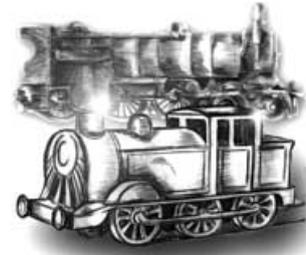


DIGITAL COMMAND CONTROL FOR MODEL TRAINS



JOHN WALLER

How the computer age has caught up with controlling model trains

EARLY model trains used steam or clockwork as the energy source for their locomotives. Indeed, some of the earliest steam locomotives were tested in model form.

Between 1920 and 1930, electric energy sources with analogue control were introduced. Some early examples used batteries, although trains operating off transformers soon followed.

Until recently, full-size ("real") electric traction motors were nearly all of the series-wound commutator type, which have a very favourable torque-speed characteristic for traction use. These motor types have a field winding and armature in series, and have the useful property that reversal of the current does not affect the direction of rotation.

This property allows the motor to operate off alternating current (a.c.) as well as direct current (d.c.), provided that the a.c. frequency is not too high. This type of motor is still common in mains-powered hand tools, where 50Hz or 60Hz is tolerable for power outputs which are a fraction of a kilowatt.

In "real" a.c. locomotives, 50Hz is too high in frequency for the much larger motor size. Frequencies around 20Hz were introduced, and are still in use in some places.

But, for model trains which use a.c. and series-wound motors, 50Hz to 60Hz is quite satisfactory. Such trains, exemplified by manufacturers Lionel and Märklin, used variable transformers to control train speed. A special relay was fitted to the locomotive to reverse direction, which was activated by sending it a high voltage pulse.

TWO-RAIL RUNNING

Early electrically powered model trains mostly used a three-rail system. Sometimes the third rail was disguised as a series of small posts between the running rails.

This evolved into the two-rail concept, which is now ubiquitous. The two running rails, to which the track voltage is applied, are electrically isolated from each other. All wheel sets in the train must have electrically isolated wheels. Some or all of the locomotive wheels are designed to pick up track current, as well as the wheels on any car which requires current.

Traction motors are separately-excited d.c. motors, with permanent-magnet field. Train reversing simply means reversing the track current. Speed control, before the advent of solid-state electronics, was usually by rheostat. In terms of locomotive operations, a rheostat is a somewhat retrograde step compared with the variable transformer.

ANALOGUE CONTROL

Solid-state technology spawned a spate of d.c. train controllers from series regulators to pulsed methods. Model train buffs still argue over the relative merits of smooth d.c. and pulsed d.c. A common method of using pulses is shown in Fig.1, wherein the d.c. controller generates a series of pulses, which are effectively smoothed by the locomotive motor, although the motor will chatter if the pulse frequency is too low.

Advocates of the pulsed method claim that the high voltage improves slow speed

running in the presence of poor contact between wheel and track, although the author has never seen the results of a controlled comparison.

Nearly all electric motor types also act as generators. In the case of the d.c. motor, the generator effect is called *back electromotive force*, or *back-e.m.f.* for short. If the locomotive motor is spun it will generate a voltage proportional to the rotational speed, and this is the back-e.m.f. In practice, the motor adjusts its speed until the impressed voltage, back-e.m.f. and torque out to the load are in balance.

The latter is conditional, of course, upon the motor being able to generate the necessary torque. Also, if the load torque is too low, the motor speed could increase until it destroyed itself. In a model locomotive, the motor usually has too much self-friction for this to occur.

Smart pulsed controllers soon emerged which measured the back-e.m.f. by sensing the track voltage between pulses, as shown in Fig.1. The back-e.m.f. as seen by the controller is "noisy" as it is subject to varying contact resistance between wheel and rail.

A smoothed version of the back-e.m.f. is compared with a control voltage set by the user, with the difference used to control pulse width. The peak pulse voltage of 14V shown is typical for small scale model trains.

SIMULATED INERTIA

A real train, if left with its brakes released, will run away (without the help of any traction) on a very small gradient in the track. A model train with locomotive coupled will never run away, as the friction in the motor is too high. Many model locomotives will jerk to a sudden stop if power is removed, although very good locomotives, with a large

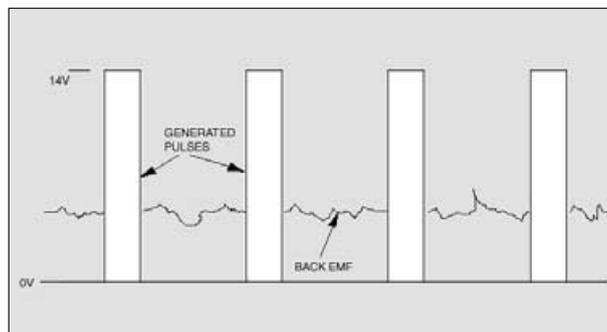


Fig.1. Locomotive pulsed power with feedback.

fraction of their interior devoted to flywheels, will coast several centimetres.

The obvious remedy is to vary the control voltage to simulate inertia, and this is now commonly done.

FORMS OF MULTIPLEXING

The limitations of the "analogue" train control systems described so far are that a given locomotive needs its own dedicated section of track to operate. To operate several trains, the track layout must be divided into electrically isolated sections, each with its own control switch. In addition, without some auxiliary power system, train lights, for example, extinguish when the train stops; not very realistic.

Various forms of providing multiplexed signals to the locomotive have been developed, using power split up into frequency bands, with each locomotive assigned a specific frequency, or using time slots in a waveform. In any case, the signal also provides power, which then becomes common throughout the layout, obviating the need for isolated track sections.

Power is applied to the track whether trains are moving or not, so lights can be on all the time.

Obviously, any multiplexing system requires the locomotive to be fitted with a decoder. The system which has come to the fore is called Digital Command Control (DCC).

BRIEF HISTORY OF DCC

In 1980 Lenz Elektronik of Germany started marketing a system called Digital Plus. In 1990 the National Model Railroad Association (NMRA) in the USA formed a working group to survey all the multiplexed command control systems on the market. The Digital Plus system stood out as having a high signal-to-noise ratio, and the flexibility necessary for expansion.

The NMRA then defined the standards and recommended practices for DCC, using Digital Plus as a starting point, but moving far beyond it. Lenz has two patents in Germany for the technology, but relinquished the rights outside of Germany. The DCC group is now a separate entity within the NMRA structure, and may be visited at www.nmra.org.

The whole philosophy with DCC is to specify the minimum standard which will allow a locomotive decoder from any manufacturer to work with a control system from any other manufacturer. This basically means any signal connected to the track running rails must follow the standard. Signals elsewhere in the system, such as what is done with the output of the decoder in the locomotive, or inputs from the user into the control system, are the individual manufacturer's prerogative.

This approach is taken to encourage innovation. Items which meet the NMRA standard carry their stamp of approval. In all respects DCC is more revolutionary than evolutionary, and offers a degree of realism to the modeller not previously attainable.

Although DCC is primarily aimed at locomotive traction functions, decoders may also be used in ancillary equipment, such as level crossing gates, signals, and points (turnouts in North America).

Table 1. Bit Details of a Typical Data Packet

Preamble	Address byte	Instruction byte	Error detection byte
1111111111	OAAAAAAAA	01DUSSSS	EEEEEEEE
Always all ones	Contains the address of the intended recipient of the packet	The 'D' bit is direction; the 'U' bit is undefined; the 'S' bits are speed	Each bit is the exclusive OR of the corresponding bits in the address and instruction bytes

Table 2. Bit Timing and Tolerance

One bit	Zero bit
Nominal cycle duration 116µs	Each half nominally ≥ 100µs, but maintained nominally equal to each other
Each half duration between 55µs and 61µs	Each half duration between 95µs and 9900µs, but total duration ≤ 12000µs

DCC PROTOCOL

Digital Command Control is an asynchronous serial protocol. It is unusual among such protocols in that the control signal itself also contains all the power necessary to operate all the receivers (locomotives and ancillary items) connected to the system.

DCC is only applicable to two-rail electrification, but, in principle, is independent of the track gauge or scale of the train. Typical track voltage for HO scale trains is 14V, with a current capacity of 10A or more. The DCC controller sends power to the track continuously.

The power form is described as "alternating d.c.", meaning the voltage on the track is constant, but switches polarity about 1500 times each second. Of course, the system has finite bandwidth, and the transition from one polarity to the other takes a finite time, but this does not adversely impact operations.

The switching protocol contains asynchronous serial data as a series of zeros and ones denoted by the time interval between successive polarity switches.

Each locomotive in any train contains a decoder which is set to recognise an address in the serial data, which precedes instructions, such as a change in speed, for that particular locomotive. Details of the data packet format are shown in Fig.2, which shows how zeros and ones are transmitted at different spacings, and Fig.3, which shows a complete packet.

Further information is shown in Tables 1 and 2, which are based on the NMRA standards; see www.nmra.org and www.tttrains.com for complete details.

The decoder also enables ancillary functions so that, for example, the train lights may be turned on or off from the DCC

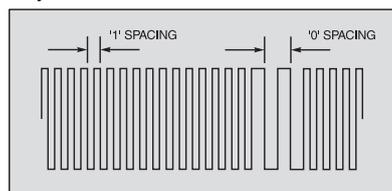


Fig.2. A small snippet of DCC protocol packet.

controller. Other ancillary capabilities include simulated steam exhaust noise, firebox flickering light, whistles, diesel engine rumble, and many others. The essential differences between analogue control and DCC are shown in Table 3.

A consequence of the high current available from DCC track power sources is that short-circuit currents must be interrupted very quickly. Typically, a power source will have fold-back protection so that all trains will stop suddenly in the presence of a short. Unless corrected, a prevalent source of shorts is the "frog" on points, the frog being the place where two running rails of opposite polarity cross.

Special points are now available where the check rail on the frog is insulated to reduce the possibility of shorts. Existing points may be modified by inserting an insulating section in the check rail.

SIGNAL ENCODING

The DCC signal is typically encoded as shown in Fig.3. The aim is to keep the d.c. level of the signal close to zero, to allow

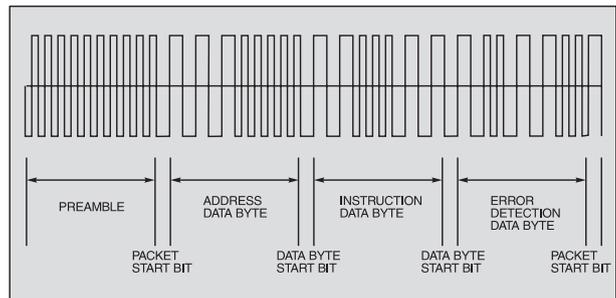


Fig.3. A typical data packet.

the decoder to measure the time between zero crossings, much the same as where digital data are transmitted by radio.

Each "packet" is preceded by a preamble, which is just a string of square waves, at "1" spacing, to allow the decoder to synchronise or re-synchronise in the presence of dirty track. Beyond the preamble, each part of the packet is preceded by a start bit at "0" spacing.

The NMRA standards allow for 9999 locomotive addresses. Naturally, they cannot all be used at one time! The DCC controller has means of placing locomotive addresses, and their action orders, on a queue, with other addresses and orders. The contents of the queue are then transmitted in the packet as just described. The length of time taken to send the packet is clearly dependent mostly on the number of

Table 3. Differences Between Analogue Control and Digital Command Control

<i>Analogue</i>	<i>DCC</i>
Each train must operate on its own electrically isolated section of track	The whole track is connected to a single source of power, there are no electrically isolated sections, and all trains receive the same power
The train speed is determined by the track voltage within its own section	The track voltage is constant and train speed is determined by the track voltage pattern; each train being controlled has its own address
There are no universal standards	The NMRA sets DCC standards. A DCC controller by a particular manufacturer, which has been approved by the NMRA, must operate correctly with a decoder from any manufacturer, which has been likewise approved
Train ancillaries, such as lights, must have their own power supply if they are not to be dependent on track voltage (the lights go out when the train stops)	Constant lighting, and other ancillary features, specified in the DCC standards, are supplied from the track voltage and can be activated at will by the user
The overall control system characteristics must be a compromise among the various locomotives in use	DCC allows each individual locomotive to have its own control settings; no compromising is necessary

locomotives in the queue, with a limit of 30 being typical.

SIGNAL DECODING

A baseline decoder is shown in Fig.4, which is based on an illustration in the EasyDCC manual from CVP Products. The locomotive wheels pick up current from the running rails to power the decoder.

This is a critical part of electric model train operations, and DCC is no exception. The track running rails must be clean, as well as the locomotive wheels and the brushes which collect current from the wheels.

The decoder is looking for its address in the packet protocol of Fig.3. If found, the subsequent bits are decoded and action taken accordingly. For the simple decoder shown, the actions comprise setting speed and direction, and turning the lights on and off. As already mentioned, other decoder functions are often included, and there are decoders designed for static ancillary functions.

The decoder controls motor speed and direction, using a closed-loop system, but without the complication of wheel to rail contact resistance being present within the loop. Furthermore, the decoder can be programmed to provide inertia. As mentioned earlier, this is available in advanced analogue systems, but there is always a

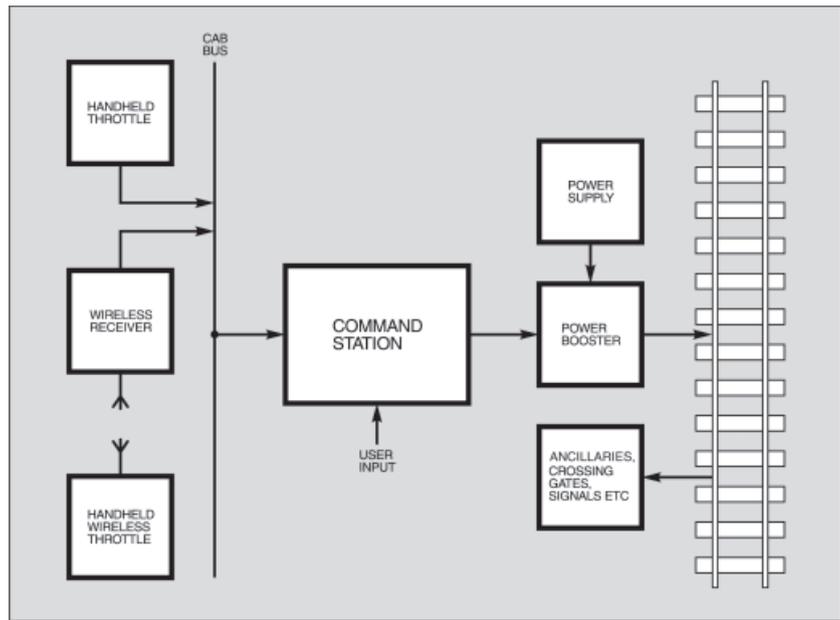


Fig.5. Representative elements of Digital Command Control.

compromise in setting the amount of inertia to suit all the locomotives on the layout.

Performance differs markedly among individual locomotives. With DCC decoders, each locomotive may be given inertia appropriate to it and it alone. Acceleration and deceleration may be set to different values from each other.

Additionally, friction requires that the locomotive motor receives some minimum current before it will move from a standstill. Again, the DCC decoder allows the user to program each individual locomotive with its own starting current, to obtain a more realistically smooth start.

REPRESENTATIVE DCC SYSTEM

The heart of the DCC system, shown in Fig.5, is a Command Station (CS), which generates the serial protocol shown in Fig.3. The output from the CS is boosted to the power level necessary to run all the trains on the system (an HO loco typically requires about 0.5A), together with any ancillaries drawing power from the rails.

The CS has its own user interface, in addition to the "cab bus" shown. A cab, in DCC parlance, refers to the locomotive driver's compartment, or engineer's compartment in North America.

The cab bus allows several users to be controlling trains simultaneously, through hand-held throttles (regulators) connected to the cab bus, either directly or through a wireless link.

The CS provides facilities for controlling trains, setting locomotive and ancillary decoder parameters, and matching these parameter settings with those for the CS. For example, DCC standards provide three speed step values, covering the range from

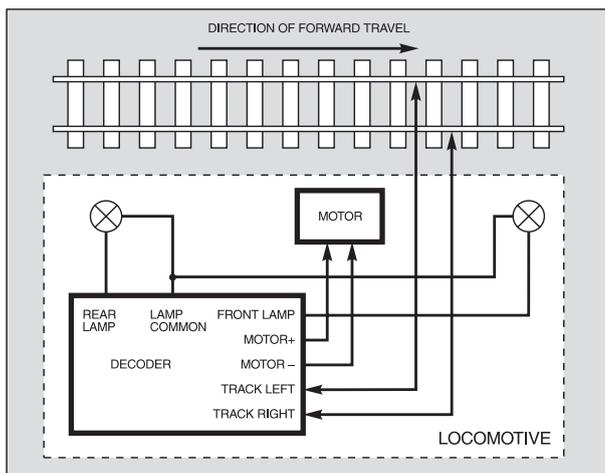


Fig.4. A Baseline locomotive DCC decoder.

slowest speed to maximum speed in 14, 28, or 128 steps, respectively.

For a given locomotive, a throttle, whether hand-held or on the CS, must match the speed step setting for that locomotive. Depending on the CS configuration, a locomotive decoder's parameter values are set by placing the locomotive on a special programming track, on the main track, or either. Any attempt to control a locomotive or train from more than one throttle simultaneously produces erratic (and sometimes hilarious) results.

DRAWBACKS OF DCC

Although Table 3 lists the impressive advantages of DCC, the system of Fig.5 suffers from a potential drawback. Particularly in large layouts, where trains can disappear from view, maybe for minutes at a time, users can lose track of which train has which address, and where it is.

In an analogue system, a user, out of sight of other users, will be in charge of a particular section of track, and can prevent collisions by adjusting that section's track voltage. This is not a satisfactory method for DCC, as the principle of track voltage being the same everywhere is violated.

The out-of-sight user must be furnished with a list of trains, and their addresses, identify the train at risk, adjust a throttle to the correct address, and set the train speed for safety. But this will not be successful unless other users do not have that train's address selected on their throttles.

PIC CONTROL

The author has been working to overcome this problem, and has designed and built a PIC-based Smart Throttle, which keeps track of trains and resolves conflicting speed orders. The prototype, whose block diagram is shown in Fig.6, uses a PIC16F877 with RS232 interface to an EasyDCC CS.

Track sensors allow the Smart Throttle to track trains, always matching a train's position to its decoder address, and reducing train speed as required to avoid hazards. The user still has control over trains, but the user-set speed is

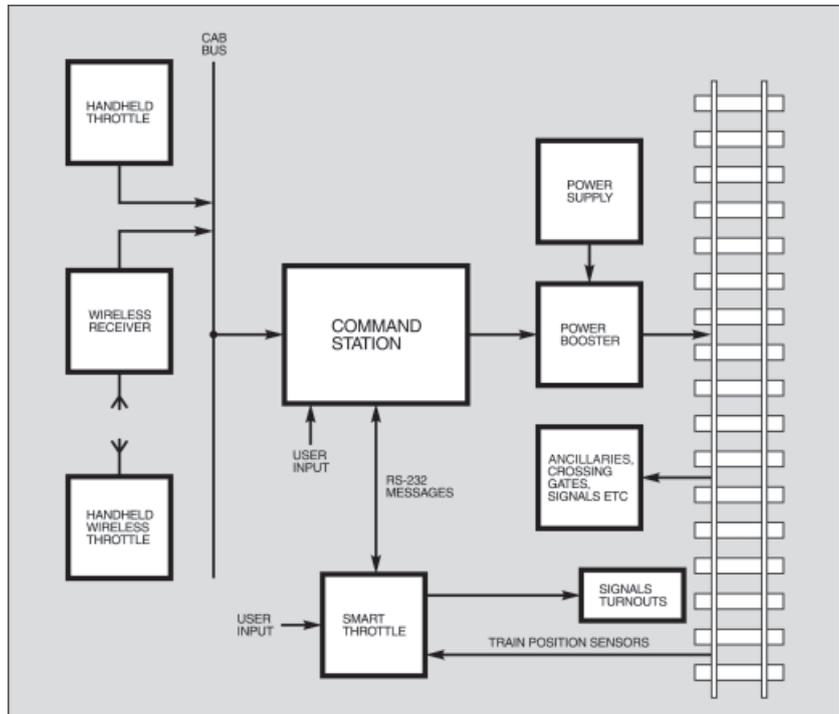


Fig.6. Adding a Smart Throttle to Digital Command Control.

overridden by the Smart Throttle, where appropriate, in a block and signal control system.

Again, if the Smart Throttle is controlling a given train, all other throttles must deselect that train. But, within the Smart Throttle environment, conflicting speed orders are resolved by rules, such as always selecting the slower (slowest) speed to send to the CS.

The prototype Smart Throttle controls a small layout to demonstrate the effectiveness of sensor inputs, and the various control algorithms. Signal values (colour or semaphore position) are output directly to user-visible signals, but they are for information only.

Potentially, points can also be controlled. Unlike most "real" trains, but universally so in models, the signals do not directly con-

trol train speed. In principle, the signal values could be sent from the Smart Throttle to the CS, and thence to ancillaries. The Smart Throttle divides the track layout up into sections or blocks, and no train may enter a block, unless it is declared vacant.

The Smart Throttle prototype is specifically configured for the simple track layout used for development.

For the concept to be viable, it must be adaptable to any layout, and preferably work with a variety of DCC systems. The author continues to work on these aspects.

DCC MANUFACTURERS

A list of some manufacturers of DCC Command Stations is given in Table 4. There are other manufacturers who make decoders and ancillary equipment. There are 12 manufacturers listed, of whom five report currently having an RS232 interface, with one more (ZTC) scheduled for completion in September 2003.

Those manufacturers listed as "not known" in the third column did not answer correspondence on the matter. The author has been using CVP Products for all work so far, but intends to add a ZTC product, as soon as the interface is made available, to give the project an international flavour.

CONCLUSION

The advantages of DCC for the serious railway modeller are considerable. Any hobbyist, whether beginner or otherwise, is well advised to take them into account when starting or modifying a model train layout. Improvements to DCC, including those by the author, will continue to occur.

ACKNOWLEDGEMENT

The author is indebted to Brian Barnt, the DCC Manager for the National Model Railroad Association, for the history of DCC model control. □

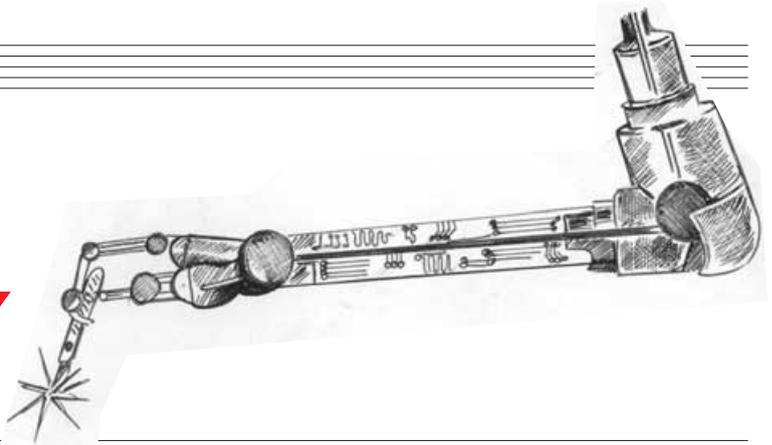
The author may be contacted at john.waller@snet.net.

Table 4. DCC manufacturer's web sites

Manufacturer	Web address	RS232 Link
Arnold Digital, Germany	www.arnold-digital.de	Not known
CVP Products, Texas, USA	www.cvpusa.com	Yes
Digitrax, Inc., Georgia, USA	www.digitrax.com	Yes
Ernst Paul Lehmann Patentwerk LGB, Germany	www.lgb.com	Not known
Lenz Elektronik GmbH, Germany	www.lenz.com	Yes
Model Rectifier Corporation, New Jersey, USA	www.modelrectifier.com	No
North Coast Engineering, New York, USA	www.ncedcc.com	Yes
ROCO Modellspielwaren GES. M. b. H. & Co. KG, Austria	www.infodellbahan.de	Not known
TRIX Modelleisenbahn GmbH & Co.KG, Germany	www.modellbahanhersteller.de	No
Wangrow Electronics, Inc., Illinois, USA	www.wangrow.com	Yes
ZIMO Elektronik, Austria	www.zimo.at	Not known
ZTC Systems, UK	www.ztccontrols.co.uk	Sept. 2003?

CIRCUIT SURGERY

ALAN WINSTANLEY
and IAN BELL



Our surgeons offer a brief introduction to SPICE during the process of trying to unravel some mysteries of a reader's inverter circuit.

The SPICE Boys

Muhammed Abdallah Saif from Uganda emailed about his inverter circuit.

I am designing an inverter using a 555 timer, with the output at pin 3 fed to a 4013 dual D-type flip-flop. The 4013 outputs (Q and \bar{Q}) are connected through a 1k Ω resistor to BC558 transistors with collector resistors of 330k Ω . Their outputs are connected to two 2N3055 power transistors.

The timer has frequency of 200Hz, which should give 50Hz from the 4013. The supply is 12V d.c. The output from one transistor is higher than the other, why? Also, can the 4013 really produce bi-phase outputs?

We'll try to answer the question shortly, though from your written description it is difficult to work out exactly what circuit you are using. This is often the case with the written circuit descriptions that we receive, as in general it is very difficult to describe circuits in prose form.

If you do manage, the description will inevitably be very long and complicated. For this reason it is always better to include a schematic diagram when corresponding with us (or anyone else) about a circuit.

When using email you can scan a drawing or create a drawing on the computer using an image editor and attach it to the email. There are of course packages that are specifically for drawing circuit schematics, but these may have their own formats, which cannot be read by other software.

It is often better to use standard image formats (e.g. jpeg or PDF) that don't require very specialist programs to read them. If you email images, make sure the file sizes are as small as possible whilst being legible. It is bad netiquette to send people large images unless they are expecting them!

If you are restricted to using plain text for any reason (e.g. if posting into an online forum) it is possible to draw "ASCII-matics" using symbols from a non-proportional font such as Courier, but this can be hard work done by hand. A great program that creates ASCII pictures or

drawings by converting image files is available at <http://go.to/ascgen>.

Netting a List

An alternative way of describing circuits is to write a *netlist*. This is a defined format for writing a wiring list in text. There are a number of formats in use, but perhaps the best known is that employed by the industry standard analogue simulator known generically as SPICE. We will describe a simplified form of the SPICE netlist as it will be of use to many readers.

Each line of a SPICE netlist has the following format:

ComponentName Connections [model] Parameters

The component name identifies an individual component in the circuit. The first letter of the component name identifies the component type as follows (for basic analogue devices). Obviously this can be extended for other components.

C	Capacitor
D	Diode
I	Independent Current Source
J	Junction Field Effect Transistor (JFET)
K	Mutual Inductor
L	Inductor
M	Metal-Oxide-Semiconductor FET (MOSFET)
Q	Bipolar Junction Transistor (BJT)
T	Transmission Line
V	Independent Voltage Source

A different *ComponentName* must be used for each component. The component type determines the number of connections and the order in which they are listed

The *Connections* are lists of nodes or "wires" in the circuit. So each interconnection must be given a name, as well as the components. The nodes may be numbered or given meaningful names such as input1 or control. Node zero is always the ground node if numbering is used. The order of the connections is not important for some components such as resistors, but is obviously so for transistors.

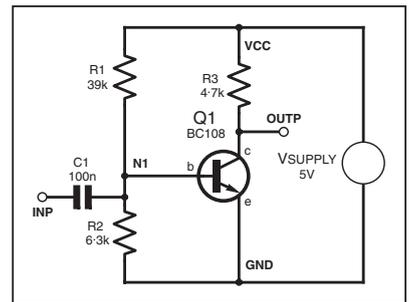


Fig.1. Circuit diagram for a netlist example.

The *Parameters* are component values for passive devices and data such as gain for transistors. They may be listed in a pre-defined order or listed by name.

The *Model* is optional and typically used for transistors and diodes. For our purposes it is simply the name of the transistor or diode type used (e.g. 2N3055).

It is best to illustrate the idea of a netlist by example, so here it is for the circuit in Fig. 1. The transistor connections are listed in the order base, emitter, collector. Note that the "wires" are named INP, N1, VCC, OUTP and GND.

```
Q1 n1 gnd outp bc108
C1 inp n1 100n
R1 n1 vcc 39k
R2 gnd n1 6.3k
R3 outp vcc 4.7k
Vsupply vcc gnd 5V
```

Inverted Views

Next month we'll discuss the use of SPICE in more detail. Returning now to the main subject of Muhammed's letter, the basic form of the circuit we assumed is being used, is shown in Fig. 2. This can be described as a "driven push-pull inverter" (self oscillating push-pull inverter circuits are also possible). The drive circuit (in this case the 555 oscillator, 4013, and BC558s) provides two 180 degrees out of phase waveforms to the drive transistors' bases.

The problem of different voltages on the transistors outputs is difficult to evaluate. We do not know the specific circuit, and the reader does not say exactly what was