Experiment with "Synthetic Psychology"!

Build a Braitenberg vehicle

These fascinating little devices can behave like simple living creatures, exhibiting traits similar to aggression, fear or love — yet they require surprisingly little circuitry (and no fancy microprocessors) to achieve this.

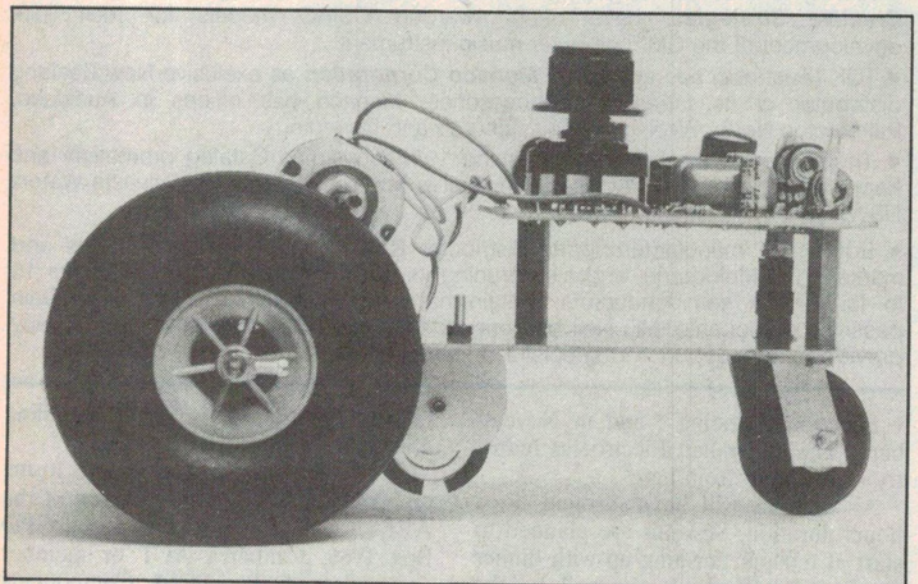
by MARK CHEESEMAN

Braitenberg vehicles were first brought to our attention by an astute reader, Mr. W. K. Henderson of Balwyn, Victoria, who discovered them in the March 1987 issue of *Scientific American*. They are claimed to be able to express 'feelings' such as fear or aggression, depending upon how they are 'programmed'. They are even more fascinating to watch when it is realized how little circuitry is actually required to make them perform these feats.

The vehicles were originally described in Valentino Braitenberg's book, *Vehicles: Experiments in Synthetic Psychology*. They consist of a base, with two independent drive-wheels and motors, and a third undriven castor. This allows the two main wheels to determine the direction in which the vehicle travels, by varying the speed of one motor with respect to the other.

The motors are driven by a signal derived from photo sensors and processed by some simple circuitry. As the circuitry connecting the sensors to the motors is analogous to neurons in a living organism, they are known as *neurodes*. There are different types of neurodes, which produce varied behaviour from the vehicle.

The light sensors in the original design produce a pulse train, the frequency of which depends on the intensity of light falling on the photocell. The neurodes then act on this pulse train in different ways and derive a drive signal for the motors. The simplest form of neurode is a simple piece of wire, which does nothing to the pulse train fed to the motor. Thus as the pulse rate increases due to increasing light intensity, so does the speed of the motor.



The finished prototype looks a little like a 'bug-eyed monster'.

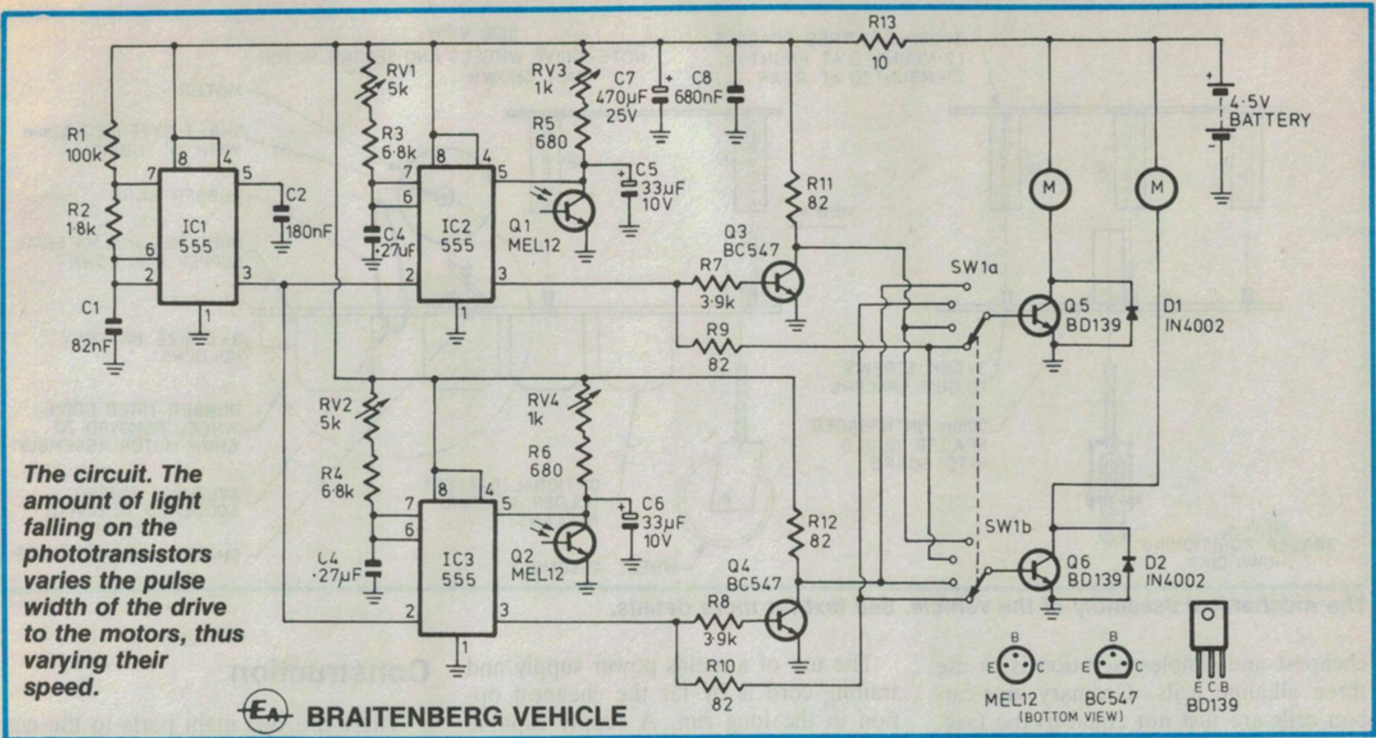
A neurode may connect a motor to the sensor on the same side of the vehicle as the motor, or the sensor on the opposite side. In the former case, the motor on the side of the vehicle will tend to increase speed, steering the vehicle away from the light source. As the vehicle withdraws further from the light source, it slows down, and eventually stops, waiting for another light source to appear so that it can "run away" from that one also.

If the wires are crossed, however, the behaviour changes from the timid sort of behaviour exhibited above, and becomes quite aggressive. As the light intensity falling on a particular sensor increases, it drives the opposite motor faster, steering the machine towards the light source, at an ever-increasing speed. This continues until the vehicle smashes into the light source.

The other type of neurode tends to invert the action of the light source, so that an *increase* in light intensity causes the motor speed to drop. As in the previous example, the motors may be controlled by the sensor on the same side of the vehicle, or the one on the opposite side.

In the first of these latter configurations, an increase in light intensity on one sensor will reduce the speed of the corresponding motor, tending to align the direction of travel towards the light source. The vehicle will eventually reach a point where all forward motion ceases, leaving it gazing at the light source in something closely resembling admiration.

If, however, the sensors control the speed of the motor on the opposite side



The circuit. The amount of light falling on the phototransistors varies the pulse width of the drive to the motors, thus varying their speed.

of the vehicle, the motor on the side of the vehicle opposite to the sensor receiving most light will tend to slow down, turning the machine away from the light. Unlike the other case when this happens, the vehicle will speed up as it disappears into the darkness, probably crashing into any dark object which gets in its way.

The original design called for stepper motors, as their speed is dependent upon the pulse rate fed to them. Unfortunately, stepper motors aren't cheap, so we have re-hashed the control circuitry to allow the use of ordinary DC model motors.

Instead of varying the pulse rate according to the amount of light falling on the sensors, the pulse rate is kept constant while the pulse width is varied. Varying the pulse width has the same effect on the motor speed as varying the voltage. The advantage of pulse-width modulation, or PWM as it is known, is that the driving transistor is either off or on, and not somewhere in between. This results in greatly reduced power loss, and eliminates the need for heatsinks on the transistors, in addition to prolonging battery life.

It is amazing to see how such a simple and inexpensive "toy" can provide such an interesting display, especially in the eyes of the uninitiated. Its reactions to its environment seem to provide a fascinating insight into human emotions, making the workings of the living brain not seem as complicated as they really should.

Circuit Details

The circuit itself is quite simple, consisting of three 555 timers, four transistors and a few other bits and pieces. One 555 operates in astable mode, producing a train of narrow pulses at a rate of about 150Hz. These pulses trigger the other two 555s, each operating as a monostable, with a pulse width which can be varied by the amount of light falling on the associated phototransistor. This is achieved using the *Control Voltage* or *Modulation* pin (pin 5) on IC2 and IC3.

IC2 and IC3 are configured as monostables. When they receive a negative going trigger pulse, the capacitor connected to pin 7, which was being held discharged by a transistor in the 555, is allowed to charge up toward the positive rail through the resistor connected between the capacitor and the supply rail. When the voltage on pin 6 (in this case connected to pin 7) exceeds the voltage on the control voltage pin of the 555, the timing cycle ends, discharging the capacitor, and the 555 awaits the arrival of the next trigger pulse.

The control voltage pin is usually held at two-thirds of the supply voltage by 5k resistors built into the 555. However it is quite a simple matter to "pull" the voltage on this pin either up or down using external components. In this circuit, the series combination of RV3 and R5 serves to pull the pin towards the positive rail, while the phototransistor Q1 will pull it down harder as more light falls on it.

The higher the voltage on pin 5, the longer the time required for the capacitor to charge up to the threshold voltage, and the longer the pulse on the output. As a continuous train of pulses is being fed to the trigger input of the 555, the output is a pulse-width modulated square wave, the duty cycle of which is dependent upon the intensity of light falling on the relevant phototransistor.

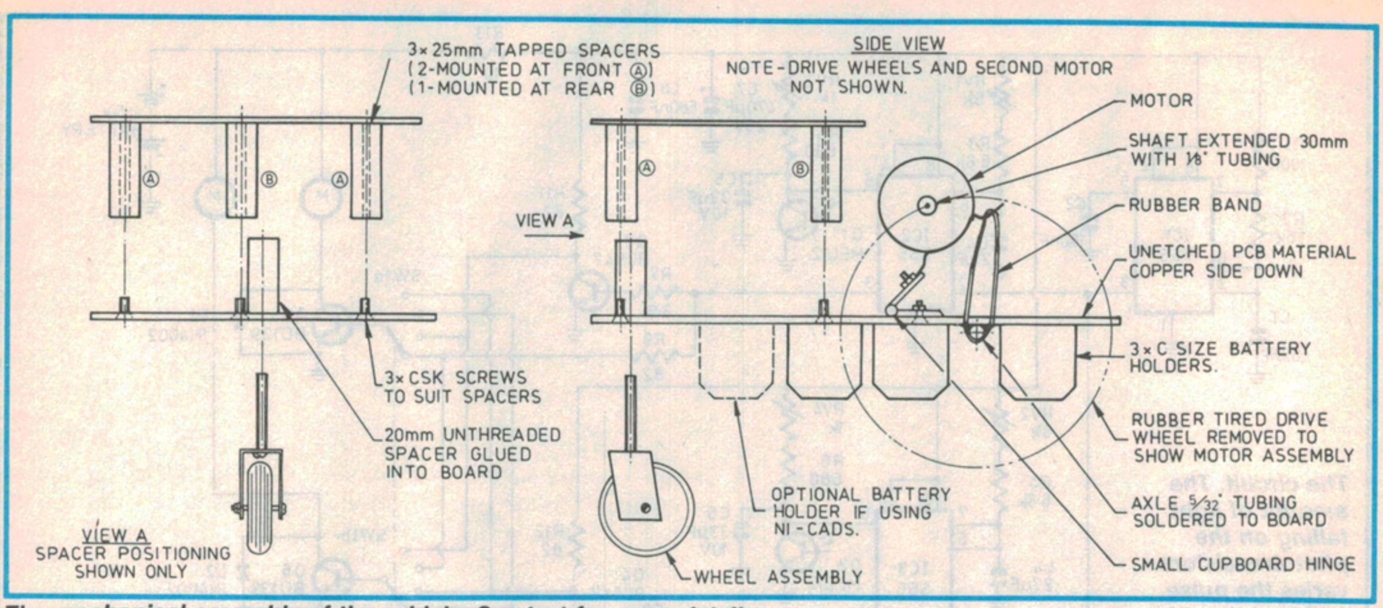
The outputs of IC2 and IC3, and their inverted outputs from Q3 and Q4 are fed to a four-position rotary switch, SW1, which then determines which signal is fed to the two power transistors. In position 1, the motor drive increases with increasing light intensity, with each phototransistor acting on the motor on the opposite side of the vehicle.

The second switch position is the same as the first, except that as the light intensity falling on the phototransistor increases, the motor drive is reduced. The third and fourth positions have the motors controlled by the sensor on the same side of the vehicle as the respective motor. In the third position, an increase in light intensity increases the motor speed, while the opposite happens in position 4.

So SW1 becomes the selector of your Braitenberg vehicle's behaviour.

The RC network formed by R13, C7 and C8 serve to isolate the electronics from the noise generated by the motors, which can be quite severe.

There are several options for the power source for your vehicle. The



The mechanical assembly of the vehicle. See text for more details.

cheapest and simplest solution is to use three alkaline cells. Ordinary zinc-carbon cells are just not equal to the task, as the motors are rather thirsty little beasties. Even with alkaline cells, battery life is rather short, and can become rather expensive in not too short a time.

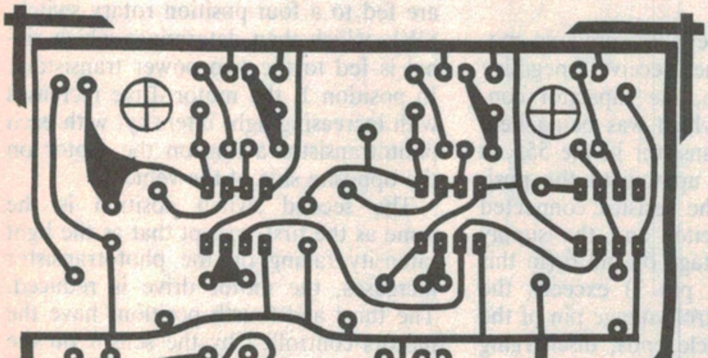
Ni-Cads are probably a more viable option, as they have a lower internal resistance and of course the ability to be recharged. Since NiCads have a lower terminal voltage than their alkaline counterparts, it is recommended that four cells be used. With the voltage drop across the transistors, the motors will still be within their voltage ratings.

The use of a mains power supply and trailing cord is by far the cheapest option in the long run. A supply capable of producing 4.5V at an amp or so should be suitable. One point to watch here is supplies with fast-acting current limiting at about 1 amp. Although the average current seldom exceeds 1 amp, because of the pulse-width modulation the peaks can be higher than this, causing the current-limiting to throttle back the supply to the circuit. The other problem associated with the use of a mains power supply is the problem of the vehicle tripping over its power cord.

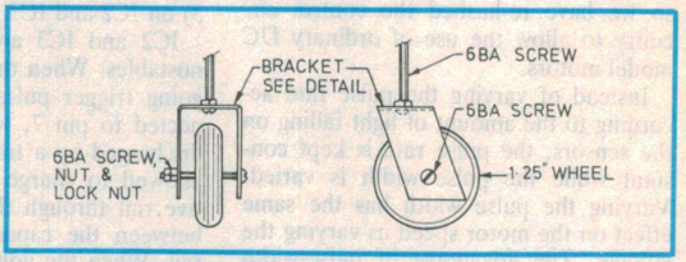
Construction

There are two main parts to the construction process of one of these vehicles: the mechanical building of the vehicle itself, and the assembly of the electronics on the PCB. The latter part is the easiest, so you might as well do this first and get it out of the way.

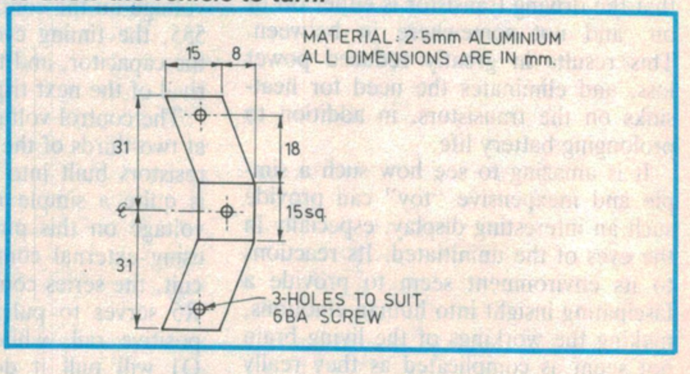
Begin with the printed circuit board, coded 88ro2, by checking it carefully for any bridges between tracks, or breaks in them. There are no static-sensitive components on the board, so the order of assembly is not particularly critical. It is suggested that you mount the lower



The printed circuit board artwork, reproduced actual size.



Front wheel assembly. This must be able to pivot freely to allow the vehicle to turn.



Detail for the front wheel support bracket.

profile components first, as you may experience difficulty in doing so later when the larger components are mounted.

Be careful with the orientation of the ICs, diodes and transistors. The two BD139 flat-pack transistors are orientated with their front (the side with the printing on it) towards the centre of the PCB. The holes for the switch need to be larger than the rest, to allow for the larger pins, and also to help locate it on the board.

The two phototransistors are mounted about 15mm above the board on long 'legs', insulated by spaghetti or heat-shrink tubing. They should not protrude beyond the edge of the base, to ensure that they are not prone to damage if an errant vehicle crashes into a nearby chair leg. The base connection (the middle leg) of the phototransistors is not used, and may be cut off.

The 'chassis' of the vehicle itself consists of a piece of unetched single-sided PCB material, measuring 134 x 80mm. The main axle consists of a piece of 5/32" copper tubing, soldered to the copper side of the board as shown in the diagram. This size of tubing was chosen to suit the diameter of the holes in the wheels. If your wheels have different sized holes, you should select the axle material to suit this.

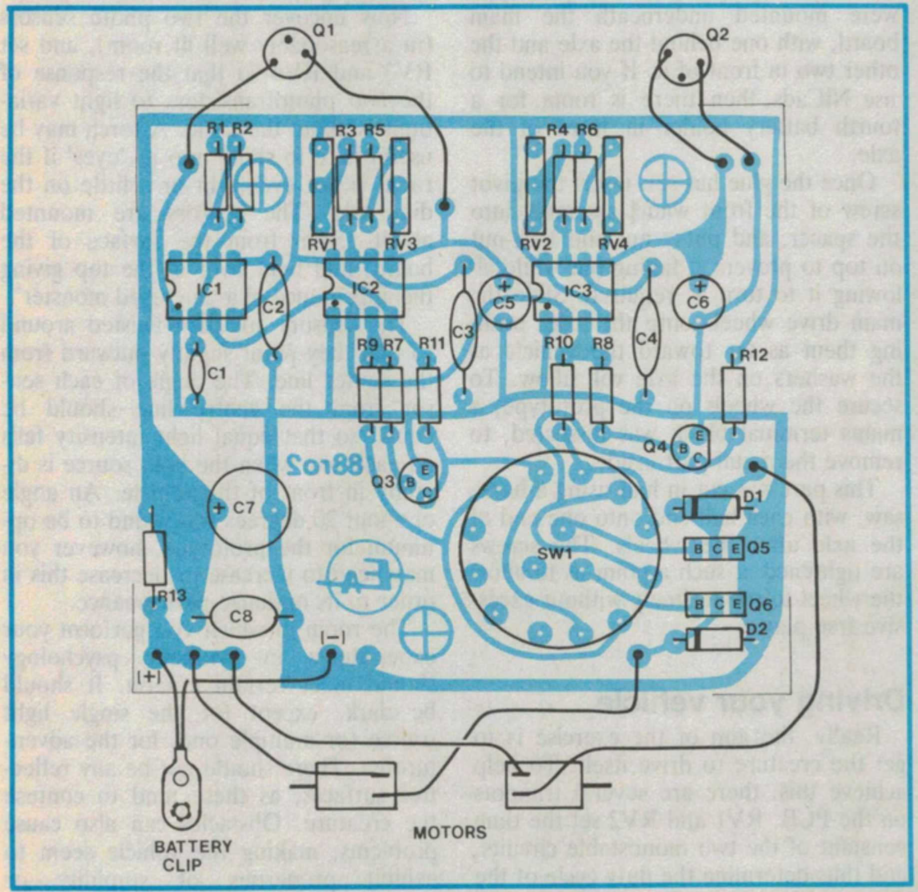
The axle for the main wheels on the prototype consists of a 160mm length of 5/32" copper tubing. This should be soldered to the copper side of the base PCB, about 35mm from the rear end. Use a high-wattage soldering iron for this, as most of the irons designed for electronics work are not capable of delivering the sheer amount of heat required for the job. I used a *Superscope* iron, which proved entirely satisfactory.

Now, find a couple of small brass washers which are a neat fit on the axle. If you can't find washers with the correct sized hole, use ones with a slightly undersized hole. This can easily be enlarged with a reamer while holding the washer tightly with a pair of pliers. To determine the final position of the washers, slide them onto the axle, followed by the wheels.

The washers should be fixed in such a position as to prevent the wheels from sliding along the axle into the body of the vehicle. Now solder the washers to the axle using a high-powered iron, removing the wheels beforehand so that you don't melt them.

The motors used in our prototypes were "Johnson" brand devices, rated at 4.5V, and were obtained from Hobbyco in Sydney. However similar units should be available from virtually any hobby retailer. They measure 25mm in diameter, and 30mm long, with a small shaft extending a further 6mm from one end. They also sport an integral mounting plate, which makes attaching them to the vehicle a breeze.

A pair of small cupboard hinges is used to support the motors, to allow them to be tensioned by elastic bands to hold the shafts against the wheels. The hinges used on the prototype were 35mm long, and their holes conveniently lined up with the mounting holes on the bases of the motors. The placement of the hinges on the base will depend on the size of the wheels which are used. They should be placed so that the motors have a reasonable amount of room to move.



The printed circuit board overlay.

PARTS LIST

- 1 PCB, 86 x 78mm, coded 88ro2
- 1 Fibreglass PCB 170 x 90mm, unetched
- 2 3" model aeroplane wheels
- 1 1.25" model aeroplane wheel
- 2 4.5V DC electric motors
- 2 35mm hinges
- 3 25mm spacers
- 1 20mm spacer
- 1 60mm long piece of 1/8" copper or brass tubing
- 1 160mm long piece of 5/32" copper or brass tubing
- 1 3 pole, 4 position PCB mount rotary switch
- 1 knob for above
- 3 or 4 single C-cell holders (see text)

Resistors

1 x 1.8k, 1 x 100k, 2 x 6.8k, 2 x 680Ω, 2 x 3.3k, 4 x 82Ω, 1 x 10Ω

- 2 1k trimpots
- 2 5k trimpots

Capacitors

- 1 82nF metallised polyester
- 1 680nF metallised polyester
- 1 82nF metallised polyester
- 1 180nF metallised polyester
- 2 270nF metallised polyester
- 2 33uF 10VW PCB electrolytics
- 1 470uF 25VW PCB electrolytic

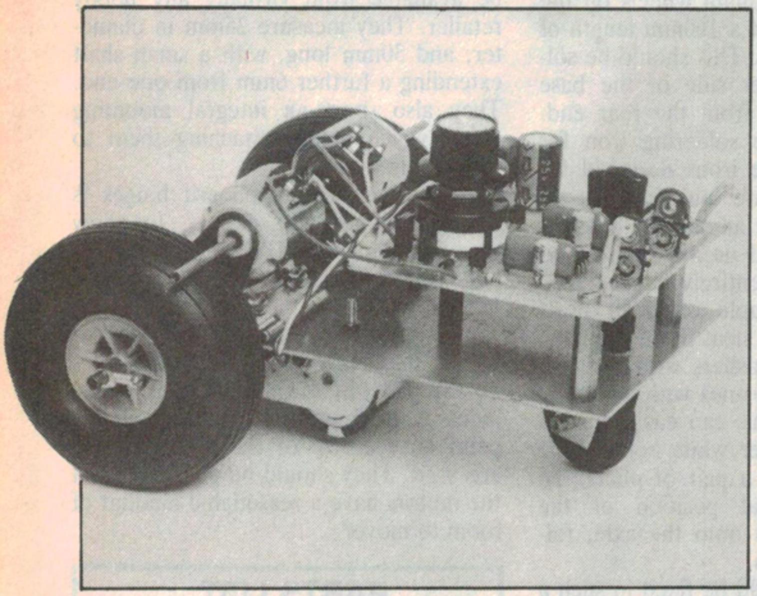
Semiconductors

- 3 555 timers
- 2 MEL12 phototransistors
- 2 BC547 npn transistors
- 2 BD139 npn power transistors

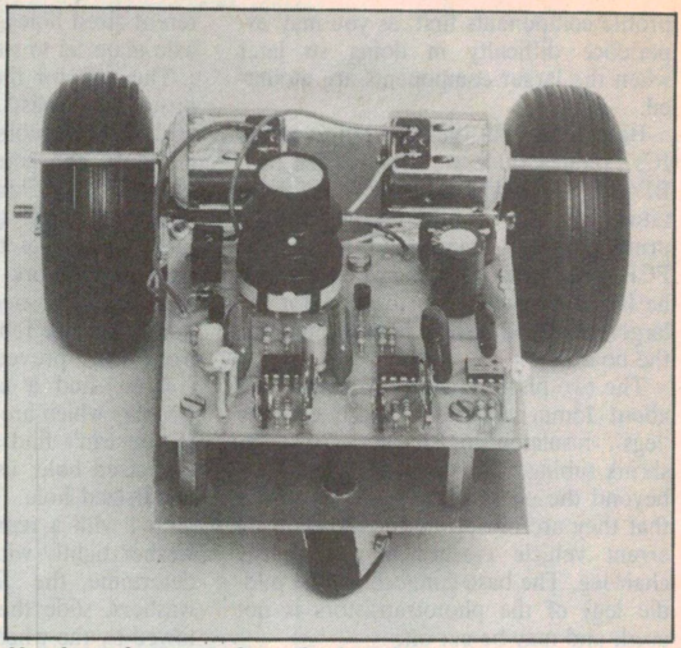
Miscellaneous

Nuts, bolts and washers, super-glue, mains terminal block, hookup wire, sheet aluminium

"Synthetic Psychology"



Side view, showing the overall assembly detail.



Head-on view. note how the 'eyes' are mounted above the PCB, which in turn is mounted on the base board.

As supplied, the shaft on the motors will probably not be long enough to ensure reliable contact with the wheels. Therefore, you should extend the shafts using short lengths (about 30mm) of brass tubing. Is is important that the inside diameter of the tubing is as tight a fit on the motor shaft as possible, otherwise the tubing will tend to get off-centre at the end, making the motors wobble about rather violently, and hindering the transfer of power to the wheels.

At this point it is a good idea to mark out and drill the mounting holes for the printed circuit board. The board should be mounted with two supports toward the front of the vehicle, and the single one toward the rear. However, do not mount the PCB yet, as the preparation of the base is not yet complete.

The small (1.25") wheel acts as a castor to allow the vehicle to turn easily. To achieve this, a small bracket is bent up from a piece of 0.5mm aluminium, with a 25mm long 6BA screw forming the pivot about the whole assembly rotates. Finally, another screw attaches the wheel to the bracket. The wheel must be free to rotate, so a lock-nut is suggested to prevent the nut from coming undone. A couple of washers may help to prevent the wheel from rubbing against the bracket.

Drill a hole in the centre of the base PCB, 15mm from the front. A round 20mm long PCB spacer is used to support the front wheel assembly, and should be a tight fit in the hole. Also make sure that the inside diameter of the spacer is large enough to allow the vertical pivot to rotate freely, but not so large as to give rise to excessive free play in it. Before inserting the spacer into the hole, apply some adhesive, such as super-glue, and also make sure that the spacer is vertical.

The battery holders on the prototype were mounted underneath the main board, with one behind the axle and the other two in front of it. If you intend to use NiCads, then there is room for a fourth battery holder in front of the axle.

Once the glue has set, insert the pivot screw of the front wheel assembly into the spacer, and put a nut and lock-nut on top to prevent it falling out while allowing it to turn as required. Slide the main drive wheels onto the axle, pushing them as far toward the vehicle as the washers on the axle will allow. To secure the wheels on the prototype, a mains terminal block was dissected, to remove the metal part inside.

This part was cut in half using a hacksaw, with each half slid onto one end of the axle after the wheels. The screws are tightened at such a point as to allow the wheel to rotate freely without excessive free play.

Driving your vehicle

Really, the aim of the exercise is to get the creature to drive itself. To help achieve this, there are several trimpots on the PCB. RV1 and RV2 set the time constant of the two monostable circuits, and thus determine the duty cycle of the pulse trains fed to the motors. To set these, cover both of the light sensors so that little or no light falls on them. Turn the switch to position 4, so that the motors will run at maximum speed, and adjust these two trimpots so that the motors both run at about the same speed when placed on the floor.

Now uncover the two photo sensors (in a reasonably well lit room), and set RV3 and RV4 so that the response of the two phototransistors to light variations is about the same. A torch may be useful here to shine into its 'eyes' if the room is not evenly lit or a little on the dim side. The sensors are mounted about 15mm from the surface of the board, and bent over at the top giving the appearance of a 'bug-eyed monster'.

The sensors are then twisted around so that they point slightly outward from the center line. The angle of each sensor from the centre line should be equal, so that equal light intensity falls on each one when the light source is directly in front of the vehicle. An angle of about 20 degrees was found to be optimum for the prototype, however you may need to increase or decrease this in order to its optimize performance.

The room in which you perform your experiments in synthetic psychology should meet certain criteria. It should be dark, except for the single light source (or multiple ones for the adventurous). There should not be any reflective surfaces, as these tend to confuse the creature. Obstacles can also cause problems, making the vehicle seem to exhibit properties of stupidity or drunkeness instead of the desired ones.