC motor. (*Small* implies operating currents of less than one ampere.)

RC Cars not acceptable These are generally physically too big, they use DC drive motors that require enormous currents and are therefore complicated to control electronically. Finally, their steering system is the wrong type: it is not differential. Lots of these are available at Radio Shack, but they should be avoided. On the other hand, some Radio Shack toys may be acceptable (see below under Army Tank).

Platform Areas As the course proceeds, it will be necessary to attach various *things* to the vehicle. These include a television camera, a circuit protoboard where cables can be attached, microswitches to detect collisions, and a guider-detector board at the front. Consequently, you shoud think about how you will attach these things to your vehicle.

Electrical Power The vehicle must be powered from an external battery pack, probably between 3 and 12 volts DC. There should also be two reversing switches, one to control each motor, external to the vehicle. It should be possible to drive and steer the vehicle with these switches.

Reliability A vehicle that is unreliable will make you crazy with problems at a later stage of this course. Make sure the vehicle is solid mechanically and that the wiring to the motors is reliable (soldered).

1.2 Example Vehicles

Some possible vehicles are the following:

LEGO Kit Vehicles using LEGO are described in the book *Mobile Robots*, listed above. LEGO vehicles are fine, but the blocks have a tendency to come appart under mechanical stress, so you may want to glue your vehicle together once it is debugged. You will have to design and build a suitable gear train to gear down the speed (and gear up the torque) of the motors. Unfortunately, LEGO is probably the most expensive method of obtaining a vehicle because the gear kits and motors are quite expensive: a LEGO vehicle would probably cost about $70 to $100 if you had to buy all the parts new.

Suppliers: Sears has good deals on LEGO at certain times of the year.

Army Tank This vehicle was found in a tox store on Spadina Avenue for about $20, which is a real deal. It has all the necessary features plus a flashing LED gun and a microphone so your voice can come out of the tank body! Probably necessary to remove the tank turret and attach a platform to the body to accept the various add-on devices. Using an army tank in this course generates brownie points for converting military into civilian hardware.

Suppliers: You're on your own for this one. Check surplus toy outlets, making sure the vehicle has separate drive motors for each wheel or tread.

Tamiya Bulldozer Kit The Bulldozer (Tamiya item number 70104**2200) is attractive for this project: it has all the right features and requires a minimum of modifications. It can be put together in an evening. (Leave off the Dozer Blade). This is the unit that your professor will be using to develop the course. .

Suppliers: A few of these may be available locally through 'Den of Trains Crafts and Hobbies', 3076 Bloor W (Royal York subway), 416-232-2129, ask for Denis. Cost, if he has them, should be about $30. You might wish to check with other hobby and science stores in the Toronto area as well. This same kit can also be ordered from Mondo-tronics in California, phone 800-374-5764 or 415-455-9330. Unfortunately, Mondo is a lot more expensive, figure about $50 Cdn.

Scratch Built A suitable vehicle may be constructed from parts available in the surplus and hobby stores. For example, a two wheeled vehicle (with plastic spoon suspension system) was constructed using DC gearmotors and rubber-tired wheels obtained at Active Surplus, Queens Street. These were attached to a platform using wood and hardware obtained at John's Hobby on Danforth Avenue (Woodbine subway). Total cost was minimal: about $25.

When you have completed the vehicle, you should spend some time practice driving it. This will show up any mechanical or electrical bugs before you do the critical demo in the lab. It will also improve your eye-hand coordination in controlling the vehicle.

1.3 Motor Wiring

For reference, the wiring of the motor circuit, switches and battery is shown in figure 2. If you buy a toy or kit, it will come with this in place. If you build from scratch, you'll have to construct this yourself.

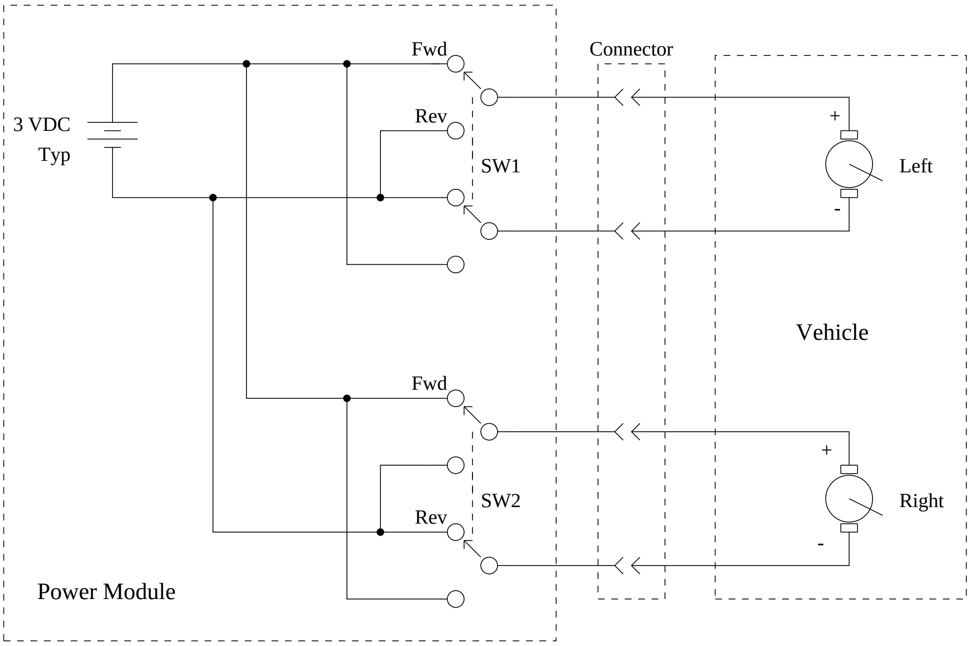


Figure 2: Motor Wiring

Each DPDT (Double Pole, Double Throw) switch (SW1, SW2) has a spring loaded, centre off position. When a switch is actuated in one direction, it applies power to its motor so that the motor rotates in the forward direction. When the switch is actuated in the other direction, it reverses the motor voltage and the motor rotates in the backward direction. In all cases, the motor receives full voltage, so operates at full speed, and this makes the vehicle difficult to control precisely.

Notice the 4 pin connector between the power module (battery and motor switches) and the vehicle itself. This is required so that, in the lab demonstration, a cable can be inserted between the power module and the vehicle.

A sketch of the connector is shown in figure 3.

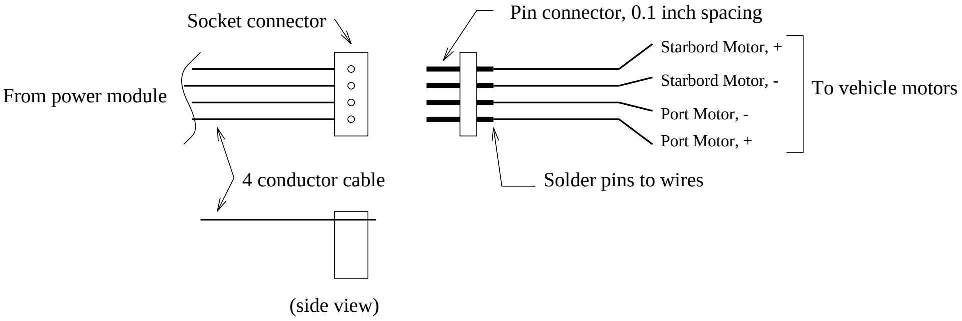


Figure 3: Motor Connector

Notice the wiring of the connector. To facilitate debugging in the lab, it is important that all vehicles be wired according to this pinout: the two outside pins are motor positive terminals, the centre pins are the motor negative terminals.

Suitable connector parts may be available surplus from Active Surplus Annex or new from Supremetronics, Sayal, Double H or Active Electronics. The critical thing is simply that there be a single row and the pin/socket spacing is 0.1 inch. If all else fails, you can purchase them from Electrosonic: The pin plug is **Panduit MFSS100-4** and the socket connector is **Panduit CE100F22-4** or **Panduit CE100F24-4** or **Panduit CE100F26-4**.

Soldering wires to these connectors is tricky: you will need a steady hand and some practice on something simpler if you have never soldered before.

Here are the instructions for soldering the motor cable to its pin connector, step by step:

- Strip the outer insulation that covers all the conductors. On each conductor, strip the insulation away for soldering to the connector. Remove only the minimum of insulation necessary, about 2mm (0.1").

- Hold the cable in a vice and *tin* each conductor, that is, melt solder onto the copper. Use *very* little solder, just enough to coat the copper. As you do this, the insulation may well melt and retract away from the hot iron. Do the soldering quickly to minimize shrinkage. Alternatively, if the insulation is too fragile to work with, substitute a different type of multi-conductor cable for the motor cable. Unsolder the existing cable at the motors and connect a new, studier version. (The flat, multiconductor cable in which each conductor has a different colour, is especially nice to work with. Find a wide piece and peel off four conductors for the cable.)

- Clamp the connector in a vice so that it doesn't wander around while you're soldering to it. Now hold the motor cable close to the tinned end so that the metal is touching a pin of the connector. Touch the pin with the soldering iron for about half a second, and the pin and wire will solder together. Give the wire a small tug to ensure that it is solidly connected.

- Repeat this for the remaining three pin-wire connections.

- If you do the connections properly, there should be very little exposed copper wire. When you twist the connector, there should be no possibility that the wires will touch. If that's a possibility, unsolder the lot and do it again. **Do not cover the connection with electrical tape.** It's more important to be able to see the connections, to determine if they are reliable. If you want to be *really* snazzy, use small-diameter heat-shrinkable transparent tubing to insulate each connection from its neighbour. Be careful when shrinking the tubing, though, excessive heat will melt the wiring insulation and you'll have to start over again.

A Note on Wire

Where the wire must flex, use *stranded* wire, about number 24 guage. If the wire does not flex, use *solid* wire of a similar guage. In all cases, the wire should be *tinned.* The ideal wire to use for connections on a protoboard is #22 AWG solid, PVC insulation. **Do not attempt to use wire scrounged from the telephone system: it's brittle and difficult to solder (because it is not tinned) and makes very poor connections.**

To see a variety of different wire types, visit the basement of Active Surplus on Queen street.

Attaching the Television Camera

If you are controlling a vehicle while observing it from a distance, it's very difficult to control when it changes direction away from you to towards you. The control switches reverse function, and this is difficult to get used to. For that reason, we have provided a video viewing system for the operator. The television camera goes on the vehicle and the operator controls via the television monitor. This, of course, mimics what happens in many remote control vehicles.

For attachement of the television camera, the vehicle must have a flat area of at least 7 by 7 centimetres. At one side of this area (front or back) there must be a square, vertical post that extends at least 2 cm in height above the area. The camera will rest on the flat area and be attached with elastic bands to the vertical post.

1.4 The Demonstration

When you are ready to demonstrate your vehicle, we will attach a television camera to the vehicle, using elastic bands. We will then plug the vehicle into the far end of a power cable, which dangles from a 'fishing rod' on the ceiling. We will adjust our DC power supply to provide the correct power for your vehicle motors.

You will then drive the vehicle, using our control switches and viewing the television monitor image, through the obstacle path.

You will probably have considerable difficulty in controlling the vehicle with the switches. This is to be expected, and we will improve on the control in later exercises.

Exercise 2: Basic Motor Speed Control

In Exercise 1, you operated the remote-control vehicle by toggle switches that applied full supply voltage to the motor. As you probably discovered, it's not easy to control the speed and direction of the vehicle in this way. In this exercise, we develop a simple speed control for the motors. In Exercise 3, we will refine that speed control into something more sophisticated.

2.1 DC Motor Voltage Control

To begin with, we list the basic equations governing the operation of an *ideal* DC motor (one with no armature resistance or frictional losses).

First,

$$E_m = K_m \omega \tag{1}$$

where

E_m	is the motor *back emf*, volts
K_m	is the motor *speed constant*, volts per rpm
ω	is the motor speed, rpm

Equation 1 says that the speed of the motor is directly proportional to the applied motor voltage.

Second,

$$I_m = K_t \tau \tag{2}$$

where

I_m	is the motor current, amperes
K_t	is the motor *torque constant*, amps per newton-metre
τ	is the motor output torque, newton-metres

Equation 2 says that an ideal motor has no mechanical load, it requires no current to spin. In practice, of course, there *are* frictional losses, so the motor current is non-zero even when there is no mechanical load. As well, a motor inevitably has some armature resistance. The effect of armature resistance is to cause the motor armature voltage to drop when when the armature current increases as the result of a mechanical load. When the armature voltage drops, the motor slows down.

An ideal motor would not slow down when a mechanical load is applied. Obviously, this is not the case in most situations, so the concept of an ideal motor is is obviously inaccurate. However, the concept is still useful to provide some insight, especially if the frictional losses and armature resistance are small enough to be neglected.

Assuming that the ideal motor is a sufficiently accurate model of the motor we are using, then the motor speed may be controlled by means of a variable voltage source. The basic concept is shown in figure 4.

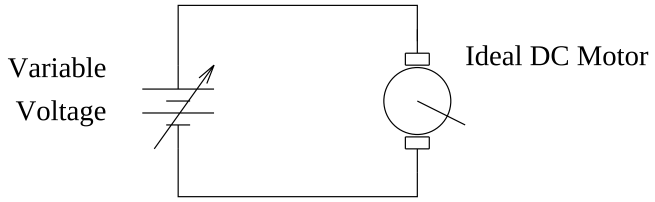


Figure 4: Variable Voltage Speed Control

The motor will run at a speed at which the back emf E_m matches the supply voltage so adjusting the motor supply voltage varies the motor speed.

2.2 Variable Voltage Supply Design

The key requirement of the controller is that it behave like an ideal voltage source. That is, when the motor is loaded mechanically, the voltage source must supply significant current, but the motor voltage should not change.

The basic concept of a voltage controller circuit is shown in figure 5.

The *speed* potentiometer generates a voltage at its wiper which is proportional to its rotation, so this is a useful device with which to generate a predictable control signal. However, the pot wiper voltage cannot be used to drive the motor directly because the internal resistance of a potentiometer is too large. In other words, the pot could not by itself function as a constant voltage source for a DC motor.

On the other hand, the input current requirement of an operational amplifier is very small, essentially zero. Thus the pot *can* supply enough current to establish the reference voltage at the input to an op-amp. In the circuit shown, the pot wiper voltage establishes the setpoint voltage at the op-amp non-inverting terminal.

The operational amplifier, if it is powerful enough, can drive the motor directly. In this circuit, the op amp senses the motor voltage (at its inverting terminal) and corrects its output voltage (the motor voltage) until the feedback and reference signal are exactly equal. In this way, the op-amp forces the motor voltage to track the pot wiper voltage exactly. As the wiper of the pot is moved, the motor voltage will then change, and the motor speed will change proportionally.

One useful way of looking at this circuit is that the op-amp functions as a *voltage follower*, presenting a high resistance to the pot and a low internal resistance to the load.

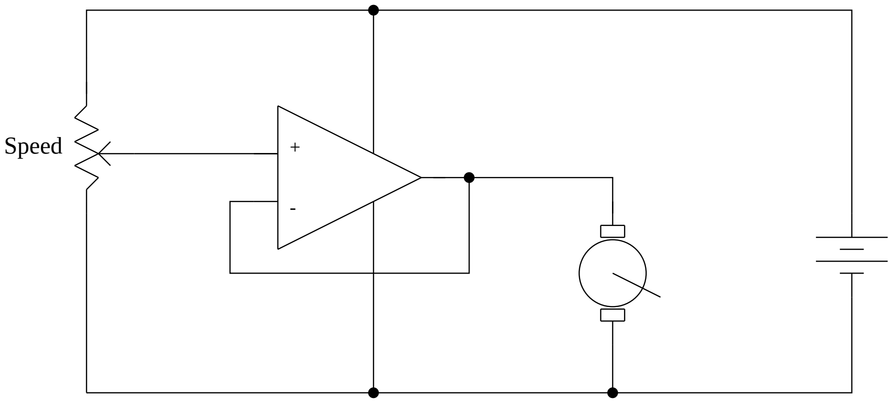


Figure 5: Voltage Controller Concept

2.3 Increasing the Output Current

One can actually buy op-amps that can drive motors. Unfortunately, they are expensive not readily available. The op-amp we'd prefer to use in this circuit is the LM324N, a device manufactured by National Semiconductor. This particular part has a number of attractions: it's readily available, there are *four* op-amps in one package, it's inexpensive (about $1.00), and it will operate off a single, low voltage power supply. (Many op-amps require a dual voltage supply.)

Unfortunately however, the LM324N can only supply a few milliamps of output current to its load: it makes a great brain, but lacks muscle. It is certainly not capable of driving the motor directly.

Fortunately, muscle is not difficult to obtain. It comes in the form of the BJT (Bilateral Junction Transistor), in which a large current can be controlled by a small current. In the transistor we will use, the TIP120, the ratio between the input and output currents is about 1000, so we say that the device has a *current gain* of 1000. The controller circuit with the addition of a BJT is shown in figure 6.

In this circuit, the output of the op-amp drives the base of the BJT with a very small current, and a much larger motor current flows out of its emitter. With this addition, we're closer to a solution: this circuit will work, but it can still be improved.

The problem with the BJT in this circuit is the voltage drop from base to emitter.

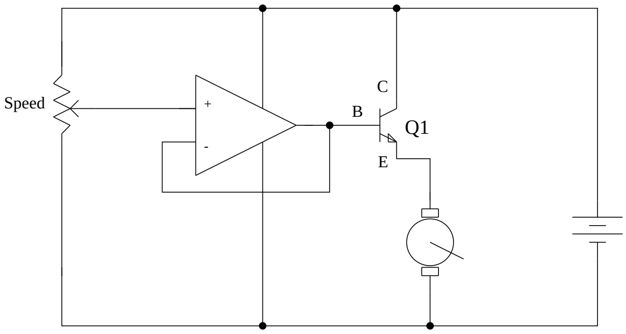


Figure 6: Voltage Controller With Current Gain

It turns out that the voltage at the emitter of the BJT is about 1.2 volts lower than the voltage at its base. As a result, the motor voltage is no longer exactly equal to the pot wiper voltage: it tracks the pot wiper, but offset by 1.2 volts.

However, if we derive the feedback signal from the motor voltage as shown in figure 7, then the op-amp will adjust the base voltage of the BJT automatically, and the motor voltage will again track the pot wiper voltage exactly. The voltage drop between the base and emitter terminals of the BJT will be compensated-for automatically.

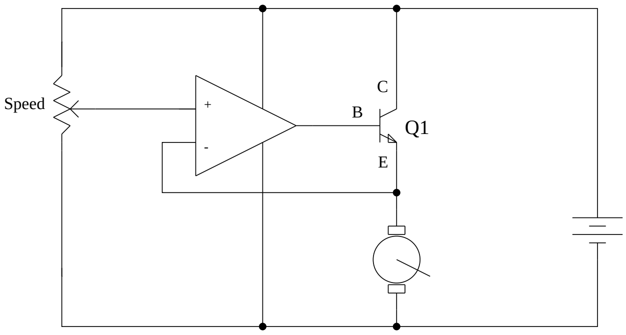


Figure 7: BJT Current Amplifier moved Inside the Loop

This is a very important point: in a negative feedback system such as this one, the op-amp does whatever is necessary to make the error signal zero, that is, make the feedback signal equal to the reference signal. In this case, the op-amp must move its output terminal up by 1.2 volts to make the feedback signal equal to the reference. In fact, within certain limitations, the exact voltage at the base of the BJT in this circuit is now irrelevant, since the motor voltage is made to track the pot wiper voltage.

2.4 Final Circuit Configuration

The final circuit for the motor controller is shown in figure 8.

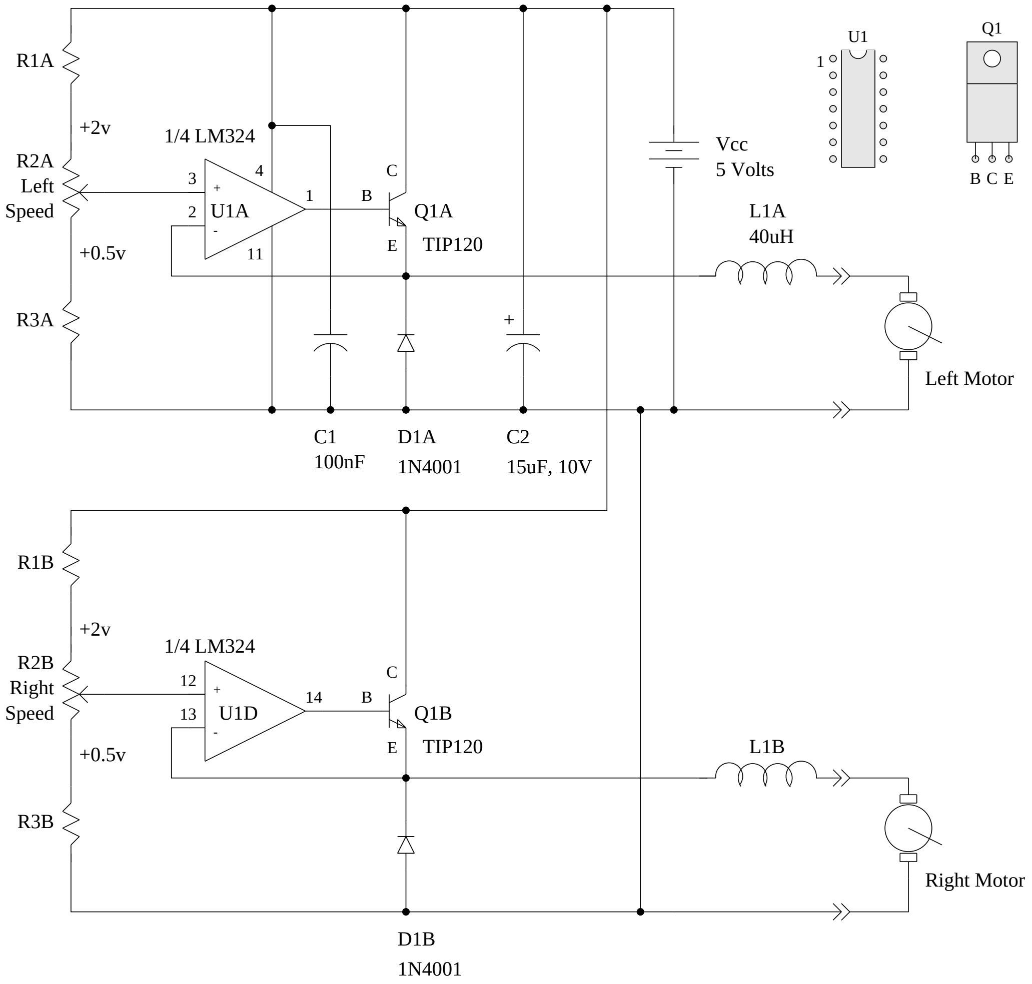


Figure 8: Motor Controller: Final Circuit

Here are some points with regard to the circuit:

Two Circuits Required You need to speed control two motors, so you need two of all components except the power supply Vcc, the op amp (one LM324N contains four op-amps), and the capacitors.

Potentiometer R2 A starting point is to choose the potentiometer R2, which will depend on what's available. In the absence of other information, 10KΩ is a good value, but any value will work. Lower values will waste more current, so stay above 1KΩ or so. It is important that the pot have a *linear taper*, that is, that its output voltage be directly proportional to shaft rotation. The other possibility is *audio* or *log* taper. Stick with linear pots. Choose a nice knob or lever to mount on the pots while you're at it.

Ideally, for best control in steering the vehicle, the pots should be mounted as shown in figure 9. Each pot should be on the same side as the vehicle motor that it controls, and pushing the pot lever forward should increase the speed of that motor.

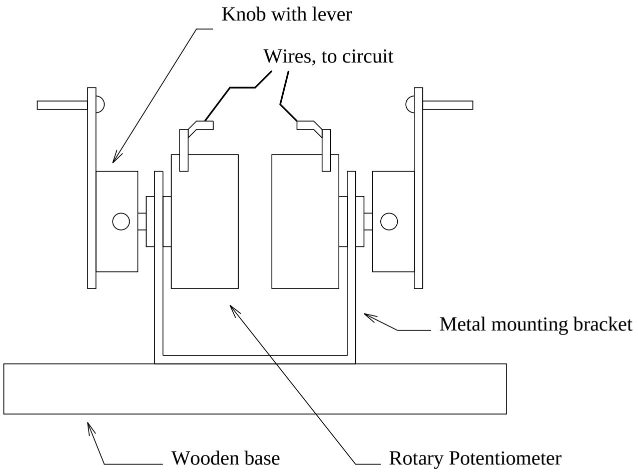


Figure 9: Speed Control Pot Mounting

If you can find them, linear slider motion pots make nice speed controls. Be sure to check that the resistance characteristic is linear, and not audio taper.

Resistors R1,R3 The size of these resistors will depend on the value of the pot that you chose for R2. Using the voltages shown on the diagram, calculate R1 and R3 to suit. Choose standard value resistors near the required values and plug them into the circuit. If you find that a motor does not stop completely when the pot is turned down, reduce R3. If you want to increase the maximum voltage to the motor, decrease R1.

Diode D1 This is shown as a 1N4001 but any one-amp power diode will work. The diode is there because the inductance of the motor winding interacting with current interruptions caused by the motor commutator causes voltage spikes that could fry the BJT. Normally, the diode is reverse biased and doesn't do anything. However, a negative spike across the motor will forward bias the diode, preventing the spike from exceeding the forward voltage of the diode, 0.6 volts. Don't worry if you don't exactly understand this, but put the diode in the circuit anyway.

Capacitors C1 and C2 . Capacitor C1 is a *ceramic* type and should be mounted as close to the power pins of the op-amp package as practical. It is non-polarised and voltage rating is not important. It's function is to smooth the voltage into the op-amp. Capacitor C2 is an *electrolytic* type, which means that its polarity is important. **Connected backwards, it may explode, with consequent risk to nearby humans**.

This capacitor may be marked with a band to indicate the negative terminal, or there may be a minus sign graphic pointing to the negative end. The negative terminal of an electrolytic is the outside can, and if you look carefully you can see which lead is connected to the outside container. Check and recheck your connection, and consult someone knowledgeable if in doubt. As well, the voltage of capacitor C2 must exceed the supply voltage, so anything above 10 volts or so should be fine. Capacitor C2 acts as a short-term storage resevoir for motor current.

Transistor Q1 This transistor is technically an *NPN Power Darlington Transistor with internal clamping diode.* Any other NPN transistor in this series such as the TIP110 or TIP112 should work fine.

In this circuit, the transistor can disappate considerable heat. Typically, under stall conditions (maximum motor current), the motor current might be about 0.8 amps. When stalled, the speed is zero so the voltage across the motor is zero, so the full supply voltage, 5 volts, is across the transistor and the transistor disappation is then the product of its voltage and current, 4 watts. The thermal resistance to ambient of a small transistor is quite high. Without a heat sink under these conditions, it's junction temperature will exceed it's allowable maximum, 150^oC, in a matter of seconds, and this will destroy the device. (This happened to your instructor during the testing of this circuit.) A suitable heat sink has an area of 9 cm^2 (1.5in^2), so you'll need to find two of these and bolt one to each transistor.

Output Inductor L1 When we tested the circuit, we discovered that it would run correctly on the bench but not when a long cable was installed between the controller output and the motor. The effect of the cable was to add about 1.5 nanofarad load to the output of the controller, and this destabilized the feedback action of the circuit sufficiently to make it unstable. The result was sustained oscillations at about 1MHz. (Load capacitance destabilizes a negative feedback system because it adds a phase shift that delays the feedback signal. At high frequencies, the phase shift internal to the op-amp, added to the phase shift caused by the output resistance of the op amp interacting with the load capacitance, is sufficient to make the feedback positive rather than negative at that frequency.)

The cure to this problem is to add an inductor of about 40μHenries in series with the output. The inductor changes the net load impedance from capacitive to inductive, and the oscillation disappears.

An off-the-shelf suitable part is the Hammond 1536P, a 40μHenry Hash Choke, available for about $8 each from Electrosonic Supply. Alternatively, toroidal chokes that are widely available surplus from switching power supplies also seem to work well. A toroid of 0.75 inch diameter (or greater) with at least 25 turns of enamel wire (#20 to #24AWG) provides the necessary inductance. Ideally, the toroidal core should be *tape wound* rather than *ferrite*, but ferrite also seemed to work satisfactorily. Tape-wound cores have a coloured plastic coating, white or yellow. Ferrite cores use a powdered iron compound and are uncoated, black in colour. The tape wound cores have lower permeability than ferrite, so the number of turns for a given inductance has to be higher. However, ferrite cores tend to saturate easily when carrying DC current, as in this case, in which case their inductance drops drastically. If you have access to an inductance meter, you can check that the choke has the necessary inductance.

The addition of the choke has the beneficial side effect that the commutator noise spikes from the motor are attenuated from 15 volts peak at the motor, to about 2 volts peak on the controller side of the choke. This may contribute to the correct operation of the circuit and/or the reliability of the components.

A useful test of correct circuit operation is to clip a 1.5 nanofarad capacitor across the output terminals of the controller while operating the motor. The motor speed should be unaffected. If you have an oscilloscope, you should be able to check that the capacitive load does not cause the controller to oscillate.

Operational Amplifier The LM324 comes in various packages, some of which are very difficult to use. Make certain that you get the Dual Inline Package (DIP). In the circuit diagram, we have shown amplifiers 1 and 4 of the quad op amp being used: the other two of the four op-amps in the package are unused. If you find this layout a bit crowded, you can use two separate LM324 packages, changing the wiring to suit.

The complete pinout for the LM324N op amp is shown in figure 10.

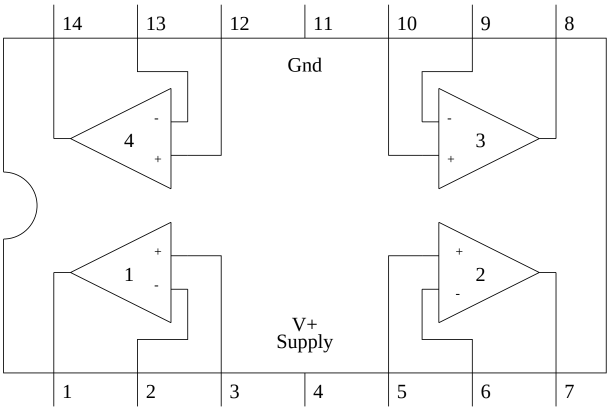


Figure 10: LM324 Quad Operational Amplifier, Pinout (Top View)

2.5 Constructing and Testing the Circuit

1. Make a list of all the electronic parts you require, together with a suitable protoboard and hookup wire, and do the necessary purchases.

2. Make a scale drawing of the circuit layout. You can do this as a sketch on squared paper, or use a computer drawing program. (Your instructor uses Xfig running under the Linux operating system.) An example, to use as a guide, is shown in figure 11. This figure is incomplete and not to scale. Your figure should include all components and be close to scale size.

3. Mount and wire the parts for one controller circuit on the protoboard, using your layout drawing. One student should do the wiring and then the other student check it out. Wiring errors may cause components to burn out, so check and recheck your wiring. At this stage, R1 and R3 are replaced by jumper wires and the motor is not connected.

4. Hook up 5 volt DC power to your circuit. Power the circuit on while touching the op-amp and power transistor and watching the current meter on the DC power supply. If the op-amp or transitor get hot, or if the power supply ammeter shows any appreciable current draw, immediately turn the power off and look for a wiring error.

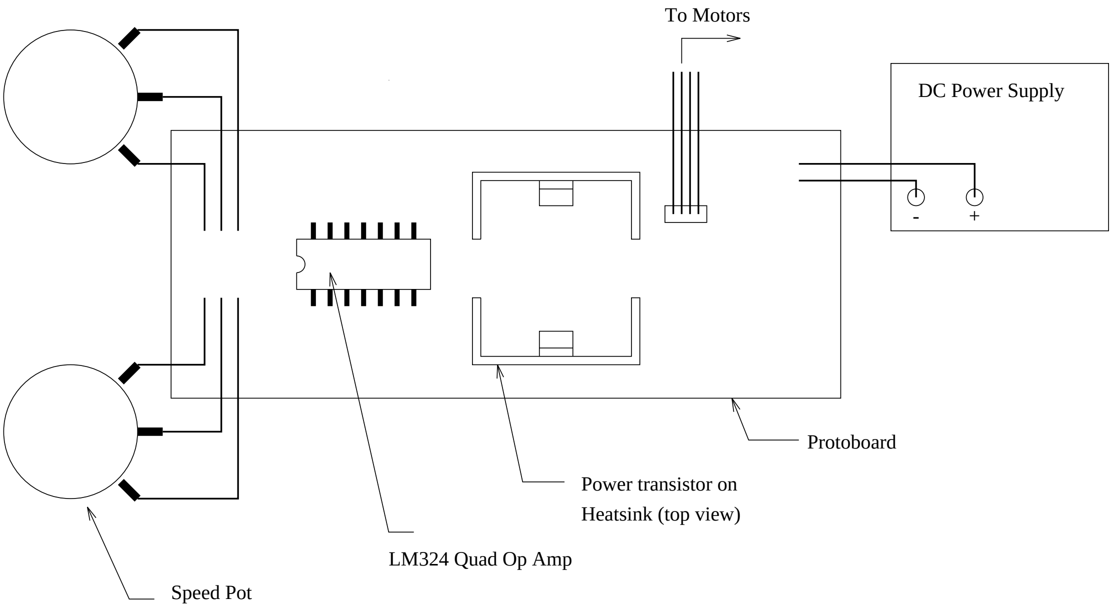


Figure 11: Example Protoboard Layout

5. If nothing catches fire or explodes my this point, use a voltmeter to check the op-amp supply voltage. It should be 5 volts. Now connect the voltmeter where the motor would normally attach, and adjust the speed pot. The voltmeter should show a variation as the pot is adjusted.

6. Now connect a DC motor to the controller and adjust the speed pot. The motor should be adjustable from slow to fast speed. As described above, you can then measure the threshold and limit voltages on the pot R2, and calculate suitable values of R1 and R3. Obtain these resistors, install them on your protoboard, and retest the circuit.

7. If this all works, congratulate yourself, construct the second controller circuit, and test it in the same manner.

If you like, once you have tested the circuit on a protoboard, you can reconstruct it on perforated board and solder all the connections. This will make a much more compact, attractive and reliable package but is not essential for the demonstration.

2.6 The Demonstration

- As in the previous exercise, you will be expected to demonstrate your motor speed control circuit by driving your vehicle through a specified route, steering by viewing a video camera image. In this case, the route will be somewhat more complex, the better to test the capabilities of your motor control system.

- You will be asked to show your schematic diagram and parts layout diagram, and the quality of these documents will be assessed as part of the lab mark.

- For the next exercise, you will need to know the armature resistance of the motors in your vehicle. The most reliable way of doing this is to operate the motor from it's rated voltage (typically 3 volts), stall the motor by holding onto the shaft, and then record the power supply current. If the power supply has an ammeter on the front panel, then you can simply read the value from that. Some power supplies have a switchable meter: change it to read current.

  Alternatively, you can read the resistance of the armature using an ohmmeter, but this is not as reliable a method because the resistance may be a function of current, and the ohmmeter test current is quite small compared to the motor operating current.

  In both cases, you should take two or three readings, allowing the motor to rotate between readings, and average the result.

Exercise 3: Compensated Motor Control

In Exercise 2, you operated the vehicle with controls that adjusted the applied voltage to each motor. This allowed better vehicle control than the toggle switches of Exercise 1, but we can do better still. In this exercise, we design a motor speed controller which senses the load on the motor and automatically compensates for this load, thereby keeping the motor speed essentially independent of mechanical load. The effect is to allow very precise control over motor speed, which is especially useful at low motor speeds, and allows the vehicle to be steered very accurately.

3.1 Real DC Motor Behaviour

Recall the two fundamental relationships of an ideal DC motor:

- The motor speed is proportional to the voltage across the armature.
- The motor torque is proportional to the current through the armature.

The electrical system of Exercise 2 assumes that the armature resistance of the motor is zero and adjusts the armature voltage to control the motor speed. In fact, the motor armature resistance is not zero. As a result, when the motor is loaded and the motor current must increase to output mechanical torque, the voltage across the armature resistance increases, leaving less voltage for the armature itself, and the speed decreases. This corresponds to our experience of a DC motor: increasing the mechanical load causes the motor current to increase and the speed to decrease.

This effect may be modelled as shown in figure 12.

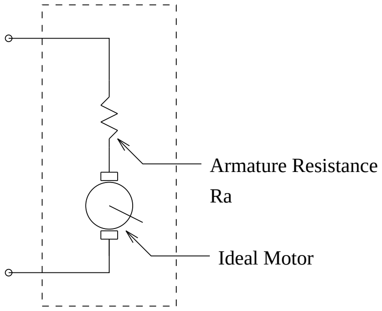


Figure 12: Real Motor, Equivalent Circuit

A real DC motor consists of an ideal motor (in which the speed is exactly proportional to the voltage across it) in series with an armature resistance R_A.

Now, here is the main idea for this control concept: If the voltage across the *ideal motor* could be maintained constant in spite of changes in current through the motor, the motor speed would be independent of the load torque. For this to be accomplished, when the motor load increases, the supply voltage must also increase by an amount equal to the voltage drop across the armature resistance.

This is intuitively what happens when a human being is controlling the speed of a DC motor in response to varying loads. As the motor is loaded, the human controller detects that the motor is slowing down and increases the motor voltage in order to restore the motor speed back to its correct value.

If we had a controller that would increase the motor supply voltage automatically in response to increased mechanical load, the *speed regulation* would be very accurate: the motor speed would not change substantially with increasing loads.

3.2 The Control System

To begin with, we set up the motor control circuit shown in figure 13.

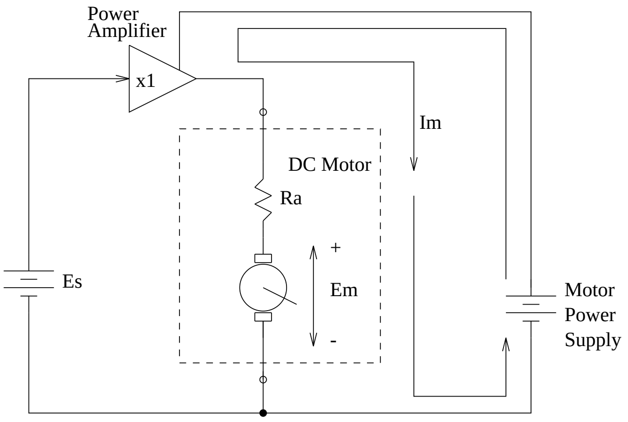


Figure 13: Motor Power Circuit

This circuit we will refer to as the *motor power loop*. In this circuit, the motor supply voltage is controlled by a power amplifier (much like the opamp-bjt circuit of figure 7 on page 22. The amplifier controls the power supply current into the motor such that the power amplifier output voltage is the same as its input control voltage E_s. We can control the voltage at the output of the power amplifier, and hence the speed of the motor, by adjusting the voltage E_s at the input to the power amplifier. Notice that the power amplifier is labelled as ×1, to indicate that its output voltage is the same as its input voltage.

In the next step, we add the control circuitry for regulating the speed of the DC motor, shown in block diagram form in figure 14.

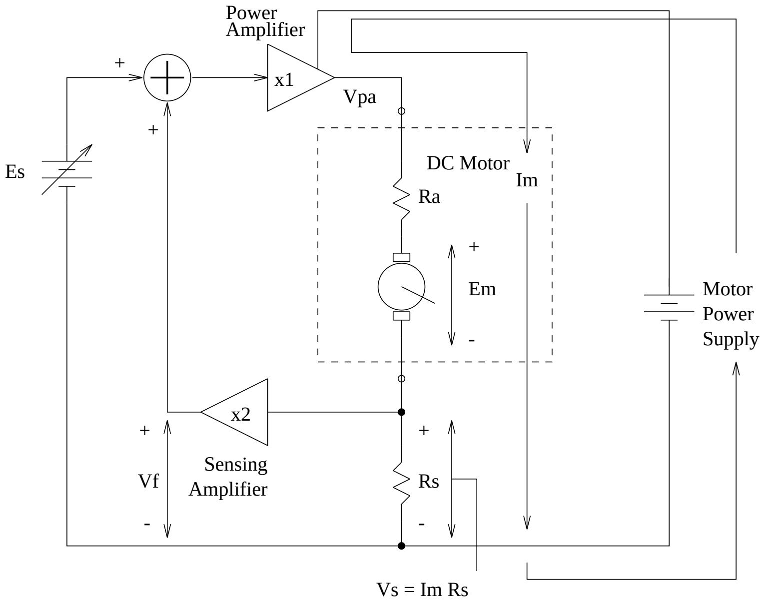


Figure 14: Motor Speed Controller Block Diagram

There are a number of additions to this circuit.

- A *current sensing resistor* R_s is wired in series with the motor. Without additional circuitry, this resistor would worsen the speed regulation of the motor, but we will be adding additional control circuitry to compensate for the voltage drop across this resistor. The voltage developed across this resistor is proportional to the motor current. This same voltage is therefore also proportional to the motor torque, so the resistor creates a voltage that we can use in our control system to signify the magnitued of the motor torque.

- A feedback amplifier with gain ×2 multiplies the voltage across R_s by 2 and delivers it back to the adder.

- The input voltage to the power amplifier is now equal to the control voltage E_s plus the voltage at the output of the feedback amplifier.

If we make the sensing resistor R_s is equal to the armature resistance R_a, then the feedback system will always add on a voltage to the control voltage E_s, by an amount equal to *twice* the voltage across the armature resistance. This voltage appears at the output of the power amplifier and drives the DC motor. The net result is that the armature voltage is exactly equal to E_s, regardless of the armature current, and so the motor speed is regulated exactly.

3.3 Control System Equations

We can prove this last paragraph by writing the equations for the control system, as follows:

The voltage across the ideal motor armature is E_m. By Kirchoff's voltage law around the control loop including the motor:

$$+V_{pa} - I_m R_a - E_m - I_m R_s = 0 \tag{1}$$

where I_m is the motor current.

The power amplifier output voltage is equal to the power amplifier input voltage, which is in turn equal to the sum of the control and feedback voltages:

$$V_{pa} = E_s + V_f \tag{2}$$

The feedback signal V_f is equal to the voltage V_f across the current sensing resistor times the gain of the feedback amplifier. In figure 14 the gain was shown as ×2, but we will give it the symbol K_f, so that:

$$V_f = V_s K_f \tag{3}$$

The voltage V_s across the sensing resistor R_s is

$$V_s = I_m R_s \tag{4}$$

Substituting in equation 1 from equations 2, 3 and 4 we have

$$\begin{aligned}
+V_{pa} - I_m R_a - E_m - I_m R_s &= (E_s + V_f) - I_m R_a - E_m - I_m R_s \\
&= E_s + (V_s K_f) - I_m R_a - E_m - I_m R_s \\
&= E_s + (I_m R_s) K_f - I_m R_a - E_m - I_m R_s \\
&= 0
\end{aligned}$$

We want the value of the motor voltage E_m to be equal to the control voltage E_s, so that we can substitute zero for $E_s - E_m$ in this equation. Substitute zero for $E_s - E_m$ in the above equation to obtain:

$$E_s + (I_m R_s)K_f - I_m R_a - E_m - I_m R_s \;=\; 0$$

from which

$$I_m R_s K_f - I_m R_a - I_m R_s \;=\; 0$$

Cancelling I_m from this equation, we have

$$R_s K_f - R_a - R_s \;=\; 0 \tag{5}$$

One possible configuration to satisfy this equation would be to make $R_s = R_a$ and $K_f = 2$, that is:

$$2R_a - R_a - R_a \;=\; 0$$

This condition will ensure that the motor voltage E_m will be equal to the control voltage E_s, and was the setup shown in figure 14. However, we can do better than this.

The motor current is significant, so that we will waste considerable power in the sensing resistor R_s if we make it equal to the armature resistance R_a. It would be better to make it as small as possible. Intuitively, it seems possible to increase the gain of the feedback amplifier to compensate for the smaller value of the sensing resistance. For example, we could choose

$$R_s = \frac{1}{5}R_a$$

Then from equation 5, substituting $R_a/5$ for R_s we have:

$$\frac{R_s}{5}K_f - R_a - \frac{R_s}{5} \;=\; 0 \tag{6}$$

$$\tag{7}$$

Solving for the value of K_f, we obtain that

$$K_f = 6$$

That is, the gain of the feedback amplifier must be 6 volts/volt to obtain the same control system as before.

3.4 Electronic Circuit

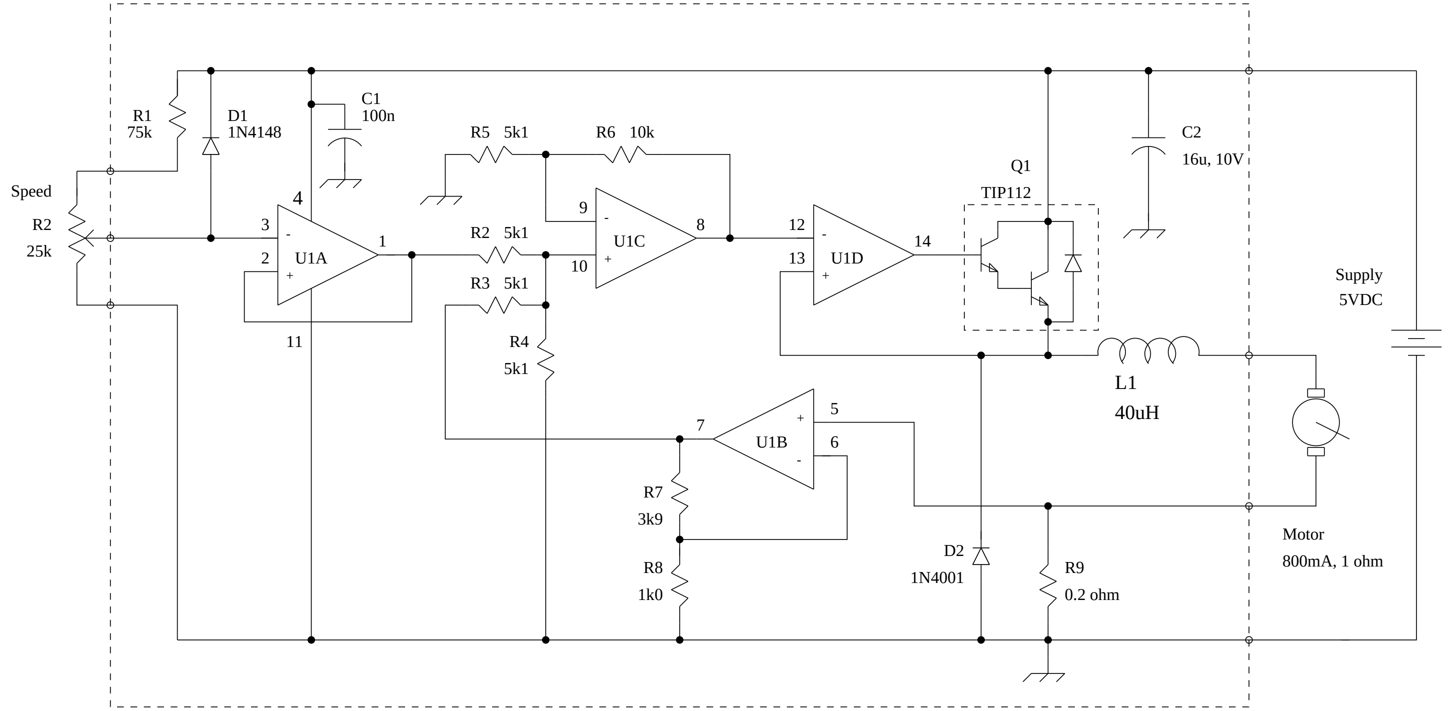
The circuit diagram of the complete motor speed controller is shown in figure 15.

Some parts of this circuit are straightforward:

- Resistor R2 is the *speed* control. Notice that its voltage can go right down to zero, signifying that the motor speed is controllable right down to zero speed.
- Opamp U1A is configured as a voltage follower, and buffers the signal from the speed potentiometer.
- Opamp U1D and transistor Q1 form the power amplifier, configured as a voltage follower, so that the output (motor) voltage is the same as the input voltage.
- Resistor R9 is the current sensing resistor R_s. The motor resistance R_a for this type of motor is typically about 1Ω, so that $R_s = R_a/5$, as in the previous example.
- The feedback amplifier U1B is a non-inverting amplifier with gain

$$\begin{aligned} A_v &= 1 + \frac{R7}{R8} \\ &= 1 + \frac{3900}{1000} \\ &\approx 5 \text{ volts/volt} \end{aligned}$$

According to our previous theory, the voltage gain of the feedback amplifier should be 6 volts/volt for perfect compensation. However, when the circuit was constructed and tested with a feedback gain of 6, it was found that the motor had a slight tendency to *creep* when it was supposed to stop completely. This was fixed by reducing the gain of the feedback amplifier, thereby undercompensating the system slightly, so that the motor is slightly affected by load torque.



NOTES:

Q1 may be any NPN type TIP series Darlington transistor.

Q1 must be on a heat sink, area 3 inches squared

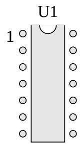
Op amps are from Quad Op Amp, LM324N or LM324AN (DIP package).

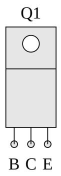
Recalculate resistor values to suit other components.

For D1, any small signal silicon diode may be substituted

For D2, any 1N4000 series diode or 1 amp diode may be substituted.

R9 is 5, 1 ohm resistors in parallel





Motor Speed Controller

Ryerson Polytechnic University
Peter Hiscocks, October 30, 1997
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Revision: 0.1
File: motcon2.fig

Figure 15: Motor Speed Controller Circuit Diagram

A trick is used to construct the adder in the circuit. The traditional adder circuit is inverting: for a positive input voltage, the output is negative. This is a nuisance here. If an op-amp is to produce a negative output voltage, it must have a negative power supply. Everything else in this circuit operates nicely from a positive supply, so it would be really convenient if we could somehow make an adder that produced a positive output for positive inputs. The solution is shown in figure 16:

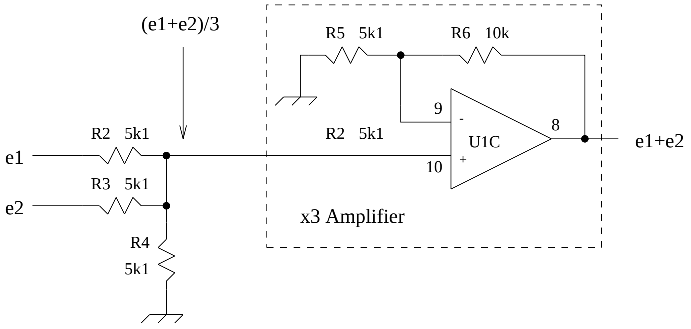


Figure 16: Positive Voltage Adder

Resistors R2, R3 and R4 function as a lossy adder circuit: the output, which may be verified using the superposition theorem, is

$$\frac{e1 + e2}{3}$$

If this is followed by a non-inverting amplifier of gain 3, then the output of the amplifier is simply the sum of $e1$ and $e2$.

3.5 Constructing and Testing the Circuit

This is quite a complicated little circuit. It requires all four op-amps in the LM324 package, so a controller for two motors will require two LM324's. There is lots of scope for wiring mistakes, so it is essential that you be systematic in constructing, checking and debugging the circuit. Plan ahead, be neat, and carefully check your wiring.

1. Check the resistance of your motor. If it is significantly different than 1Ω, then you will have to recalculate the value of the current sensing resistor R_s.

2. Make at least two copies of the schematic diagram: one to check off when wiring, one to check off when verifying the circuit.

3. Make a layout diagram of the circuit, similar to figure 11 on page 28. You will need at least one standard sized protoboard (approximately 13cm x 4cm), but 2 protoboards may make the wiring less crowded.

4. Remember, each power transistor *must* have a heat sink. Otherwise, the power transistor will be destroyed.

5. Wire one motor controller completely, according to your layout diagram. Without the motor connected, apply power to the circuit. Immediately check that the op-amp has the correct power on pins 4 and 11. Reversing the power will destroy the op-amp in a few seconds.

6. Re-apply power, checking for excessive current from the power supply. All components should remain cold to the touch. If anything gets hot, shut off the power and find the wiring mistake.

7. If all is well, monitor the motor voltage (still without the motor connected) and it should change as the speed pot is adjusted. Ideally, the motor voltage should be equal to the voltage at the wiper of the pot. Check this.

8. Connect the motor, hold your breath, and bring up the motor control voltage. The motor should run correctly and should change speed as the pot is adjusted.

9. Now check that the compensation is working correctly. Set the pot so that the motor runs at mid-speed. Connect a voltmeter to measure the motor voltage. As you apply a load to the motor, the motor voltage should *increase* and the motor should not slow down appreciably.

10. Repeat for the second motor control circuit.

11. Take the vehicle for a test drive. It should be *very* easily controllable from full stop up to maximum speed, and it should be easy to steer the vehicle precisely.

12. The object of this exercise is to be able to drive the vehicle as slowly as possible, and still have complete control. Practice driving at a slow speed.

3.6 Design Review: Tidying Up the Circuit

Once the circuit works correctly and you can control the vehicle precisely, tidy up the wiring and make it as solid and permanent as possible. This controller will be used to operate the vehicle for the rest of the course, so it is important that it be as reliable as possible. New bugs in a later section of the lab you do not need.

You can consider this as the pre-production maintenance exercise. Here are some of the things to check out:

- If you have used any telephone type solid wire in your circuit, it might be a good idea to replace it with #22 AWG copper wire. Telephone wire is small in diameter and tends to corrode, making intermittent connections with the protoboard contacts.

- Can the wiring be simplified? A simpler layout is easier to troubleshoot and more reliable to boot - there are fewer connections to become unreliable. Moreover, a simple, direct wiring arrangement is less likely to oscillate, or, if it does oscillate, is easier to troubleshoot. However, don't go to herculean efforts to reduce the size of your circuit. Very compact circuits are also difficult to fix or modify.

- Connectors are a common source of problems in an electronic circuit. Is there any possibility wires can short circuit if the connector is twisted? Are there stray little bits of stranded wire that could cause a short circuit? Are any of the connections liable to break under stress? Can the contacts pull out of the plastic body when the wire is tugged? If any of these are a problem, redo or replace the connector.

- Is it easy to steer the vehicle? For example, crossed controls (left pot operates right motor) make the vehicle almost impossible to drive. Controls should be mounted solidly, with control shafts pointing left and right (not out the front of the panel) and preferably with a *lever* control, not a knob. (Imagine trying to control the speed and direction of an automobile with two knobs on the dashboard!) The direction of rotation should be such that moving the left lever *forward* should speed up the left motor. A little effort in improving the ergonomics will go a long way in making the vehicle more controllable.

- Are there parts that are possibly subject to breaking off while being transported? For example, some heatsinks stick up out of the protoboard and can cause the power transistor leads to be bent or pulled out of the protoboard. A better arrangement is to use a smaller heatsink or mount the heatsink to a baseplate and run leads back into the protoboard. Can the leads on components, such as resistors and capacitors, be made shorter? Can the components be re-organized and re-wired so that they lie down close to the protoboard? If so, this will make the circuit more reliable and easier to troubleshoot.

Remember Murphy's Law:

If anything can go wrong, it will. If things go wrong, they will do so at the worst possible time.

Exercise 4: Optical Line Sensing

In this exercise, you will equip your vehicle with sensors that signal the type of surface, red tape or black background, below the vehicle. The sensors mount on the front of your vehicle, together with amplifier circuits that increase the signals before they are sent back to the driving station.

A sketch of the prototype arrangement on the Tamiya Bulldozer is shown in figure 17.

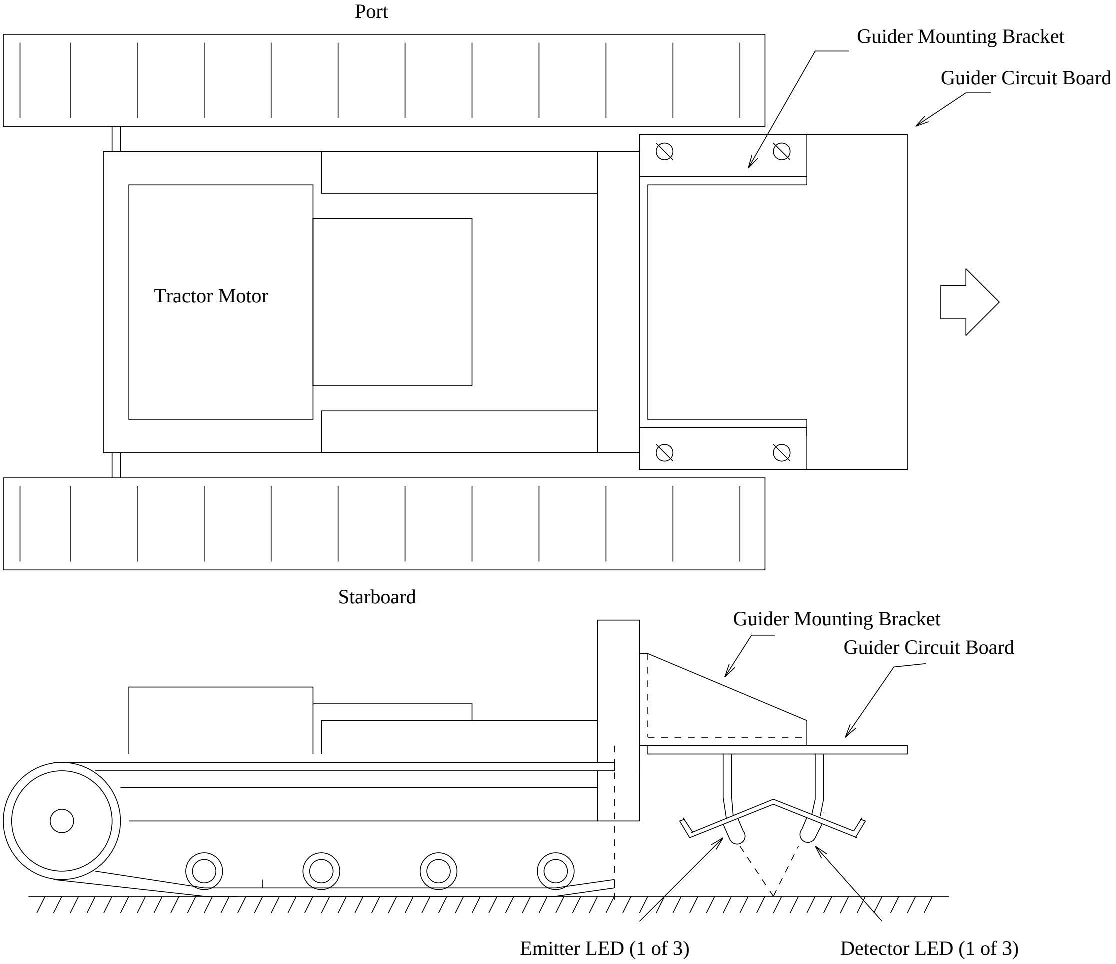


Figure 17: Guider Circuit on Tamiya Bulldozer

In the laboratory demonstration, the driver's station video display will be removed and replaced with three *thermometer* display readouts that give a continuous indication of the outputs of the three sensors on the vehicle. Students will be expected to guide their vehicle around the course using these three thermometer displays as steering information. In a later exercise, signals from the tape sensors will be used by a computer to guide the vehicle without operator intervention.

4.1 Guider Circuit

The circuit of the guider is shown in figure 18.

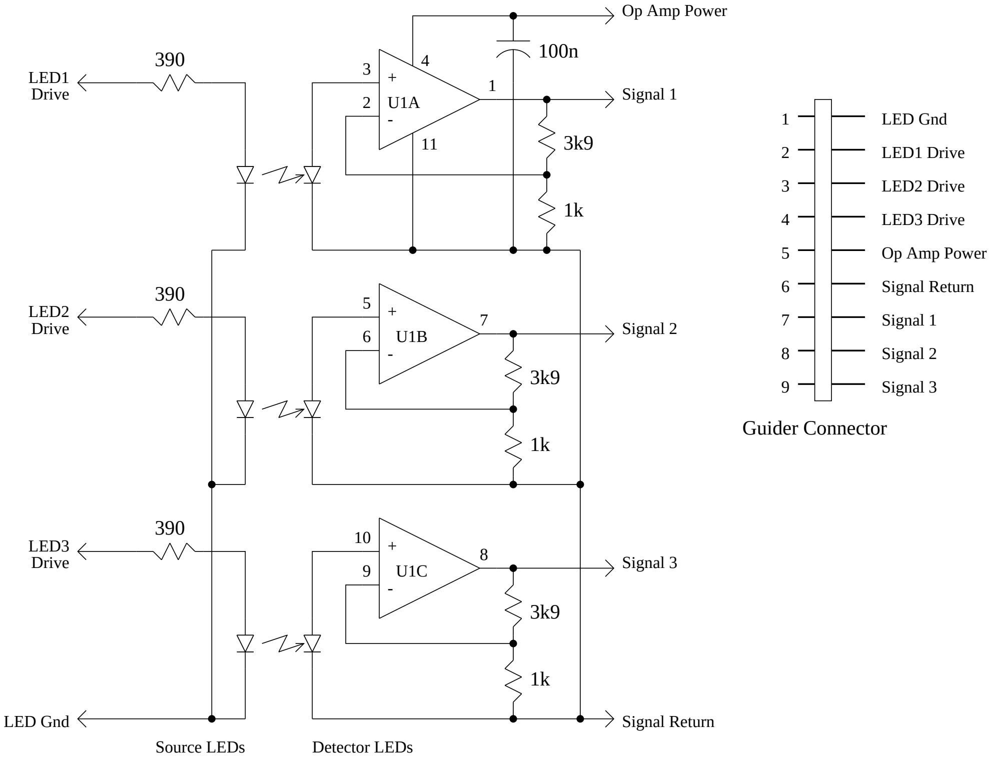


Figure 18: Guider Circuit

The line sensor assembly uses of three high-intensity red LEDs to illuminate the road surface. Three identical LEDs are positioned such that each each one sees the road surface illuminated by one of the LED emitters. The voltage across each LED detector changes by about 0.7 volts between the black tile surface and the red tape surface. For example, typical output levels from a detector LED are 0.2 volts over the black tile surface and

0.9 volts over the red tape surface. To provide some gain at the line sensor, an op-amp on the vehicle boosts the photo-diode detector signal by a factor of about 5 volts/volt.

When the vehicle is centered over the red tape, the centre LED has a high output signal and its neighbours on either side have a low output. The operator can then interpret the signals from the three detectors to steer the vehicle to stay over the red tape.

4.2 The LED Emitter and Detector

The same type of LED is used both as an emitter of light and a detector in this circuit. It is a *high intensity* (*bright*), red LED. The prototype circuit used the LiteOn type LTL4213 (or LTL307P), which emits in the visible spectrum at 627 nanometers and has an emitting angle of about 40^o. These devices are listed in the Electrosonic catalogue. Unmarked devices available from surplus electronic stores should work acceptably, but check that they are bright red and that the light output is focussed into a narrow beam.

Some red, high intensity LEDs are packaged in a clear plastic package, and this is preferable to a red plastic package, since the beam of light will be less diffused and more focussed. LEDs are inexpensive enough that you can buy several different types and experiment.

You might also want to try *high efficiency red* LED devices, which operate at an optical wavelength of 635 nanometers. They may or may not work acceptably: you'll have to experiment.

Choose LEDs with the T-$1\frac{3}{4}$ package. This is just under 0.2 inches in diameter and 0.3 inches in height from the emitting end to the plastic shoulder.

4.3 Testing the LEDs

To test the LED you have chosen, hook up one LED as an emitter by wiring it into a circuit with a resistor and DC power supply. (The cathode of the LED is always marked with a small flat spot on the plastic body of the LED. Do not rely on the lengths of the LED leads to identify the cathode: this is not reliable.) The voltage drop across the emitter LED will be about 1 volt, and the resistor should be chosen to set the current through this LED to between 5 and 10 millamps.

A test circuit is shown in figure 19.

Direct the light from this LED at a sample of the red electrical tape used in the lab: the lab instructor can supply you with a small sample. Connect a second LED as a detector, to a high impedance (digital readout) voltmeter. (A voltmeter with an analog or *moving coil* readout probably will require too much current from the LED detector to indicate properly. An LED operated as a photo-diode detector cannot supply more than a few *nanoamps* to its measuring circuit, so an electronic meter with a high input

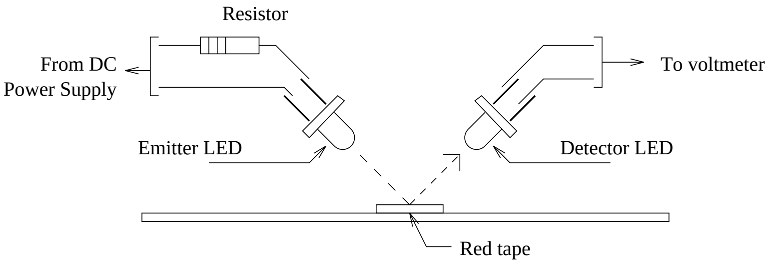


Figure 19: LED Test Circuit

impedance is required.) Aim the detector LED at the illuminated area and measure the output voltage with the emitter LED on, and then with the emitter LED off. Ideally, you should read a change in voltage from the detector of about 0.5 volts.

4.4 Mounting the Guider

Now you need to design and construct the hardware that mounts the emitter and detector LEDs at the front of your tractor or tank.

There are several requirements of the guider construction:

- The guider LEDs must be mounted so that each detector LED sees the light from its corresponding emitter. This requires that both emitter and detector LED are spaced a precise distance from the road surface, so the mounting arrangement must include some provision for adjusting the height of the guider assembly.
- The guider LEDs must be mounted so that the emitter and detector LEDs are angled in towards one another, so that they both see the same area. A larger angle allows the LEDs to be closer to the road surface, which is desireable, but this spreads out the lighted area. In the prototype, the optimum angle between emitter and detector was found to be about 60^o.
- The mounting material for the LEDs may also be extended into a *roof*, so that some of the ambient room light is prevented from affecting the area under the emitter and detector LEDs.
- The spacing between the three groups of LEDs should be such that the outer LEDs are just at the edge of the red tape when the centre LED is in the middle of the tape. The tape is 0.7 inches (1.77 cm) in width, so this sets the spacing of the LEDs.

- The amplifier for the detector LEDs should be as close as possible to the LEDs in order to minimize noise pickup. In the prototype, the detector circuit board is directly above the LEDs.
- You will eventually glue the LEDs into their mounting plate (don't do this yet), and mount the assembly securely to the tractor. It is essential that the guider position not change while the tractor is in motion.

The guider mount can be constructed from aluminum, thin steel sheet, or wood, providing it meets the requirements listed above. A sketch of the LED mounting in the prototype is shown in figure 20.

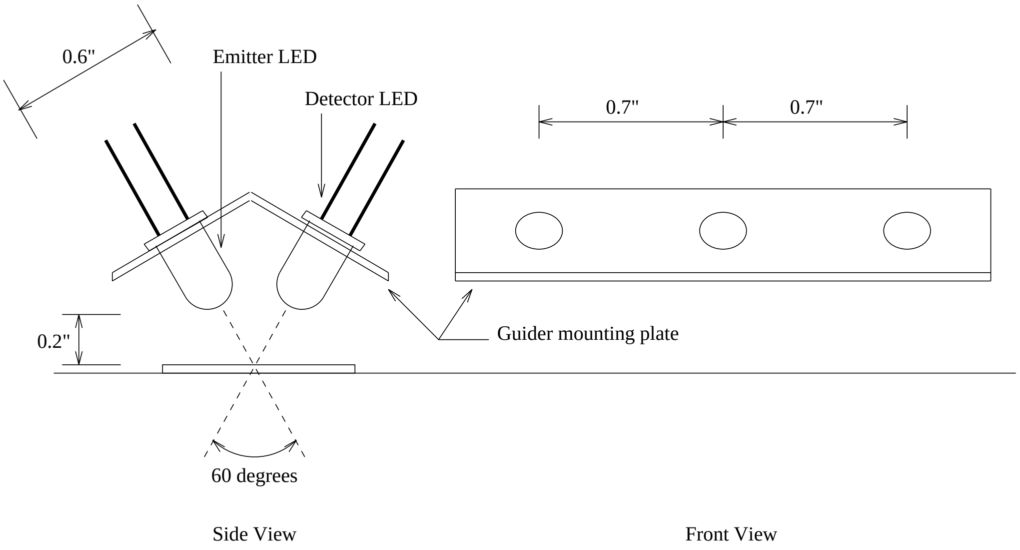


Figure 20: Guider Critical Dimensions

4.5 Wiring the Guider

The lab setup provides a multi-conductor cable terminating in a socket connector at the vehicle end. The other end of the cable is set up to provide +5 volts for the LED emitters, operational amplifier power, and thermometer readouts for the detector signals. The circuit on the vehicle must contain the parts shown in figure 18 on page 41 and must also attach correctly to the laboratory control cable.

There are two ways to organize the wiring of the guider.

- Mount a small, perforated circuit board directly above the LEDs on the guider assembly. This circuit board contains the resistors and amplifiers for the emitter and detector LEDs. Also on this circuit board is a pin plug which mates with the lab control cable according to the pinout shown in figure 18 on page 41. The laboratory control cable plugs into the connector on this guider circuit board and then goes back to the control console.

- Mount a small protoboard, containing the various resistor, amplifier chip and connector on the tractor body. Solder very light stranded or solid wire to attach to the LED leads at one end. Then solder a plug at the other end of these wires, and plug it into the protoboard on the vehicle. (The wiring pinout of this connector is your choice.) Then provide *another* pin connector, according to the pinout of figure 18 on page 41, to mate with the cable going back to the control console.

Whichever method you use, **do not use solid telephone wire. It's too stiff and brittle, does not solder well, and does not make reliable contact in the protoboard.**

4.6 Debugging and Testing the Guider

1. Before gluing the LEDs into the guider hardware, test them using the method described above in section 4.3.

2. Now construct the guider hardware and mount the LEDs into the hardware. Mount the guider onto the tractor and power up the emitter LEDs. (Virtually any DC power supply of about 5 volts should do here.)

3. The emitter LEDs should create three small spots of light, each about a centimetre in diameter. Adjust the height of the guider until the detectors seems to be aimed at the light spots.

4. Using a high-impedance voltmeter, monitor the voltage directly across one of the detector LEDs. Move the tractor so that this detector sees red tape and then a flat black background. You should see a significant (about half a volt) change in reading from a red to black background. You may wish to tweak the guider up or down to improve on the detector signal.

5. Repeat this measurement with the other two detectors, choosing a compromise location for the guider that produces a useable signal from all three detectors.

6. Finish the amplifier wiring. Power up both the amplifier circuit and the LED emitters from +5 volts. Now check the output of each amplifier as the detector

is moved over red tape and a flat black background. You should see a significant change, two or three volts, from red to black.

7. Tidy up loose wires, secure the guider in its final position, and prepare for a test run!

4.7 Appendix: The Thermometer Circuit

A *thermometer display* is a vertical row of LEDs connected to an electronic *display driver* circuit. As the input signal voltage increases, more and more LEDs light up. At full scale deflection (FSD, which is 5 volts for this circuit), all the LEDs are lit.

For reference, the circuit used to make the thermometer LED display is shown in figure 21.

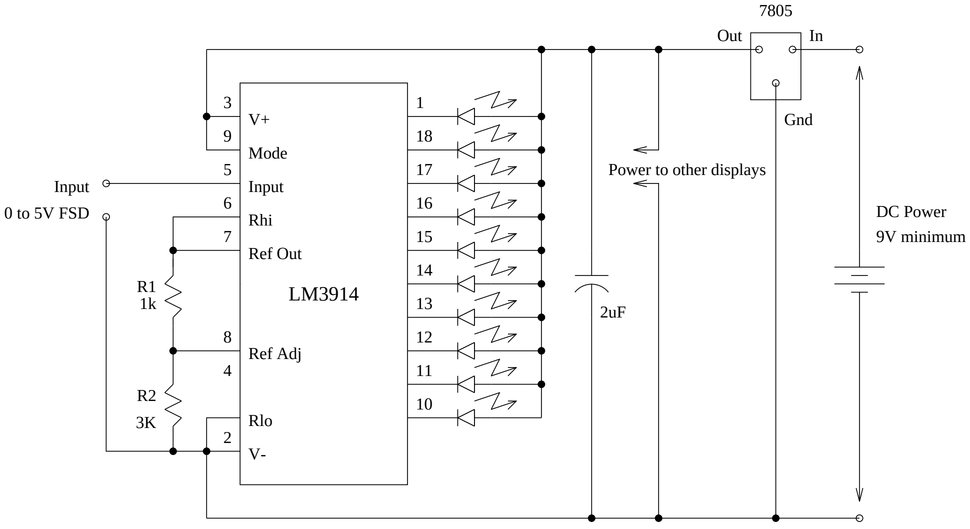


Figure 21: Thermometer Display Schematic

If you are considering building this circuit, it might be wise to consult the datasheet for the LM3914. The LM3914 which is manufactured by National Semiconductor, and their *Linear Databook for Special Functions* contains the information.

The main points are these:

- To avoid oscillation of the chip, the circuit should be *star-grounded* to pin 2. That is, ground wires should not be bussed but run directly to a point as close to pin 2 as possible.

- A regulated power supply is not required. In fact, the circuit as shown is specified to work from anything between 3 and 25 volts. However, a power supply regulator is an inexpensive precaution and so a 5 volt regulator IC is shown in the schematic. The regulator IC may require a small heat sink.

- The current of each LED is given by

  $$I_{LED} = \frac{12.5}{R_1}$$

  so in the schematic, the individual LED current is about 12 milliamps. A suitable value for LED current is between 5 and 15 milliamps.

- The full scale deflection of the circuit is given by

  $$V_{FSD} = 1.25\left(1 + \frac{R_2}{R_1}\right)$$

  so in the schematic, an input voltage of 5 volts will drive the display to maximum output.

We built up three of these circuits, one for each detector channel. The LEDs that make up the thermometer were arranged to project out of one edge of the circuit board, so that the board was viewed on edge. Then 3 boards were mounted together, using spacers to separate them, to make up a three-channel thermometer display. One it wall adapter power supply, 9 volts and 500mA, was used to power all three displays.

Exercise 5: Computer Assisted Guidance

To this point in the exercises, the operator has controlled the vehicle directly. The steering potentiometers directly controlled the speed of the two motors, and thereby the direction of the vehicle.

In this next exercise, the computer is interposed between the operator controls and the vehicle speed controller. As shown in figure 22, the operator moves a potentiometer, which changes a control voltage. The control voltage is sensed by a computer. After some calculations, the computer outputs a suitable voltage to control the speed and direction of the vehicle.

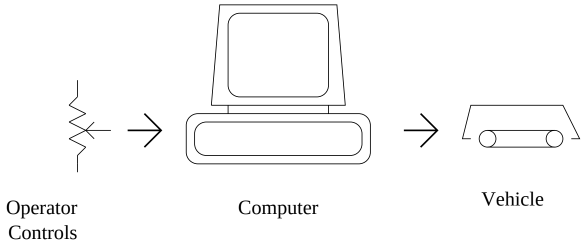


Figure 22: Computer Assisted Guidance

In this system it is possible to arrange for the operator to have joystick control of the vehicle. Moving the stick forward and backward controls the speed of the vehicle. Moving it from side to side controls the direction. This is an excellent user interface for the vehicle operator, but the vehicle motor voltages must be derived by a calculation on the signals from the joystick potentiometers.

5.1 A Practical System

Several additional blocks must be added to figure 22 to make a complete system.

Analog-Digital Converter The control potentiometers each generate an *analog*, that is, *continuously variable*, control voltage. For the computer to deal with this signal, it must be converted into a stream of numbers – *digits* – by an analog-digital (A-D) converter. In our system, the A-D coverter is part of an Input-Ouput board, which is plugged into the computer. The A-D converter is 8 bits, that is, it converts the input voltage into numbers between 0 and 255. There are a total of 8 *input channels* on the I-O Board, so up to 8 voltages can be read by the computer. One limitation of the hardware is that only one of the 8 channels can be read at a time, so the inputs must be read in sequence.

Computer Program The computer instructions direct it to execute a loop of instructions:

```
Loop
          Read A/D Computer SPEED voltage
          Read A/D Computer DIRECTION voltage
          Calculate STARBORD motor control voltage
          Calculate PORT motor control voltage
          Output STARBORD motor control voltage
          Output PORT motor control voltage
Endloop
```

Digital-Analog Converter The outputs from the computer are in the form of numbers, which must be converted back into a control voltage. This is accomplished, also on the Input-Ouput board, by means of a Digital-Analog (D-A) converter. The D-A converter produces a voltage of between 0 and +5 volts, corresponding to digital numbers between 0 and 255. **Output values must be limited to the range of 0 to 255. Numbers outside this range will produce unpredictable output voltages.**

Analog Motor Controller The D-A converter on the I-O board is not capable of supplying more than a few milliamps of current. To operate the motors of the vehicle, a motor controller circuit is required. The motor controller is the circuit you developed in Exercise 3. The controller is modified so that the manual potentiometers used to set motor speed in Exercises 2 and 3 are removed and the input control voltages driven from the D-A outputs.

A complete wiring diagram of the system is shown in figure 23.

5.2 The Joystick

A *joystick* is a controller that has two independent outputs, which are both controlled by the position of a *stick*. One output is proportional to the vertical (Y axis) position of the stick, the other to the horizontal (X axis) position.

Obtaining a Joystick

Joysticks are commonly used as a computer game accessory and are sometimes found in electronic surplus store bins. Check the innards of the joystick before you buy – some joysticks contain *switches* that are actuated by the movement of the stick, and this is of no use here. Be sure to purchase a unit that has potentiometers inside.

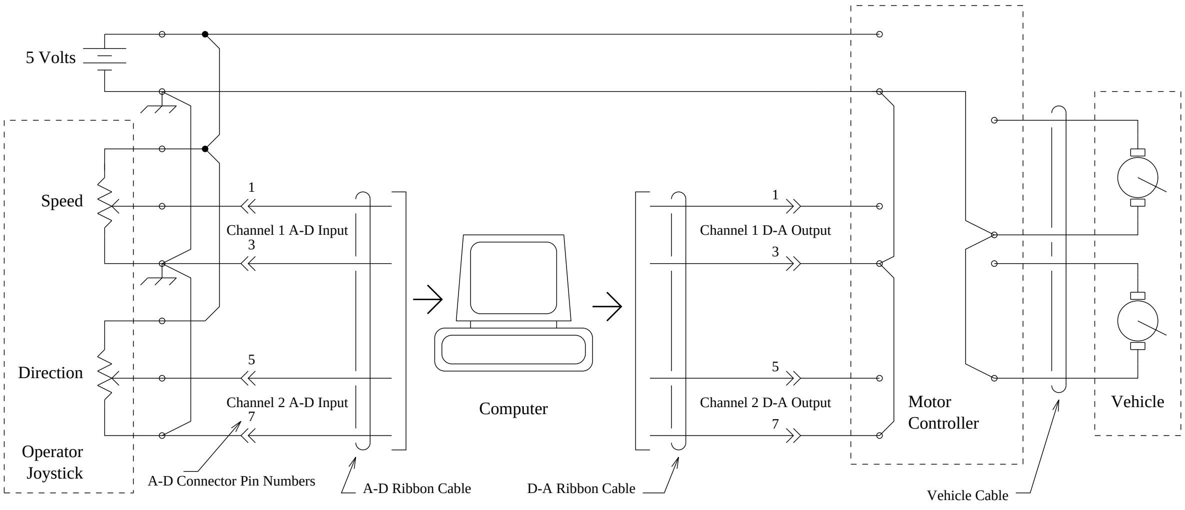


Figure 23: Computer Assisted Guidance, Wiring Diagram

You can also fashion your own joystick, which may be imagined as follows[1]:

1. The first potentiometer is attached to a plywood base by means of a metal bracket so that the pot shaft is horizontal.
2. A knob is attached to the shaft of the first potentiometer.
3. A right-angle piece of metal is attached (glued, perhaps) to the knob of the first pot such that one flange is attached to the knob.
4. The second pot is mounted through a hole in the free flange of the bracket.
5. A knob is attached to the shaft of the second potentiometer.
6. A stick is glued to the second knob, directed upwards.

It should be possible to move the stick in both the **X** and **Y** directions, and the movement of the stick should result in rotations of the pot shafts.

Various other wierd and wonderful arrangements are possible. For example, one can envisage a steering wheel mounted on the end of a vertical shaft. Rotating the steering wheel steers the vehicle: moving the shaft forward and back controls the vehicle speed.

You should use pots which have a moderately stiff movement, so that the stick does not flop to one side when it is released. Ideally, it should stay in whatever position it is put.

---

[1] If someone does a nice drawing of this device, I'd appreciate being able to copy it!

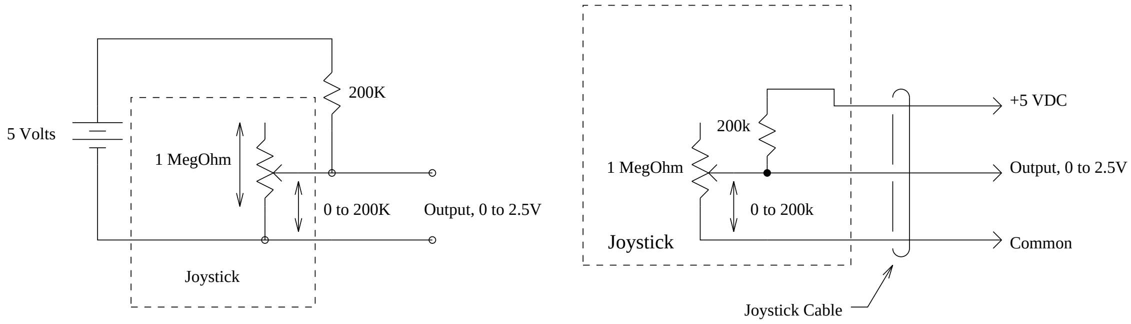
Measuring the Joystick Output

A normal potentiometer has a range of rotation of about 270 degrees, but the total amount of rotation of the pots used in a joystick is much less. This presents a potential problem, because the joystick output voltage must change significantly as the stick is moved in order to have fine control over the vehicle movement.

Put another way, what we want out of this exercise is a *measureable* control voltage into the A-D converter. The A-D converter is set up to convert a range of 0 to 5 volts into a count of 0 to 255. Thus, if we want a minimum change in reading of 100 counts, the voltage from the joystick pot must change by at least 1.96 volts. This can always be done, one way or another. With luck, this can even be done without requiring amplifiers.

Open up the joystick case and identify the two potentiometers. With an ohmmeter, measure the total resistance of the pots. (This is the resistance between the two outer terminals of the potentiometers.) In the prototype, this was about 1MΩ. Now connect the ohmmeter to measure between the centre pin and one of the outer pins, and move the joystick lever. Record the change in resistance. Repeat the measurement with the centre pin and the other outer pin. The combination of pins to use is the one with the largest change in resistance as a ratio, maximum to minimum resistance. In the prototype, the largest ratio of max to min resistance between two of the pins was 0 to 200KΩ.

To deal with this, in the case of the prototype, the wiring was arranged as shown in figure 24.



Test Circuit

Final Wiring

Figure 24: Joystick Pot Wiring

When the pot resistance is zero, the output voltage is zero. When the pot resistance is 200KΩ, the output voltage is 2.5 volts. The fixed 200K resistor was wired inside the joystick and the existing cable modified with a 0.1 inch spacing pin connector at the end, so the joystick could be plugged into a protoboard.

5.3 Testing The Analog-Digital converter

The A-D converter accepts the voltage signals from the joystick and generates a numeric value that can be read by the computer.

The next step in this exercise then is to test the A-D converters. Connect up the joystick and a 5 volt power supply to the A-D input connections of the computer as shown in figure 23 on page 50.

Start the computer with the QBasic BOOT disk in the floppy drive, and when QBasic has started, load in the test program shown in section 1.4, following page 79. Start this program and then move the joystick as the program is running. You should see a range of numbers representing the input voltage for the chosen channel. Note these down. The minimum value will be known as `AD_min` and the maximum value as `AD_max`.

Stop the computer program (press the `<ctrl>` and `<break>` keys simultaneously) and then edit the program to read the other joystick channel. Run the program a second time and note the range of input values obtained when the joystick is moved.

You now know the range of input values for each joystick, and can use this information in the design of the software, to *map* the input and output signals.

5.4 Testing The Digital-Analog Converter

The digital-analog converter does the reverse of the A-D converter – it converts a digital number in the computer to an analog voltage to drive the vehicle motors. Numbers from the computer range between 0 and 255, and the corresponding outputs from 0 to ≈5 volts. The output voltage for number N is [2].

$$V_{out} = \frac{N}{256} \times 5$$

To determine the maximum value of the output, you will need to know the voltage at the input of your controller (at the wiper of the pot in Exercise 3).

To test the D-A converter and motor controller, first connect them to the computer as shown in figure 23 on page 50. Keep the power OFF on the controller for the moment.

If you haven't already done so, start the computer with the QBasic BOOT disk in the floppy drive, and when QBasic has started, load in the test program shown in section 1.3, following page 76. This program ramps the output voltage over a range of values, which is not what we want. Edit the program so that it outputs one single value (maximum motor speed, for example) and then stops. Save this version of the program.

Now power up the controller with the vehicle attached. Run the program you just edited and the vehicle motor should run at full speed. Edit the program again, setting

---

[2] Actually, using this formula the output corresponding to number 255 is 4.980 volts: as we said, ≈5.

the output to half its maximum value. This time when you run the program the vehicle motor should run at half speed. Experiment until you have determined the maximum output you want from the D-A converter, and note that value down. In the development of the Control Algorithm, we'll need that value as `SPEED_MAX`.

Now check that the other motor channel can be controlled, and determine its maximum speed variable, in a similar manner.

Save the program: if the system stops working, it will be useful to check whether the D-A and motor controller subsystem are working properly.

5.5 The Control Algorithm

Now that both the input system, joystick plus A-D, and the output system, D-A plus motor controller, are known to be working correctly, it is possible to develop software to connect the two in the computer.

The primary function of the computer in this system is to determine the output motor control signals from the two joystick signals: technically, this is the *mapping* between these two sets of variables. The *algorithm* is the *set of rules* or *systematic procedure* that governs the production of the output signals from the inputs. The next challenge is to determine a suitable mapping algorithm.

We begin at the input of one of the channels: figure 25 shows the relationship between the A-D reading and the angle θ of the joystick on one of the input channels.

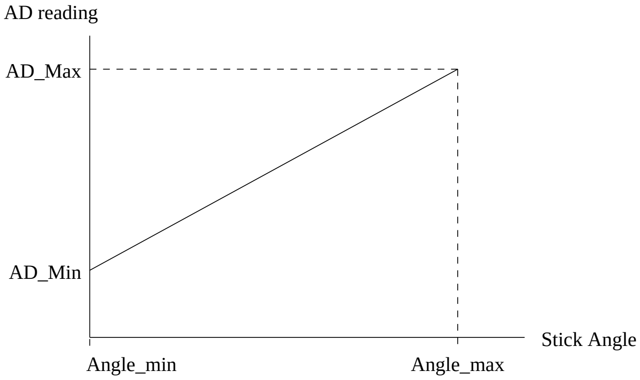


Figure 25: Joystick Output Function

The first step in the algorithm is to subtract out the Y intercept value, `AD_min`. This is applied to both the `speed` and `direction` signals from the joystick so that both functions pass through the origin as shown in figure 26.

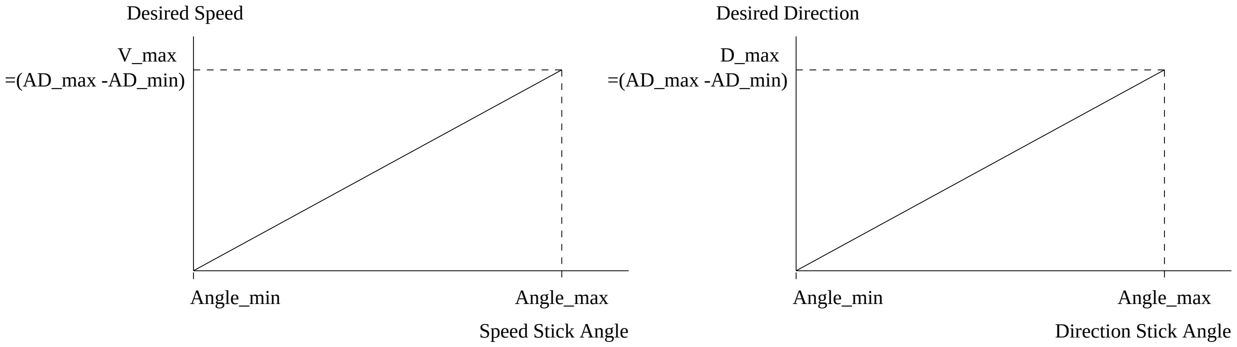


Figure 26: Joystick Output, Offset Subtracted: Speed Function

It will simplify things later if the functions shown in figure 26 are *normalized* so that the variables run from zero to 1, rather than zero to some arbitrary maximum. For example, in the direction function, this is accomplished by scaling the vertical axis in units of D/D_{max}: the results for both the speed and direction functions are shown in figure 27.

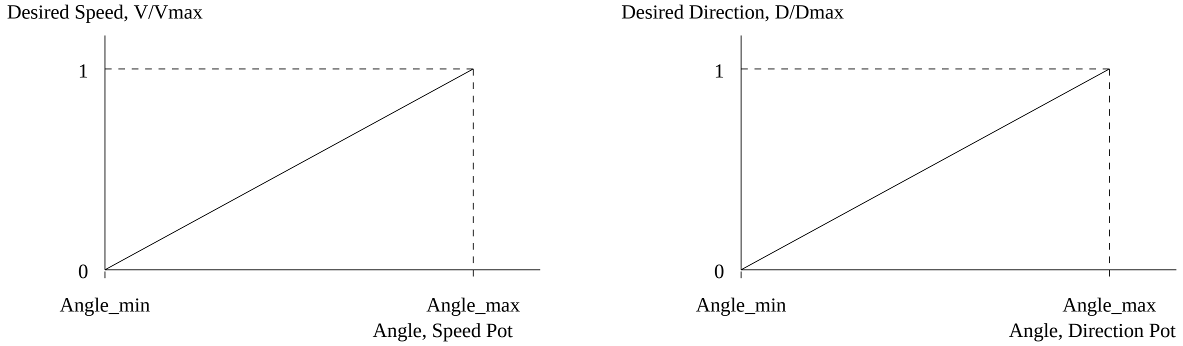


Figure 27: Speed and Direction Functions: Normalized

Now we are in a position to generate the signals `PORT_SPEED` and `STARB_SPEED` to specify the speed of the vehicle motors.

To accomplish this, we construct two new functions, `LEFT` and `RIGHT`, as shown in figure 28.

These functions describe how voltage should be apportioned to the two motors, based on the `DIRECTION` variable. When the `DIRECTION` signal is at centre, each motor gets an

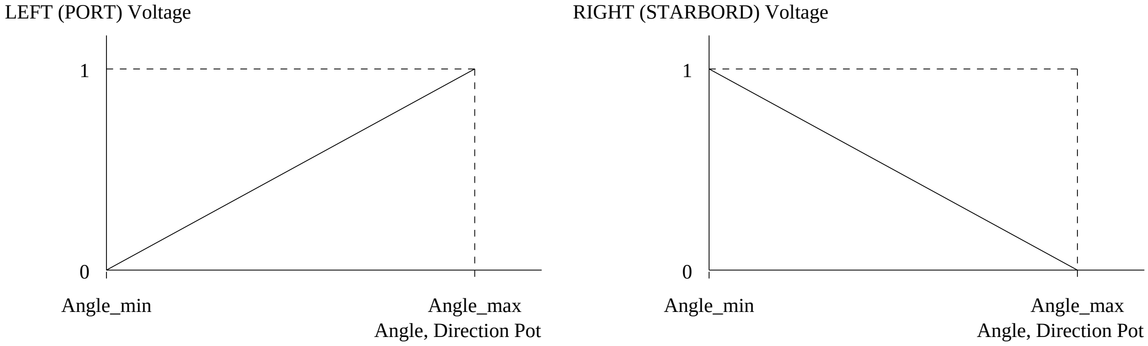


Figure 28: Direction Functions: PORT and STARBORD

equal amount of the power. If the `DIRECTION` signal moves to the right of centre, the port motor receives more power and the starbord motor less power. The effect is to cause the vehicle to turn to the right.

In formula form, the `PORT` signal is equal to the `DIRECTION` signal D

$$\mathrm{PORT} = D$$

The `STARBORD` signal is equal to $1 - D$:

$$\mathrm{PORT} = 1 - D$$

Now we can combine the direction and speed signals. The actual outputs to the two motors must also be *multiplied* by the speed, so that the motor speed is zero when the speed variable is zero. In formula form

$$\begin{aligned} \texttt{PORT\_MOTOR} &= \texttt{PORT}\times V \\ \texttt{STARBORD\_MOTOR} &= \texttt{STARBORD}\times V \end{aligned}$$

These signals run from zero to 1, but when they actually operate the motor controller we wish them to run from zero to some maximum value, so they must be *denormalized*. This is accomplished by multiplying the previous results by maximum motor speed variable, `SPEED_MAX`.

The value of `SPEED_MAX` will depend on the voltage required to operate the vehicle motor at full speed. For example, if the maximum output voltage was 2 volts, the value of `SPEED_MAX` would be

$$\begin{aligned} \texttt{SPEED\_MAX} &= \frac{2}{5} \times 256 \\ &= 102 \end{aligned}$$

(This is discussed more fully in section 5.4.)

Denormalizing the motor equations with this constant, we have

$$\begin{aligned}\texttt{PORT\_MOTOR} &= \texttt{PORT}\times V\times\texttt{SPEED\_MAX}\\ \texttt{STARBORD\_MOTOR} &= \texttt{STARBORD}\times V\times\texttt{SPEED\_MAX}\end{aligned}$$

When the `PORT_MOTOR` and `STARBORD_MOTOR` signals are converted from numbers to analog voltages, they will control the speed of the motors according to the signals generated by the joystick.

5.6 Algorithm Summary

1. Read the A-D inputs to determine the speed and direction control voltages.
2. Limit the voltages to the expected range of signals.
3. Subtract the offset (if any) from both these signals.
4. Normalize both signals by dividing them by their maximum values.
5. Generate the complement of the normalized direction signal.
6. Multiply the speed signal by the direction signal and its complement to generate the normalized port and starbord motor control signals.
7. Denormalize the port and starbord motor control signals: multiply them by the maximum motor voltage.
8. Limit these motor controller signals to the range 0 to 255.
9. Output the denormalized port and starbord motor control signals.

5.7 The Computer Program

In this Mechatronics project, we are using the QBasic language to write the control program. The reasons in favour of this choice were:

Simple Machines Suffice There are much better languages to use for this type of project, languages that are structured and support the generation of nice computer displays, such as Visual Basic or TCL (Tool Control Language). Unfortunately, these nice languages require the Windows95 or Unix (X Window) operating system, and this in turn requires a fairly powerful machine.

QBasic will run under the DOS operating system on the most simple hardware imaginable. Even a hard drive is not required: the program can boot off a floppy disk. This makes QBasic economical to provide in the lab.

It's an Interpreter Interpreted languages, such as QBasic, support a much nicer development environment than a compiled language, such as C. Under QBasic, to determine the value of a variable, simply halt the program and print out that variable in direct mode. The program can be modified and tried very quickly: make a change and re-run the program. The price to be paid for this convenience is that QBasic programs run much slower than compiled programs. In the days when computer hardware was slow this was a significant issue. In our case QBasic is fast enough and so speed isn't an issue.

It tells you when you're wrong When you type in a statement, QBasic will immediately tell you if the syntax of the statement is incorrect. In fact, it won't let you proceed until you fix it. When it detects an error in the operation of your program, it halts with an indication of the line where the error occurred.

Help available There is an extensive `HELP` facility included with QBasic, and you can read its entries to determine the syntax of the language.

Those are the advantages, but there are disadvantages. Most importantly, the QBasic language is not very structured. It's possible to make a spaghetti mess out of the program unless the program is carefully designed and structured. As well, large QBasic programs are not easy to read and maintain. Fortunately, this is a relatively short program, so limitations of QBasic are not insurmountable. We recommend the following rules:

Overall Structure Plan to use the overall `Main Loop` structure sketched out under *Computer Program* on page 49.

`GOTO` **Statement** Avoid the `GOTO` statement like the plague. You should need no more than one of these, to complete main loop.

Formulae A number of simple calculations are required to implement the control algorithm. It's tempting to combine them into one formula, but it's simpler to debug the program if the calculations are done in stages, each stage one small formula. Then you can track what's happening by printing out the various formula results.

Provide Displays Especially when first debugging the program, put lots of `PRINT` statements in your program. (You'll have to tinker with the `PRINT` statements so the screen display is neat and readable). You can comment them out later if you don't need them.

Test as you go Start with a small program. Test and debug it, and then add stuff, debugging as you go.

Variable Names Use informative names for the variables. A variable name of `X` means nothing: a variable name of `DENORM_PORT_V` (for denormalized port motor voltage) conveys some information.

Variable Type QBasic supports several types of variables - strings, floating point numbers and integers. In our case, all the numbers are derived from and destined for binary registers, such as the 8 bit output register of the D-A converter. The most suitable variable to use in this environment is the *integer*, which is indicated to QBasic by a % suffix. You can see this in use in the hardware test programs of the Appendix: I/O Board Specifications on page 74 and following.

Boolean Operators In this type of control program, you must input and output various binary words, in which the bits are to be set or cleared. You *must* understand the effect of writing to a particular machine register, and how to change certain bits in that register without affecting the other bits. The relevant operators are `AND`, `NOT`, `OR` and `EOR`.

Program Defensively Expect the worst and design the program to check for errors. For example, if you know that the maximum expected input number from the A-D converter is 128, check that the input is between 0 and 128 in that part of the program. Then, if the joystick wiring fails and the input voltage goes up to +5 volts, the A-D reading will pop up to 255 but the program will recognise that an error has occurred and signal that to the operator.

If you haven't programmed in QBasic before, there are a few books in the library and in computer bookstores. However, QBasic is like pointy shoes: it's considered to be out of fashion in the computer world, and you'll have to dig for information.

5.8 Applications of Computer Control

It is challenging to install a computer between the operator controls and the motors of the vehicle. However, once that is in place and has been debugged, it is very easy to modify and enhance the performance of the control system by changing the features of the software.

In this exercise we improved the operator interface by building software to deal with signals from a joystick. We could do many other things with this control system:

- Make the control response *non-linear* to compensate for deficiencies in the hardware.
- Install *time constants* so that the vehicle accelerates and de-accelerates smoothly.
- Provide various status displays and readouts of the vehicle operation.

- Further improve operator control with, for example, `HIGH SPEED` and `LOW SPEED` modes of operation. In `LOW SPEED` mode, the vehicle can be manoevred precisely, and being able to switch to `HIGH SPEED` mode mimics the effect of a vehicle transmission.

All of these features could be added by modifying the software. In an industrial environment, these features constitute *value added* to the product. They require certain engineering development costs for the additional software, but the incremental (per unit) cost of software in a product is very close to zero. Consequently, it is very attractive for a manufacturer to be able to enhange a product with software features.

Exercise 6: Fully Automatic Guidance

In this final exercise, we configure the computer to guide the vehicle entirely automatically. Stand back and watch your vehicle guide itself around the course!

6.1 Guider Signals

To accomplish this, the computer must have reliable guidance information from the section guidance system constructed in Exercise 3, Optical Line Sensing.

In that exercise you will recall that an array of three light emitting diodes illuminated the roadway and a second array three light emitting diodes detected the reflected light. The amount of light reflected off the red guidance tape is much larger than the amount reflected off the flat black background, and this information was used by the human operator to guide the vehicle.

To automate vehicle guidance, we could simply direct the signals from the three detectors into three channels of the A-D converter. The computer would read the detector signals and compare the signals to a fixed threshold: if the signal is above threshold, the background is red. If it is below the threshold, the background is black. Guide the vehicle accordingly. However, there is a potential problem here: background light.

Consider the illumination that a given detector receives: it could be from its illuminator LED, **or** it could come from the room ambient light, or some combination of the two. We are not interested in the total light into the detector: we want to know *how much of the light from a given source is reflected into its corresponding detector.* This may be accomplished in the following procedure

- switch LED source 1 off
- measure the output from LED detector 1 (V_1, say)
- switch LED source 1 on
- measure the new output from LED detector 1 (V_2)
- subtract V_1 from V_2 to get the detector signal due to the LED source.
- repeated this process for the other two source-detector pairs.

Under this system, if one of the source LEDs fails for some reason the output from the corresponding detector, after subtraction of the background, is zero or very close to it. If the background is not subtracted, the output is non-zero, even when the source LED is off. Subtracting the background light thus provides a reliable way of checking that a given source LED and its corresponding detector are functioning.

Why not turn operate all the LEDs at once? If all the LEDs were on at the same time, some light could leak from a source into an *adjacent* detector LED, as well as the desired (*corresponding*) detector LED. By actuating the sources one at a time, the detectors can discriminate between light from their own source and light from an adjacent source.

As you might expect by now, turning the source LEDs on and off may be done by the computer. We could use 3 of the the 4 relays on the I/O board for this. However, the digital outputs are more appropriate, since the switching must occur frequently, and frequent switching of a relay will wear out the mechanical contacts. An all-electronic solution is preferable.

For that to work, however, we have to ensure that a digital output can drive a guider source LED. The basic digital output circuit that we would use to drive an LED is shown in figure 29.

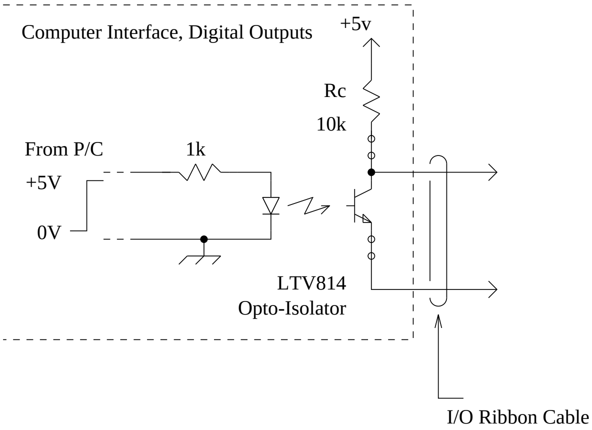


Figure 29: I/O Interface, Digital Output Circuit

A little thought along the following lines establishes that this circuit cannot drive an LED directly:

- The opto-isolator LED is driven from 5 volt logic signals, resulting in about 4mA forward current in the opto-isolator LED.
- According to the data sheet for the LTV814 Opto Isolator, the CTR (Current Transfer Ratio) is 20% worst case, in which case the collector current in the opto-isolator transistor would be about 0.8mA.
- The maximum current through the 10k collector resistor R_c is 0.5mA (5 volts minus V_{cesat} (V_{cesat} is ≈ 0) divided by 10k).

- So: although the output of the opto-isolator will switch from zero to +5 volts into an open circuit it can only source about 500μA or sink about 800μA.
- The vehicle guider LED requires about 10 times this much current to operate properly, so a transistor amplifier is required.

After noodling around with various amplifier configurations, a suitable amplifier circuit arrives in the form of figure 30.

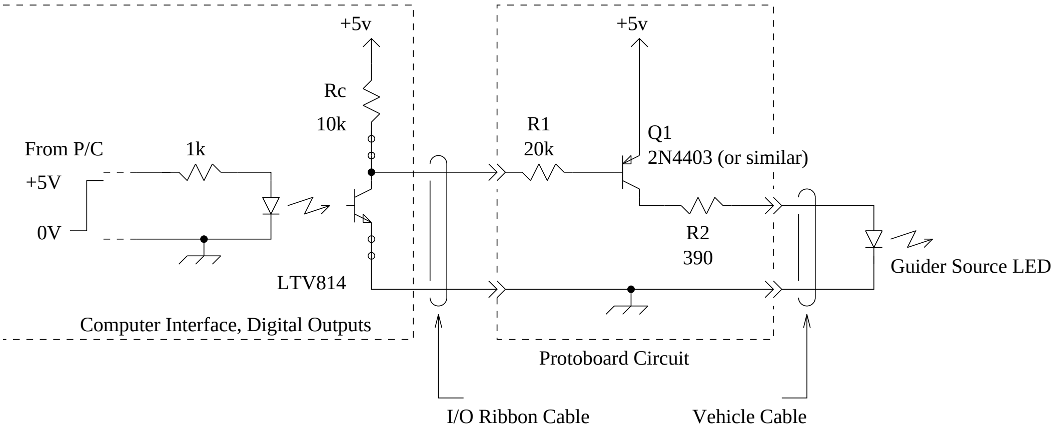


Figure 30: Concept: Computer Control of Source LEDs

The control signal, zero or +5 volts, arrives from the computer and actuates the opto-isolator LED. The phototransistor part of the opto-isolator is activated whenever the opto-isolator LED is `ON`. When the opto-isolator transistor is `ON`, it allows base current to flow in transistor Q1, which causes the vehicle guider LED to turn `ON`. Thus a logic 1 (+5 volts) from the computer turns the vehicle guider LED `ON`.

A complete wiring diagram, showing pin numbers of the Digital Output cable, is shown in figure 31.

6.2 The Guidance Algorithm

Now that we have a reliable detection of the guider tape, one hopes, we can turn our attention to the rules governing the guidance of the vehicle. For reference, typical outputs from the guider are counts of 38 for black background and 172 for red background.

Some typical patterns of guider signals are shown in figure 32.

First of all, we can deal with some *pathological* cases, which should be flagged as errors.

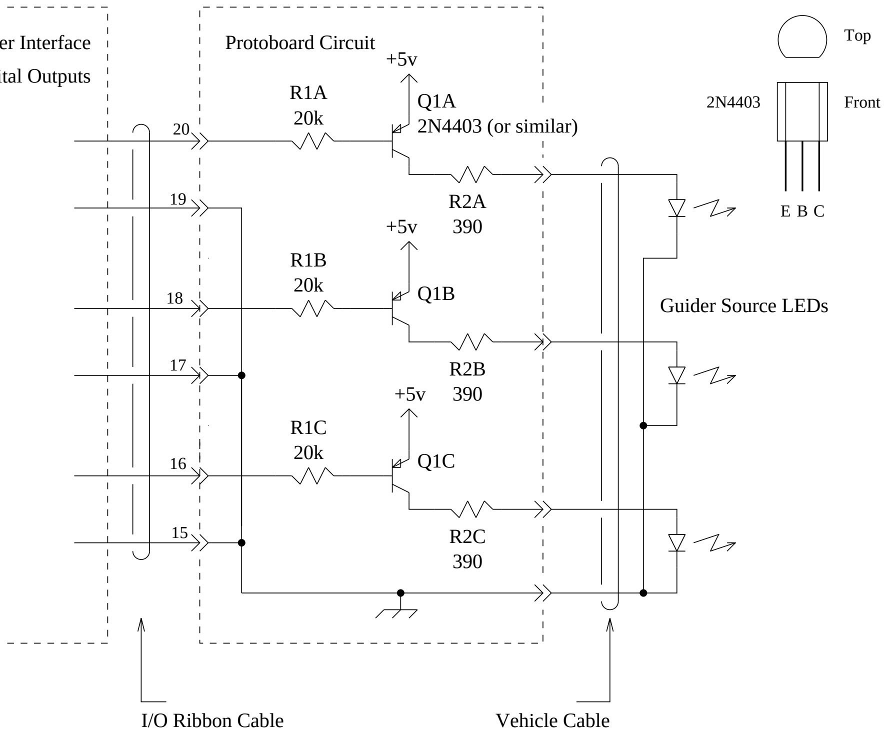


Figure 31: Computer Control of Source LEDs

- If the output from any of the detectors is below a certain threshold, something is wrong: one of the detectors is defective.
- There is no reason to expect an output to go higher than usual, but we can easily check for that as well, and flag it as an error case.
- If no output is significantly different from the other outputs, then the vehicle has lost track altogether and none of the detectors is over the tape.

In all these cases, the vehicle should stop and ask for help.

Now, determining the guidance signal: if a sensor output grows larger, that sensor is moving over the guidance tape. In the first two patterns of figure 32, we can readily determine that the vehicle is over the tape, but slightly to one side or the other. How can we quantify this?

One possible method would calculate the *centre of gravity* of the pattern in the horizontal direction, as shown in figure 33.

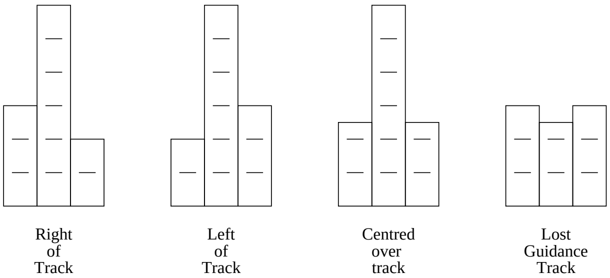


Figure 32: Typical Guider Signals

The shaded portions each exert a turning moment about the origin equal to the product of their area and their horizontal distance from the origin, that is:

$$\text{Turning Moment}_x = 0.5 \times 3 + 1.5 \times 2 + 2.5 \tag{8}$$

This is equivalent to a total concentrated 'mass' of 10 units acting at the horizontal component of the centre of gravity:

$$\text{Turning Moment}_x = 10 \times CG_x \tag{9}$$

Then, in general, the centre of gravity CG_x is given by the sum of the individual moments divided by the total area, or in general:

$$CG_x = \frac{0.5H_1 + 1.5H_2 + 2.5H_3}{H_1 + H_2 + H_3} \tag{10}$$

If the pattern is symmetrical about the middle column, the CG_x will be 1.5 units. Considering this signal as the *feedback signal* in a negative feedback system, we should *compare* (subtract) it from a reference signal. In this case, on the centre line is 1.5 units, so this should be our reference.

The result of this subtraction is the error signal ϵ of the negative feedback system. We'll call this the *direction* signal D.

For example, the direction signal D for the first pattern in figure 32 is

$$\begin{aligned} D &= \frac{0.5H_1 + 1.5H_2 + 2.5H_3}{H_1 + H_2 + H_3} - 1.5 \\ &= \frac{0.5 \times 3 + 1.5 \times 5 + 2.5 \times 2}{3 + 5 + 2} - 1.5 \\ &= -0.1 \end{aligned}$$

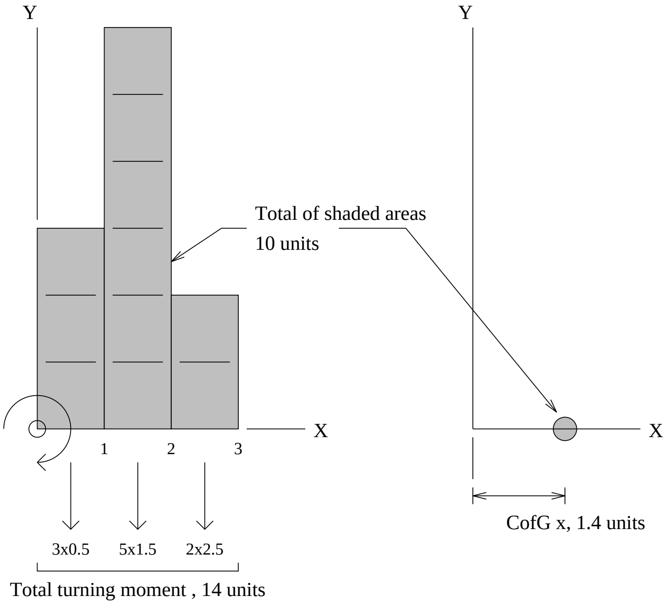


Figure 33: Centre of Gravity Guidance Concept

This should be interpreted as the CG_x being slightly to the left of the centreline and the vehicle should correct by steering slightly to the right[3].

If we add the direction signal D to 1, then we have a signal which varies around the value of 1, and can essentially be dropped into the same type of directional control system used in Exercise 5, Computer Assisted Guidance.

6.3 Algorithm Summary

1. Read three A-D input channels to determine the guider signals.
2. Subtract out the background illumination as described in section 6.1
3. Calculate the *centre of gravity* of the guider signals as described in the previous section.
4. Compare this with the reference signal, 1.5 units, generating the system direction signal D.
5. Generate the complement $1 - D$ of the direction signal.

---

[3] It's interesting to discover that this equation is simple enough that it could be implemented with analog circuits. However, we'll stick with the digital solution here.

6. Multiply the normalized speed signal (it runs from 0 to 1) by the direction signal and its complement to generate the normalized port and starbord motor control signals.
7. Denormalize the port and starbord motor control signals: multiply them by the maximum motor voltage.
8. Output the denormalized port and starbord motor control signals.
9. Check if any key is pressed and if so, modify the appropriate variable, such as the `SPEED` setting.
10. Update the screen displays.

6.4 Setting the Vehicle Speed

We have no joystick or potentiometer to set the vehicle speed in this fully automatic system. For the vehicle to track the guidance tape accurately and reliably, the vehicle speed should be slow. One possibility is to use the computer keyboard to control vehicle speed. Pressing the + key increments vehicle speed, pressing - decreases the speed. The QBasic `INKEY$` instruction is useful in this regard.

The instruction to read the keyboard should be part of the *main loop*, and should not wait for input: it should read the keyboard, check for a keypress, handle the keypress if there is any, and continue on. Otherwise, vehicle control will be lost while waiting for operator input!

While you're at it, you should program in keyboard commands that `stop` and `start` vehicle motion.

6.5 System Readouts

Readouts of the system operation can be very useful in diagnosing system faults and, let's face it, they're fun to watch.

Your software should read out the vehicle sensor voltages, `SPEED` value and the values of the two motor outputs, at a minimum. Graphical formats are nice, but numeric readouts are acceptable. Each readout should be labelled, and readouts should repeat in the same location of the screen, not scroll endlessly off the bottom of the screen[4].

---

[4] Believe it or not, one of the main readout devices at the Three Mile Island nuclear reactor was a line printer with numeric readouts that were printed in columns on paper. This goes a long way to explain how the near-meltdown occurred.

6.6 Motor Interface

The wiring and operation of the motor interface is identical to the system used in Exercise 5, Computer Assisted Guidance, and is shown in figure 23 on page 50.

6.7 Steady State Errors and Oscillation

This system constitutes a negative feedback system in which the output, vehicle position, is compared with a desired value (1.5). The difference between these two generates an error signal. The error signal modifies the output by raising or lowering the voltage to one of the vehicle motors.

Feedback theory tells us that raising the forward gain of the system (the amount by which the error signal is amplified to produce an output) will reduce the steady-state error. However, in this system, the positional error is the result of the total rotation (total shaft angle) of a vehicle motor. (Positional error in this system is actually proportional to the difference between the total shaft angles accumulated by the two driving motors, but the net result is the same.) Shaft angle is the integral of motor speed, and motor speed in proportional to motor voltage, so this system inherently contains an integrator in its plant. The steady state error of an integrator is zero, so the vehicle should ultimately track on the centre line of the guidance tape. Thus, raising the plant gain will affect the time constants of the system (how quickly it can respond to a change in vehicle path, for example) but should not affect the steady state tracking error.

Systems with a large gain around the feedback loop, accompanied by time delays or phase shifts around the loop, may cause *hunting* or *oscillation*, and this is completely unacceptable. An integrator in the plant contributes 90^o of excess phase shift, and this reduces the stability of the system when the plant gain is large.

All systems have some time delays: they are not infinitely fast. This particular feedback system has significant delays, particularly those caused by the mechanical inertia of the vehicle and its motors. If you find that the vehicle hunts, reduce the magnitude of the direction feedback signal D.

If decreasing D results in unacceptable dynamic performance (ie, tracking a curve is not successful), then a more sophisticated controller will be required. This is where a computer-based system shines: it is very simple to tinker with the control algorithm.

Appendix 1: DC Power Supply Designs

You may wish to do some of the testing of your controller at home, in which case you will need a 5 volt DC power supply. The power supply should be regulated and be capable of an output current of one amp (to run one motor) or two amps to run both motors.

These requirements rule out the 'wall adaptor' power supplies. They usually don't have enough current and their output voltage varies dramatically with current.

Regulated 5 volt DC power supplies are common on the surplus market. The ideal is a supply that will put out 5 volts and is current limited at about an amp of current. Get the vendor to test the supply before purchasing, if you can.

The supplies from old PC computers can put out +5 volts and +/-12 volts as well, often at several amps. One problem with these supplies is that the 5 volt output is capable of *many* amps, so a short circuit can be very destructive.

If a 12 volt supply, such as a battery eliminator, is available, it may be regulated down to +5 volts with a few electronic parts, and this will work very well. The regulator IC will need a large heat sink to disappate the power from the 7 volt drop times the output current.

1.1 A Five Volt, One Amp DC Power Supply

For those who are interested in constructing their own 5 volt DC power supply, this section contains the outline of a simple design. This particular design was based on parts that were available from the author's junk box. You could simply duplicate this circuit, purchasing the parts at Electrosonic Supply. However, by scrounging in electronic surplus stores for parts, you will reduce the cost considerably.

The schematic of the power supply is shown in figure 34.

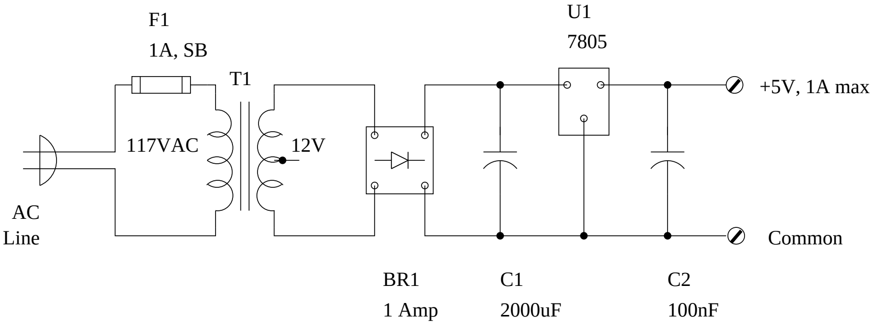


Figure 34: Five Volt DC Power Supply

This supply can deliver over 1 ampere continuously and is protected against short circuit overloads, so a short circuit will not destroy the power supply nor will it cause excessive current in the load under short circuit conditions.

Some notes on the parts used in the power supply:

Transformer T1 This is the most critical component in the power supply. You need a transformer which will step down the 117VAC line voltage to about 8 volts. I used a Hammond 166J12, a 12 volt 1 amp transformer which I had on hand. Purchased new from Electrosonic Supply, this part is about $20. Any transformer putting out between 8 and 12 volts at 1 amp should be satisfactory. Anything less than 8 volts will not drive the regulator IC reliably.

It is also possible to use a transformer with a centre-tapped secondary where the secondary voltage is equal to twice the required voltage. In this case, anything from 16 to 24 volts would work. The transformer will be bigger and heavier than the non-centre-tapped version, but it will work correctly. The rectifier configuration changes: you must use the *half wave bridge* configuration shown in figure 35 with two, one amp rectifier diodes (D1,D2) replacing the full wave bridge.

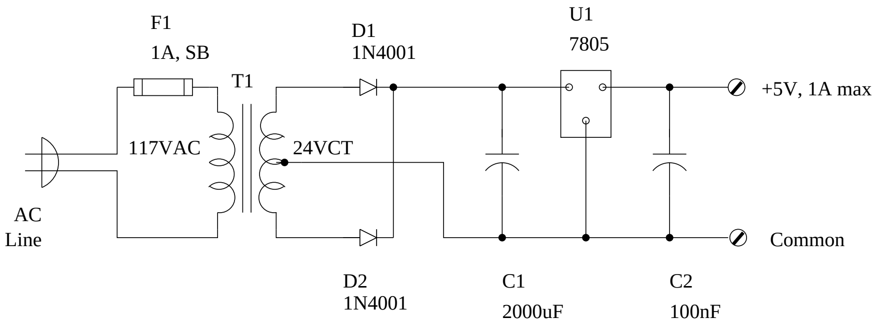


Figure 35: Power Supply using Half Wave Bridge

Fuse F1 The line fuse is shown as a 1 amp slow blow type, and you may also need a fuse clip to mount it in. Current in the secondary of the transformer is about 1 amp maximum and the current in the primary is stepped down by the ratio of 12/117, so the primary current should never get near one amp in practice. The line fuse simply protects against a catastrophic failure such as the transformer failing with a primary short circuit.

Bridge Rectifier BR1 The bridge changes the AC at the transformer secondary into full wave rectified current at its output. A one amp bridge is sufficient. Take care with the wiring of the bridge: the DC outputs are marked with + and - symbols. The AC input terminals may be unmarked or marked with ˜ symbols.

Filter Capacitor C1 To ensure that the ripple voltage is reduced sufficiently, conservative value for the filter capacitor is about 2000 μFarads. The voltage rating must be in excess of the peak value at the output of the bridge, which is about $\sqrt{2}$ times the transformer secondary voltage. A value of 25 volts is safe. I found 2, 1000 μFarad 25 volt capacitors, so I wired them in parallel.

Voltage Regulator U1 The 7805 voltage regulator is a marvel of modern electronic technology. It takes in any voltage between 8 and 35 volts DC and puts out a regulated 5 volts that does not change with output currents from 0 to over 1 amp, all this at a cost of under a dollar (CDN). However, the regulator must be suitably cooled to keep its internal junction temperature below its maximum. Calculations indicated that with a 12 volt transformer, the heat sink area should be about 18 inches^2. A lower voltage transformer would allow a smaller heat sink. The Wakefield type 401K is a suitable heat sink, available from Electrosonic Supply for about $7. The tab of the 7805 is connected to the center (ground) terminal, so it may be bolted directly to the heat sink.

Capacitor C2 It's good practice to put a small value capacitor (100 nanoFarads, for example) across the output of a voltage regulator, in order to improve it's regulation at higher frequencies.

1.2 Constructing and Testing the Power Supply

A sketch of the prototype layout is shown in figure 36

Notes on the Construction

- As shown, the 117 VAC wiring is exposed to provide clarity in the circuit wiring. However, in this state it is exposed also to human contact. **You must insulate exposed 117VAC contact points or provide an enclosure to prevent human contact or a metal short circuit at these points. A 117VAC electric shock or short circuit can be very dangerous.** As well, the line cord should be attached with a *strain relief* so that a pull does not detach it from the circuit.

- Components were mounted to the 1/2" plywood base with #6 x 1/2" round head Robertson screws.

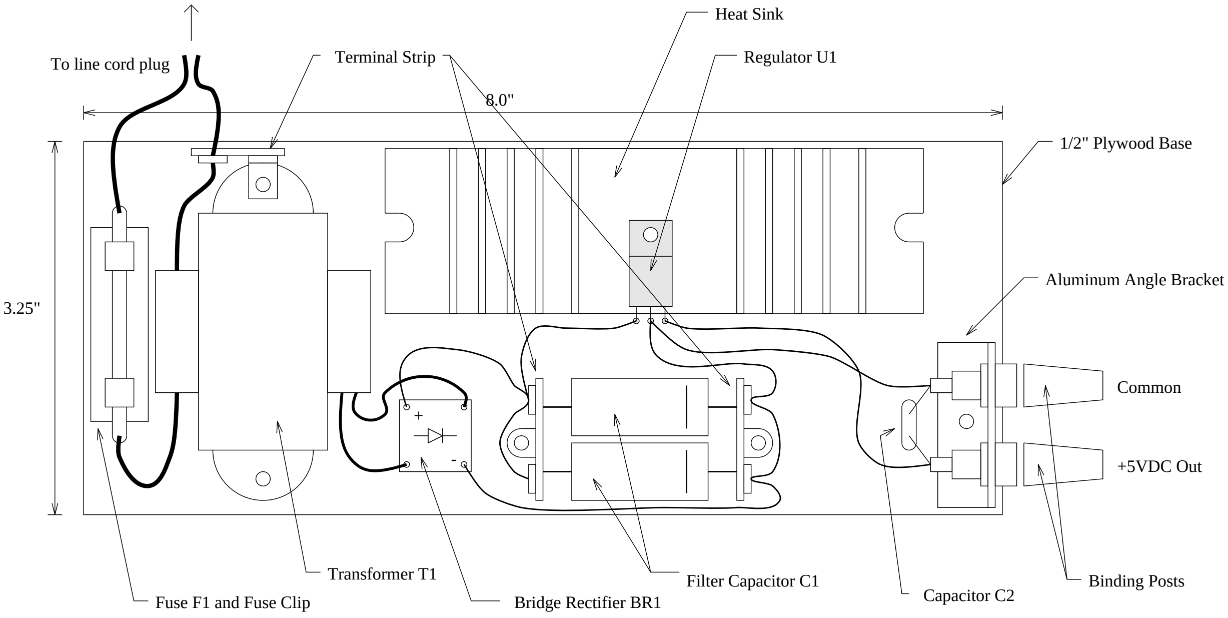


Figure 36: Five Volt DC Power Supply Layout

- The terminal strips are by Cinch Jones, and consist of several terminals mounted on an insulated support strip, with a screw hole mounting tab. They are very useful and inexpensive for this type of project.
- The aluminum angle used to mount the binding posts is available from Home Depot and other suppliers.

Testing the Supply

Before plugging the supply into a wall socket, check the resistance between the blades of the line cord. On the prototype, the resistance was about 30Ω. If you read a short circuit, the wiring is incorrect or the transformer is defective: fix this before proceeding.

Double check the polarity of the electrolytic capacitors and the wiring of the bridge rectifier before plugging in. A wrong polarity will lead to *sturm unt drang* (thunder and lightning).

If you have access to an adjustable line transformer (Variac), you can gradually bring up the line voltage from 0 to 117 volts while monitoring the voltage across the filter capacitor C1. It should increase proportionally with the line voltage[5].

---

[5] Your instructor can provide this equipment and would be happy to help inspect and test the supply.

In the absence of a Variac, stand well back and plug in the supply into the line.

Finally, check the output voltage: it should be 5 volts, plus or minus a few millivolts. If you have access to a 5 ohm resistor that can dissapate at least 5 watts, you might wish to connect it to the output of the supply to test its operation at full current. The output should remain very close to 5 volts. Leave the load connected for a few minutes and monitor the temperature of the transformer, bridge and heat sink. Nothing should become more than warm to the touch.

1.3 Variable Voltage and Other Wrinkles

A power supply in which the output voltage is adjustable, making it much more useful, is shown in figure 37.

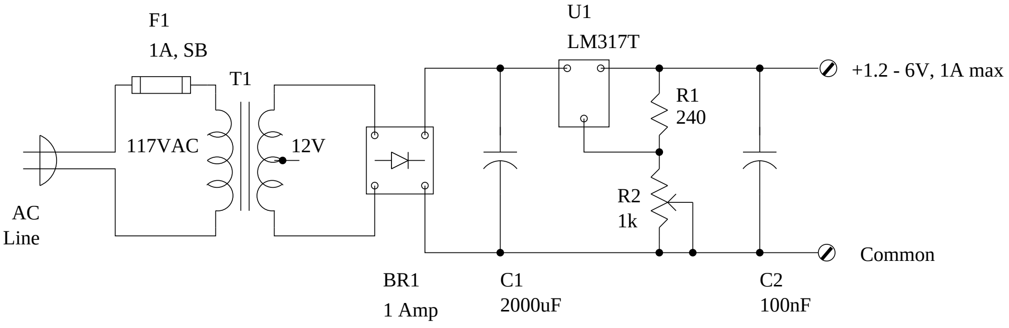


Figure 37: Adjustable Output Power Supply

The output voltage is adjustable between 1.2 volts and some maximum value determined by other components in the circuit. Providing that the DC voltage across filter capacitor C1 is at least 2 volts above the output voltage, the output voltage is given by the formula

$$V_{out} = 1.25\left(1 + \frac{R2}{R1}\right)$$

Resistor R1 must remain at 240Ω. For example, with the components shown, the maximum adjustable output voltage is 6.45 volts and the voltage across capacitor C1 must not drop below 8.45 volts. Unfortunately, making the supply adjustable down to zero volts is much more complicated, so we will leave that for another book.

The power supply could be improved in a number of ways:

- Put it in a metal *handi-case*, such as a Hammond 1411 series Aluminum Utility Case, available from Electrosonic Supply and others.

- Use a *cartridge* fuse holder to better insulate the line voltage terminals from being touched.
- Put an LED-resistor indicator, wired across the output voltage, so that there is some indication when the power is on.
- Add an on-off switch.
- The output current could be increased to 2 amps, provided the transformer is a 2 amp device, the bridge rectifier is a 2 amp device, the filter capacitor C1 is doubled in capacity, and the regulator is changed to an LM350T. If the power supply is to deliver 2 amps continuously, the heat sink size should also be increased. All of this will send the cost up to some extent.

Appendix 2: I/O Board Specifications

1.1 Overview

This section of the laboratory manual includes specifications and descriptive material on the operation of the computer I/O board.

The I/O board provides facilities for the the computer to read external electronic sensors and provide control signals back to electronic devices such as the motors in our vehicles. These input-output devices and their applications in this project are as follows:

- 4 SPDT relay outputs for controlling the direction of motors
- 8 analog input channels measuring sensor and steering potentiometer voltages
- 2 analog output channels for controlling the speed of the vehicle motors

In addition to the above, there are 8 switching transistor outputs for turning various devices on-off, but this is not used in this project.

The I/O board is mounted inside the P/C. It connects to the outside world via ribbon cables, each of which terminates in a small *adaptor* board that plugs into a student protoboard. There are either 10 or 20 numbered pins on the adaptor board which connect to circuits on the I/O board. The pin numbers on the adaptor board are shown on the wiring diagram for each input and output circuit: see for example figure 38 on page 75.

The various outputs may be controlled with `OUT` instructions from a QBasic program. Similarily, inputs may be read with `INP` instructions. In both cases, the student specifies what value is to be sent to which register location. When the computer executes that instruction, the output is controlled accordingly.

Output values are *latched*, that is, contained in a memory that stores the output until it is changed with the next `OUT` instruction.

1.2 Relay Outputs

The wiring of the relay outputs and the bit assignments in the memory map are shown in figure 38.

For example, if the value of '4' is written into location $300 of the PC memory, relay #3 will be actuated and a connection will occur between pins 4 and 6 of the ribbon connector.

A QBasic program to test the relay outputs is shown below:

```
'RELAYTST.BAS
'This is a test program which exercises the relay outputs
```

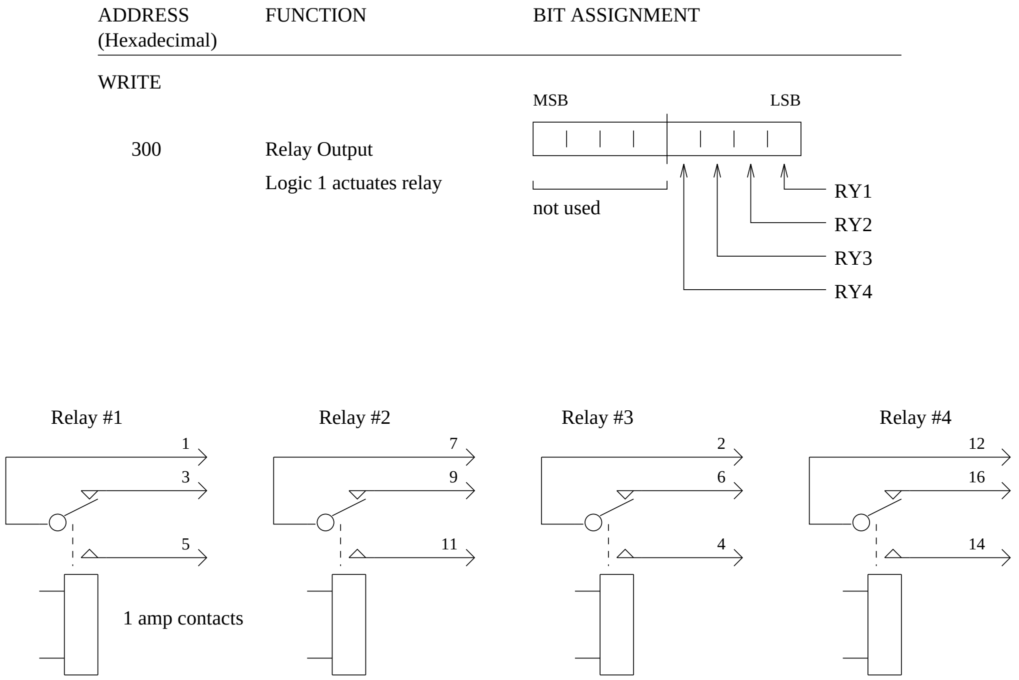


Figure 38: I/O Board: Relay Outputs

```
' of the PC I/O board.
'
'Address 300: Relay output
'
'Connect ohmmeter to the normally open contacts of the
' relays and run this program with different values in
' the data. Check that the relays operate when their
' bit is a 1.

relay = 1 'relay data, 1,2,4 or 8
OUT &H300, relay
```

If you're typing this program into a machine, the only important lines are the last two.

To test the operation of a relay, connect an ohmeter between the contacts of that relay by attaching the ohmmeter to the corresponding pins of the ribbon connector.

Load this program into the QBasic interpreter and then edit the relay data statement appropriately. Run the program, the relay should actuate (if you listen carefully you can hear it click when it closes or opens) and this should be indicated by a short or open on the ohmmeter.

Design Exercise: Relay Outputs

Design the wiring connections between a vehicle DC motor, two computer-operated relays, and a 3 volt battery such that the computer can control the direction of the DC motor.

Write a QBasic program that actuates the relays such that an **f** keypress causes the motor to run in one direction, a **b** keypress causes it to run in the other direction, and an **s** keypress causes the motor to stop.

The program should loop continuously, reading the computer keyboard and operating the output relays.

1.3 Analog Voltage Outputs

The analog outputs provide a voltage proportional to an 8 bit word inside the computer and are capable of supplying +/- 2.5 volts or 0 to +5 volts to an external load. However, the source of the voltage is a low current op-amp (LM358), so the analog output cannot supply appreciable current to a load resistance.

One extreme of output voltage corresponds to the 8 bit value `11111111` and the other extreme to the value `00000000`. The analog output is isolated from the computer ground, so the analog output ground may be connected to the student circuit without danger of damaging the internals of the computer. (That's the theory anyway...).

There are several complications in using the Analog output channel, which are dictated by the design of the hardware[6].

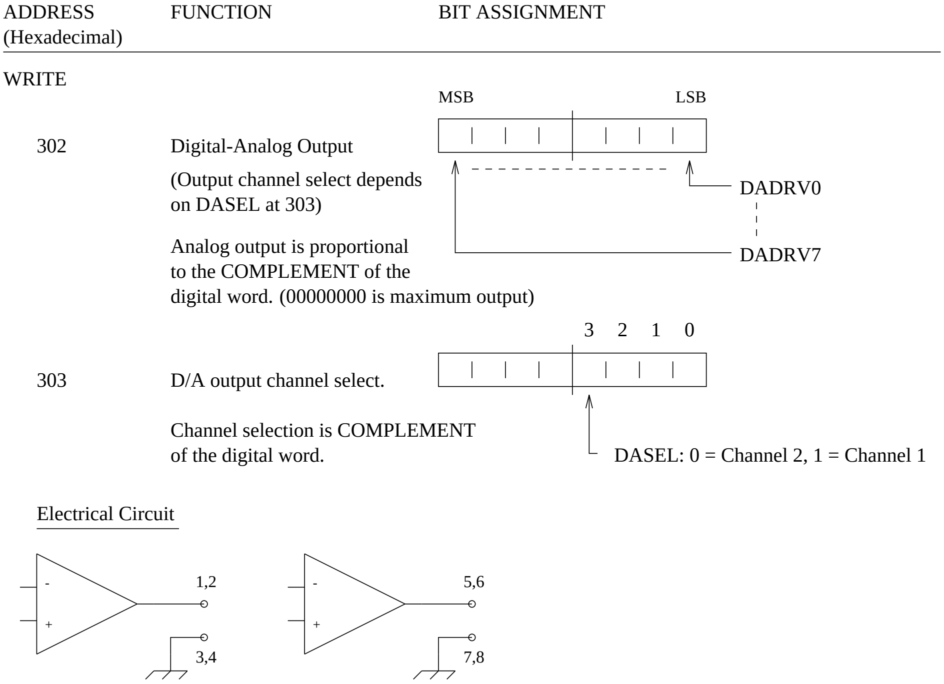
The wiring of the 2 analog outputs and the bit assignments in the memory map are shown in figure 39.

The first complication is that the output channel must be selected before a voltage is assigned to that channel. To select channel #1, write a 1 into bit 3 of the register at &H303. To select channel #2, write a 0 into bit 3 of that register.

The output voltage is determined by the value written into location &H302. The normal convention is that a binary value of zero (`00000000`) corresponds to zero volts output, and a binary value of 255 (`11111111`) corresponds to +5 volts output. However, in this case, they are the other way around: 255 causes an output of zero volts and 0

---

[6] No, we didn't deliberately set out to make it complicated, we really had to do it this way, mainly because of the limited area on the I/O board.



ADDRESS (Hexadecimal)	FUNCTION
WRITE	
302	Digital-Analog Output (Output channel select depends on DASEL at 303) Analog output is proportional to the COMPLEMENT of the digital word. (00000000 is maximum output)
303	D/A output channel select. Channel selection is COMPLEMENT of the digital word.

Figure 39: I/O Board: Analog Outputs

an an output of +5 volts. In practice, this is easily taken care of in the software by outputting $255 - x$ in place of x. Once this problem is sorted out, can be ignored.

A test program for the analog outputs is shown below:

```
'DATEST.BAS
'This is a test program which exercises the D/A Converter.
'Address 302: D/A output data
'        303: A/D input select and D/A output select
' assuming a base address of $300

'DA output channel select is bit 3 (weight 8) at $303.
' Binary 1 in this bit selects channel A
' Binary 0 in this bit selects channel B

'To halt the program, press <ctrl><break> (the 'pause' key)

'Select the channel
```

```
channel% = 8          '8 = ChA, 0 = ChB
OUT &H303, channel%  'This clobbers the ADSEL bits in the same register

'Repeatedly ramp the A/D output from maximum down to minimum.
j% = 0
adloop: OUT &H302, j%
j% = j% + 1
IF j% > 255 THEN j% = 0

'Delay
FOR m = 1 TO 1000
NEXT m

\Do it again
GOTO adloop
```

As the documentation says, the program repeatedly ramps the output from its maximum value, +5 volts down to zero. To make the program ramp upward, you would change the statement

```
 OUT &H302, j%
```

to

```
 OUT &H302, 255-j%
```

The two lines

```
FOR m = 1 TO 1000
NEXT m
```

set the speed of the ramp. Change this statement to change the speed of the ramp.

In a real program, a better method of selecting the channel would be required, using the `AND`, `OR` and `NOT` operators in the QBasic language. The line

```
channel% = 8          '8 = ChA, 0 = ChB
OUT &H303, channel%  'This clobbers the ADSEL bits
```

has the effect of clearing the other bits in the same register. These bits are used for the Analog Input selection, so they should not in general be disturbed by some other routine.

Design Exercise: Analog Outputs

Analog output from a computer has a number of applications:

Waveform Generation Write a QBasic program to generate a sine wave, minimum value 0 volts, maximum value +5 volts.

Controllable Power Supply Write a program to read the keyboard and, if a + key is pressed, increment the output voltage. If the **-** key is pressed, decrement the output voltage. Attach a voltmeter to the output and observe that the output behaves as predicted. The program should loop continuously, reading the computer keyboard and operating the output relays.

Triggerable Controller There are many applications in industry where a particular control signal is required when triggered. For example, a system might require a ramping voltage to drive a hydraulic servo system, whenever triggered. Write a program to watch the keyboard and, whenever any key is pressed, the program generates a sequence of voltages starting at zero and ramping up to +5 volts. At the conclusion of the ramp, the voltage resets back to zero.

1.4 Analog Voltage Inputs

The wiring and bit assignments for the 8 analog input channels are shown in figure 40 on page 81.

The analog inputs accept a voltage of +/- 5.0 volts and generate an 8 bit word inside the computer. One extreme of input voltage corresponds to the 8 bit value `11111111` and the other extreme to the value `00000000`. Normally, the voltage to be measured is connected to the + input of the differential amplifier on the chosen input channel, and a ground return wire is connected to the **-** input of the same channel. **Because the input circuit is a differential amplifier, a ground return must be connected to each input - terminal: one input ground return is not sufficient for several input channels, as would be the case for single-ended inputs.**

Because the analog input is *differential*, the input voltage can be measured across a floating voltage source. However, the maximum input voltage range of the op-amp must not exceed +/-5 volts. The analog input circuitry is isolated from the computer ground by opto-isolators so the analog output ground may be connected to the student circuit without danger of damaging the internals of the computer.

The input channels are *multiplexed*: they share a common A-D converter. Consequently, only one channel can be read at any instant, and that channel must be selected by writing the appropriate value into the lowest three bits of the register at memory location `&H303`. Since this register is opto-isolated from the computer, the value to be written is the *complement* of the channel selection value. For example, channel 1 would be selected with `111` and channel 7 by `000`. The three channel selection bits live in locations 0, 1 and 2 of memory location `&H303`. Bit 4 is used for the D-A output channel select, so care must be taken that writing to bits 0, 1 and 2 to select a channel does not affect the bit 4, the D-A channel bit.

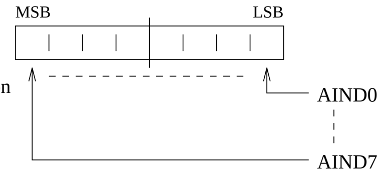
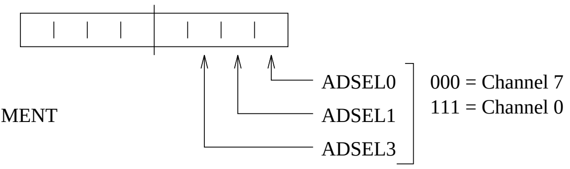
The input voltage is determined by the value that the computer reads from location &H302. The normal convention is that a binary value of zero (`00000000`) corresponds to zero volts input, and a binary value of 255 (`11111111`) corresponds to +5 volts input. However, in this case, they are the other way around: 255 is caused by an input of zero volts and 0 by an input of +5 volts. In practice, this is easily taken care of in the software by converting the input from x to $255 - x$.

A test program for the analog inputs is shown below:

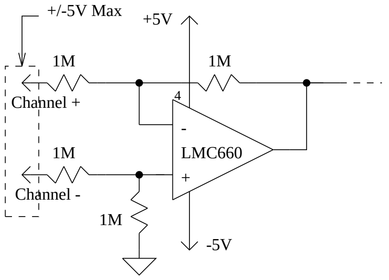
```
'Mechatronics I/O Board Test
'Peter Hiscocks, January 1998
'This is a test program which exercises the A/D Converter.
'It reads the selected channel and then prints the value of
'  the input voltage on that channel.
'Address 302: A/D input data
'        303: A/D input channel select (an output register)
' assuming a base address of $300
'A/D input channel select are bits 0,1,2 at $303.
' Channel selection is the complement of the select value.
' Example: 7 (Binary 00000111) selects channel 0.
'          0 (Binary 00000000) selects channel 7.
'Connect a DC power supply to the input channel.
'To halt the program, press <ctrl><break> (the 'pause' key)

'Select the channel
channel% = 7
OUT &H303, channel%  'This clobbers the DASEL bits in the same register

'Read and print the A/D input voltage.
adloop:
invalue% = INP(&H302)
PRINT (255-invalue%),
FOR l = 1 TO 1000       'Delay
NEXT l
GOTO adloop
```

ADDRESS (Hexadecimal)	FUNCTION	BIT ASSIGNMENT
READ 302	Analog-Digital Input Data (Input channel select depends on DASEL at 303) Input data is proportional to the COMPLEMENT of the analog signal.(00000000 is maximum input)	
WRITE 303	A/D input channel select, D/A output channel select. Channel selection is COMPLEMENT of the digital word.	

	Channel							
	1	2	3	4	5	6	7	8
Connector Pin	1	5	6	2	13	17	14	18
	3	7	8	4	15	19	16	20



1.5 Input-Output Memory Map Summary

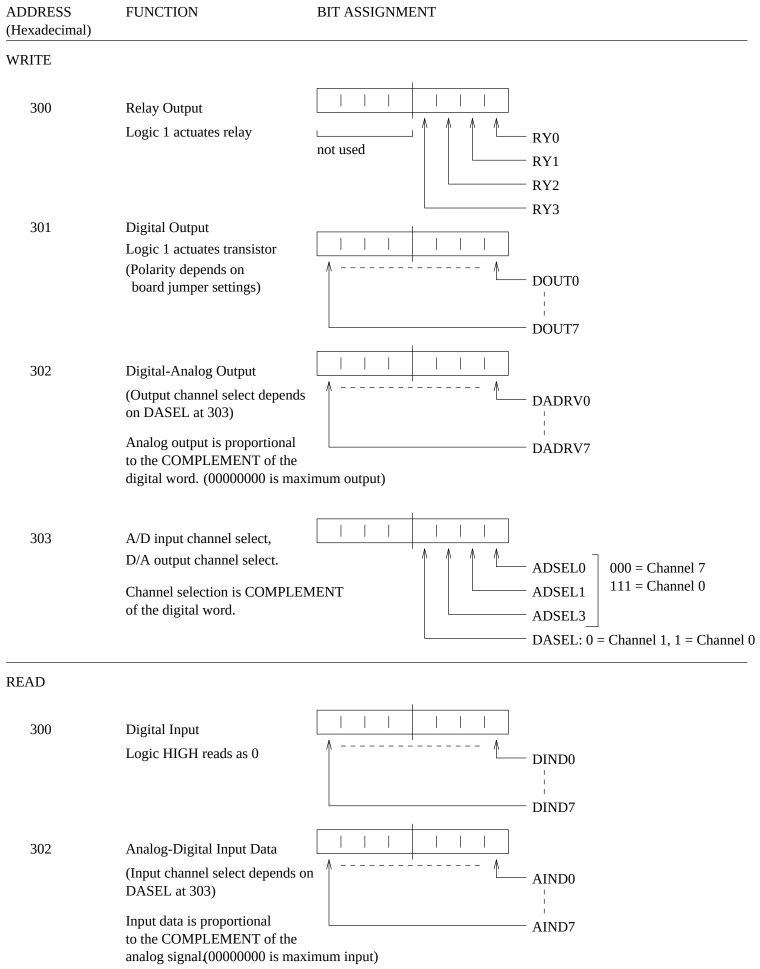


Figure 41: Input-Output Register Summary