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Contents

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Series, Features and Columns

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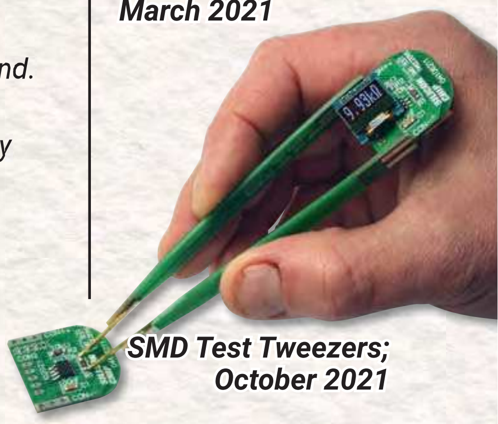

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Brighton
East Sussex BN1 3RA
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What will you build this winter?

By the time you read this, British Summer Time – or your local variant – will be over, the clocks will have gone back and the nights will get longer and chillier for nearly three months as we run into Christmas and winter. What to do as the weather turns? Electronics of course!

Now is the perfect time to look back over recent issues, see what projects you didn't have time to start and settle down with a PCB, parts and a soldering iron.

2021 – a great year for projects

We've had some really impressive projects this year, we have PCBs for all of them and while the vagaries of silicon's international supply chains are impossible to guarantee, a quick check shows that all parts are available, even if you sometimes have to hunt a little harder. Just to get the ball rolling, here are a few of my favourites.

If audio is your thing, then you should definitely try using Nutube's low-voltage valve technology in our pre-amplifier or guitar effects pedal projects from the January and March editions.

How about a sophisticated *DIY Solder Reflow Oven* with built-in PID control, which we ran in April and May? Or maybe the very handy *Touchscreen Wide-range RCL Box* – just the thing for tinkerers who like to run a lot of test with a variety of passive components.

For model railway enthusiasts, the *Complete Arduino DCC Controller* (January) was very well received.

Maybe you're a beginner. The *Night Keeper Lighthouse* (September) and this month's *Door Alarm* are both a satisfying route to getting started with real electronic circuits.

We know that PICs is a hugely popular topic with many of you, so if you've been meaning to really get to grips with this important area of digital control then why not take the plunge and build Mike Hibbett's current *PIC 'n Mix* project – the *PIC18F Development Board*.

Christmas inspiration

Last, but not least, if you're being pestered for Christmas present ideas then why not give your nearest and dearest a gentle hint about our range of PCBs – or better still, a subscription to *Practical Electronics* (digital or print)!

Keep well everyone

Matt Pulzer
Publisher

The **Fox** *Report*

Barry Fox's technology column

Not all tech progress is for the better

Watchmaker Timex broke new ground in 1994 with the introduction of its DataLink series of digital watches, which very usefully stored user information, like telephone numbers, in on-board memory. In 1997, they added the 'Ironman Triathlon' edition to the series and the Ironman name stuck.

When introduced, DataLink watches were known as 'PIM' watches – ie, 'personal information managers'. Bill Gates was known as an owner of one, and Microsoft was involved in the project – see image.

Timex cleverly enabled DataLink/Ironman to 'talk' to a PC by 'looking' at the display screen and decoding data from a sequence of light flashes – rather like a bar code reader. I used one for years, storing essential phone numbers, along with addresses, passport numbers and credit card info dressed up as phone numbers.

In 2003, and with the slow flash rate of LCD displays causing transfer problems, the optical system was scrapped. The Timex Ironman DataLink USB did what it said on the tin, and sucked data from a PC via a proprietary USB cable. Memory capacity was bigger, and the system worked very well.

New Ironmans are no longer available because everyone and their dog turned to storing personal information on smartphones. I have a couple of

The Datalink line shown (left to right): Datalink model 50 (1994), Ironman Triathlon, with the Ironman Triathlon logo on the upper part of the face (1997) and Datalink USB sports edition (2003). The small communication system lens is seen at the top of the face on both the model 50 and the Ironman. Microsoft's logo appears at the top of the model 50's display, just under the lens. (Courtesy Tasoskessaris, Wikipedia) beat-up DataLink USB devices that still work, but only when their 'sticky' control buttons can be persuaded to respond reliably.

I liked 'em!

I wish I could buy a new Ironman. Why? Because although I can buy any number of smart watches that 'talk' (by Bluetooth) to their smartphone, I have so far been unable to find one that can store anywhere near as much useful data as the old Ironmen. Usually, smart watches only cater for a dozen or so phone numbers. Perhaps some of our smart readers will have had more luck? If so, do please share the good news.

More is less

Instead of storing data, the new breed of smart watches boasts all manner of detailed health checks and analysis. One of their favourite tricks is to measure how far the wearer has walked. The top-end watch I borrowed (which stores a measly few phone numbers) consistently assures me I have walked far greater distances than I've actually travelled. It also measures my heart rate in beats per minute, displays it on the watch face and vibrates alarmingly when the rate goes high.

The only problem is that – like distance travelled – the logged heart rate is consistently far higher than BPM measured by traditional methods, such as finger on pulse or blood pressure machine readout. My posh watch usually shows around twice the actual BPM.

I have checked this by reading the watch rate while measuring BPM with a blood pressure 'pod' in a GP surgery. I have also checked it while a GP is measuring blood pressure and BPM with a surgery sphygmomanometer; and I recently checked the watch readout while being checked by a hospital ECG machine (electrocardiogram). In each case the watch was more or less doubling the actual BPM.

I asked the hospital cardiac physiologist who was running the tests, why my smart watch was reading 70 BPM and over, while his ECG equipment was showing a near-steady 44 BPM. Was the watch doing something very clever, perhaps? He sighed, with resigned exasperation, and said with a world-weary tone: 'It happens all the time. People make medical emergency calls because their watches tell them their heart rate is something like 300 BPM, when actually it's just a little bit high. Usually all they need do is to stop worrying about what their watch says'.

Early professional VTR from the BBC

Experimental VERA (Vision Electronic Recording Apparatus) linear VTR developed by the BBC in the 1950s.

In the early 1950s the BBC almost invented the world's first broadcast quality video recorder. VERA, the Vision Electronic Recording Apparatus, filled a small room and in pre-metric days boasted 20.5-inch spools of half-inch tape, running at 200 inches per second to record 15 minutes of 405-line monochrome pictures and mono sound. Two machines were ganged together to make continuous recording possible.

Previous attempts at video recording had failed because of the difficulty of capturing low frequencies on tape that had to move fast to capture high frequencies. VERA simultaneously recorded three tracks, two video and one audio. The 3MHz picture signal was split into two bands, one 0 – 100kHz, the other 100kHz to 3MHz. The high band was recorded normally on one track, like very high-fidelity audio. The low-band frequency modulated a high-frequency carrier on the other track. Complicated braking systems were needed to start, stop and rewind the tape without snapping or stretching it.

The recording heads were handmade, with insulating material hand sheared from mica sheet. The tape gave best results only after a few dozen playings had polished its surface and improved contact with the heads. The BBC used VERA for a few broadcasts, but dropped the project in 1958 when the UK and Europe adopted a new 625-line standard which needed a 5MHz bandwidth. Running VERA faster to achieve this would have reduced recording time to only a few minutes per reel.

US company Ampex had by then proved that its Quadruplex recorder, first demonstrated in 1956 under team leader Charles Ginsberg, could record a full hour of 625-line TV on a single spool. It did so by running the tape slowly but mounting the heads on a wheel and spinning them rapidly across the tape width. Although he did not like to talk about it, a young Ray Dolby was part of the Ampex team. Dolby later became famous for Dolby Noise Reduction, but that's another story.

More technology stories and images at: **https://tekkiepix.com/stories**

Practical Electronics is delighted to be able to help promote Barry Fox's project to preserve the visual history of pre-Internet electronics.

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Miraculous Transformation

Techno Talk

Mark Nelson

A famous Biblical story described the transformation of water into wine. Today the closest we can get to this is turning beer into electricity, which is somewhat less impressive but more consistently repeatable. That's not the only weirdness here: we present a new design of battery that is powered by human bodily fluids. All in the best of taste of course.

You are probably wondering why anybody would wish to turn ale into electricity. That would surely be a wicked waste of good beer. It would indeed, but only if it had been fresh. Unfortunately, during the lockdown a lot of good beer passed beyond its drink-by date. Most of this went down the drain but an enterprising brewery in Dorset had the notion of turning this surplus into green energy, generating enough electricity to power close to 17,000 average homes for one day.

The **futurenetzero.com** website relates how the family-owned Hall & Woodhouse brewery found a sustainable solution for all this expired beer by using it to generate electricity. It installed a wastewater treatment plant that creates biogas, which in turn is used to generate electricity for powering its packaging lines and utilities. What's more, the Blandford Forum brewery has set monthly targets for its use of self-generated electricity, in its aim to become fully carbon neutral. Declared head brewer, Toby Heasman: 'Although lockdown meant that many of our pubs had to return unsold beer back to the brewery, the silver lining has been that none of this has gone to waste. Thanks to our wastewater treatment plant, all of the returned beer has been used to generate green electricity.'

Health sensors powered by your own body

In case you were unaware, your fingertips are one of the sweatiest parts of the body, which is doubtless the reason why jewellers and conservers of ancient manuscripts all wear white gloves. However, if you wear medical body sensors for tracking your health and nutrition, you might be pleased to learn that small biofuel cells can harvest enough energy from fingertip sweat to power the sensors all day. PhD student Lu Yin is one of the engineers at the University of California, San Diego who have developed a thin, flexible strip like an Elastoplast that can be worn on a fingertip to generate small amounts of electricity when a person's finger sweats or presses on it.

It's by no means the first wearable power source powered by bodily fluids, but what's special about this sweat-fuelled device is that it generates power even while the wearer is asleep or sitting still. In the world of wearables this is potentially a big deal, because researchers have now figured out how to harness the energy that can be extracted from human sweat produced even when a person is not moving.

Says Yin, 'Unlike other sweat-powered wearables, this one requires no exercise, no physical input from the wearer in order to be useful. This work is a step forward to making wearables more practical, convenient and accessible for the everyday person. It also generates extra power from light finger presses – activities such as typing, texting, playing the piano or tapping in Morse code can also become sources of energy.'

A key differentiator of this latest energy harvesting technology is that it could serve as a power source anytime, anywhere. It does not have the same limitations as, for example, solar cells, which only work under sunlight, or thermoelectric generators, which work only when there's a large temperature difference between the device and the surroundings.

Power-packed plaster

Visually, the device looks just like a sticky plaster; in other words, a thin, flexible strip that can be wrapped around the fingertip. A padding of carbon foam electrodes absorbs sweat and converts it into electrical energy. The electrodes are equipped with enzymes that trigger chemical reactions between lactate and oxygen molecules in sweat to generate electricity. Underneath the electrodes is a chip of piezoelectric material, which scavenges mechanical movement to generate additional electrical energy when pressed. As the wearer sweats or presses on the strip, the electrical energy gets stored in a small capacitor and is discharged to other devices when needed. These devices can be integrated with the energy harvesters to power an integrated sensing system with dedicated electrochromic displays (see: **https://bit.ly/pe-dec21-ecd**).

Each finger pad can generate between 20 and 40µW of power. This may sound like small beer, but during 10 hours of a researcher's sleep, the device collects almost 400mJ of energy – crucially, enough to power an electronic wristwatch for 24 hours. From one hour of casual typing and clicking on a mouse, the device collected almost 30mJ. And this is just from one fingertip. Strapping devices on the user's remaining fingertips would generate 10-times more energy, the researchers say.

Where next?

The researchers have already hooked up their device to a vitamin C sensor that they developed in the lab. They had a subject take a vitamin C pill and then use the finger-powered system to read their vitamin C level. They also connected their energy harvester to an electronic system consisting of a chemical sensor connected to a small low-power display, which shows a numerical reading of the sensor's data. In yet another experiment, the researchers showed that their system could also be used with a lab-built sodium sensor to read the sodium ion level of a saltwater solution. Other potential measurement targets are heart rate, vitamin deficiencies and glucose levels.

'Our goal is to make this a practical device,' states Yin. 'We want to show that this is not just another cool thing that can generate a small amount of energy and then that's it – we can actually use the energy to power useful electronics such as sensors and displays.'

To that end, the team is making further improvements to the device so that it is more efficient and durable. Future studies will include combining it with other types of energy harvesters to create a new generation of self-powered wearable systems.

Exclusive offer

Win a Microchip dsPIC33CH Curiosity Development Board

Practical Electronics is offering its readers the chance to win a Microchip dsPIC33CH Curiosity Development Board (DM330028-2) – and even if you don't win, receive a 20%-off voucher, plus free shipping for one of these products.

The dsPIC33CH Curiosity Development Board is a cost-effective development and demonstration platform for the entire dsPIC33CH family of dual-core, high-performance digital signal controllers (DSCs). Designed from the ground-up to take full advantage of Microchip's MPLAB X IDE, the board includes an integrated programmer/debugger and requires no additional hardware, making it a perfect starting point to explore the dsPIC33CH dual-core family.

Worth $48.99 (approx £35.50) each

Microchip's dsPIC33CH family of DSCs feature dual 90 and 100 MIPS 16-bit dsPIC DSC cores with integrated DSP and enhanced on-chip peripherals. These DSCs enable the design of high-performance, precision motor control systems that are more energy efficient, quieter in operation and provide extended motor life. They can be used to control BLDC, PMSM, ACIM, SR and stepper motors.

These DSCs can enable the design of switched-mode power supplies, such as AC/DC, DC/DC, UPS and PFC, providing high-precision digital control of buck, boost, fly-back, half-bridge, full-bridge, LLC and other power circuits to reach the highest possible energy efficiency.

These devices are also ideal for many high-performance general-purpose and robust applications and have many features that help simplify functional safety certifications for ASIL-B and ASIL-C focused applications.

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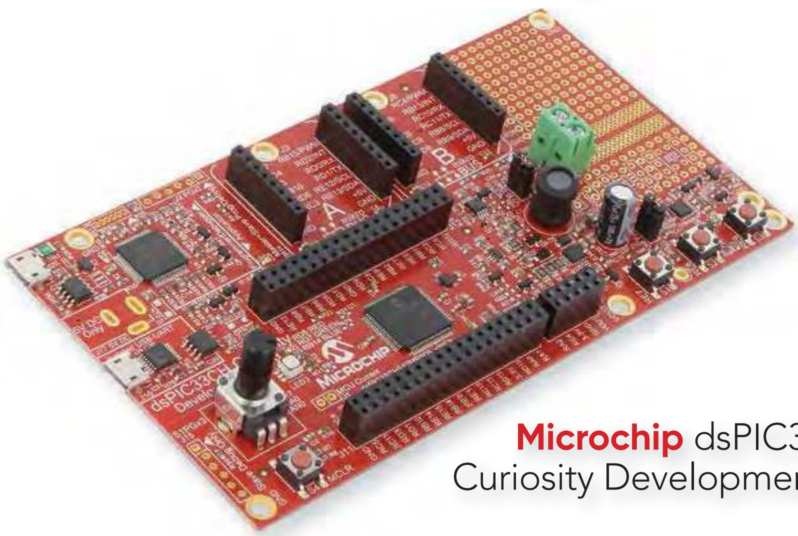

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Closing date

The closing date for this offer is 30 November 2021.

August 2021 winner

Martin Ryce

He won a Microchip SAM D21 Curiosity Nano Evaluation Kit

Net Work

Alan Winstanley

This month's *Net Work* brings you the latest topical news about technology and trends from the world of the Internet and beyond.

Ask an Amazon shopper what the Amazon logo – often seen on cartons that drop onto our doorstep – means to them and they invariably say, 'it's a smiley'. However, Amazon's strapline was at one time, *Everything from A to Z* and the 'smile' is actually an arrow pointing from A to Z in the word 'Amazon'. See the interesting timeline of Amazon's logo development at: **https://bit.ly/pe-dec21-amz**

Amazon's Smile

Another service offered by **Amazon.co.uk**, which is less well advertised, is Amazon Smile, where Amazon will automatically donate a small portion (0.5%) of your eligible purchases to your chosen charity, at no extra cost to yourself. The listed (UK) charities must be registered with the Charities Commission and signed up to the Amazon Smile programme. I had no problem locating a smaller, less well-known charity that I've adopted following a family event this year. Amazon says it has donated nearly £11m ($14 m) to date in the UK alone, and nearly £230m ($315m) worldwide. So far, mine has benefitted by the grand sum of 46p, but it's a start!

The latest mobile Amazon Shopping apps for iOS and Android are Amazon Smile-aware, so simply tap on 'Amazon Smile' within the Programmes & Features menu or Settings to enable it. Desktop PC users can donate by shopping at **smile.amazon.co.uk** (it's important to start from this URL when shopping). A Smile bookmark button can also be dragged onto the web browser menu bar; I discovered once or twice that if I'd forgotten to enter **smile.amazon.co.uk** when starting out, then if during the checkout phase I pressed the Smile button in Firefox, the Smile donation was triggered. Readers might need to double-check this in their own browser. It costs nothing to make a seamless donation this way, so if you are a regular Amazon shopper and have a charitable cause in mind, why not check if the charity has signed up to Amazon Smile and activate this option on your account.

Amazon Smile will donate 0.5% of eligible purchases to your choice of charity, at no extra cost to you. Note the 'Smile' bookmark button.

Smart glass heads-up

Readers with long memories would have to go all the way back to *Net Work*, October 2013 to find a story about Google Glass, an innovation that brought hands-free data to users in the form of a tiny head-up display carried on a spectacle frame.

Google Glass was a tiny projector fitted to one arm of special lens-free glasses, which sported a tiny acrylic prism that acted as a micro screen that users could focus on with their operative eyeball. I wrote that Google Glass would enable the wearer to check their phone through Bluetooth, access the web or connect to Wi-Fi, check navigation directions on a display or interact with the device's built-in camera. Sound was transmitted through a bone-conducting transducer. Perhaps consumers weren't ready for this quantum leap in Internet paraphernalia, as the product quietly disappeared, but not before Google gleaned a lot of practical know-how from the project prior to re-purposing it for industry.

Google's Glass for Enterprise is a micro heads-up display that builds on earlier models.

Fast forward to today, and Google Glass is alive and kicking in the form of a wearable enterprise version for use in industry and commerce. The fascinating Android-powered Glass Enterprise has 3GB of memory and 32GB of Flash memory, dual-band Wi-Fi, an 8MP camera, a 640 × 480 micro screen, a mono speaker, three near-field beam-forming microphones, and plenty more besides. Google Glass is finding new roles in logistics, production, maintenance and medicine as a way of presenting data and information to its wearers, leaving them hands-free to get on with their job. For example, a repair technician could view machinery diagrams 'on screen' in real time without having to thumb through a manual or scroll through a laptop or tablet. A YouTube walk-through (**https://youtu.be/5IK-zU51MU4**) shows that when coupled with augmented reality software, these devices could assist humans with all manner of roles in the future. A tantalising taster of how this might work is shown at: **https://youtu.be/dVzfYDaWbZc**

For everyday Internet users who fancy the idea of wearable smart glasses, there are a few choices in this emerging market. Ray-Ban recently launched its first generation 'Stories' smart glasses in a variety of classic Ray-Ban styles. Priced at £299, they come in various colours as well as polarised and graduated lenses (prescription lenses are also available), and they connect via Bluetooth to an app hosted on the wearer's smartphone. The glasses are mainly intended to capture

(Left) Ray-Ban's Stories smart sunglasses connect to a Facebook app to record images and video clips; (Right) The 'Capture' LED warns those close by that the Ray-Ban glasses are recording.

photos, 30-second video clips or carry audio from phone calls. Ray-Ban Stories smart glasses integrate tightly with Facebook, via the Facebook View app.

Someone else's spectacles secretly recording you might feel a bit creepy, and Facebook goes to some lengths to highlight the privacy aspects of these devices and remind wearers of their responsibilities. Facebook's over-simplified privacy policy covering these devices is at: **https://bit.ly/pe-dec21-fb**

The policy flags up the tiny 'capture' LED that supposedly warns anyone in the immediate vicinity that the glasses are recording. However, if it's under bright sunlight (they are sunglasses after all), the capture LED may not be noticeable at all – as Facebook says, '[the capture LED is so] you won't catch anyone *near you* off guard.' More details are at: **https://bit.ly/pe-dec21-rb**

As an alternative, audio brand Bose offers their 'Audio sunglasses' with built-in sound but none of the smart gadgetry, see further details here: **https://bit.ly/pe-dec21-bose**

Amazon.com is marketing its $250 second-generation Echo Frames Smart Glasses (not yet available in the UK) with microphones (but no cameras) for use with Alexa, and they are also available with prescription lenses. Amazon's blurb can't resist having a dig: 'Designed to protect your privacy – Amazon is not in the business of selling your personal information to others. Microphones are designed to respond to the voice of the person wearing the frames and turn off with the double-press of a button.'

Amazon also sells a few obscure brands of smart glasses that include a camera, such as 'OHO 4K Ultra HD Water Resistance Video Sunglasses, Sports Action Camera with Built-in Memory'.

Text-to-speech

Ever since flatbed scanners first hit the streets, OCR (optical character recognition) software has been available to computer users and text-to-speech programs can convert the digitised results into audio. Visually impaired persons or those having reading difficulties can now benefit from a new class of wearable technology. The Orcam MyEye is a small scanner device that clips magnetically onto the side of spectacles, and will OCR text and convert it to speech. It's demonstrated here: **https://youtu.be/bbEEmc0xtvw**

This technology is eye-wateringly expensive though: the RNIB (Royal National Institute for the Blind) website lists MyEye at £3,500 + VAT. A lower-cost, handheld device is the Orcam Read, which has laser guides designed to help with reading. It may appeal to those with dyslexia or anyone whose eyeballs and brain are simply suffering from 'reading fatigue'. Street prices are around £1,500. More details are at: **orcam.com**

Aibo – not such a good boy?

As wearable technology continues to improve and costs fall, smart glasses with built-in cameras will eventually become more commonplace. Privacy infringement is likely to become a concern too, and some smart devices have already fallen foul of privacy regulations, including Sony's $3,000 Aibo robot dog. The sensor-packed pooch cleverly uses facial recognition to train it to behave differently around familiar people, which was enough to cause the state of Illinois to ban the purchase or use of Aibo by its residents, citing infringement of the state's Biometric Information Privacy Act.

Sky without its sky-based signal

Meanwhile, satellite broadcaster Sky is launching a new streaming service called Sky Glass, comprising a Sky-brand 4K UHD 'carbon neutral' flat screen package offering 43-inch, 55-inch and 65-inch screen sizes in a range of five chassis colours. Voice control is built in and there are three HDMI ports. It signifies Sky's gradual move away from satellite towards broadband-based delivery – Sky's new all-in-one screens are a dish-free and box-free service and require Wi-Fi or wired Ethernet. This self-contained screen may be enough to finally tempt some TV stick-in-the-muds onboard, with packages starting from £13 a month (variable) for the 43-inch package, with Netflix bundled in for 18 months. There are reams of small print worth digesting, and more details are at: **www.sky.com/glass**

Taxing times

One of the claims commonly voiced today is that tech corporations such as Amazon, Facebook, Google and eBay should somehow 'pay more tax', as they are often criticised for paying minimal tax on the billions of dollars' worth of trade they generate in any particular country. It's a reasonable point to make, and after an initial outcry, these firms now 'book' sales more ethically (in our case, to UK-sourced trade, rather than shifting sales abroad in an effort to reduce their tax bills) and they are eager to state that they comply fully with local tax codes.

As the Internet started to evolve, the world grew smaller which created all kinds of problems for governments wanting to levy taxes on digital trade, where no physical goods actually crossed borders. From the taxman's point of view, how do you treat the sale of advertising or digital marketing if the sales office is in London or Dublin, but the buyer is somewhere in Europe? Where is the digital service actually 'produced'?

As one solution to raising badly needed tax revenues, some countries including France and the UK implemented a Digital Sales Tax (DST), a headline-grabbing gesture that was immediately rebuffed by the US, which threatened to retaliate for supposedly targeting US tech giants (a stance they hold to this day). More than half of Europe is still working towards introducing their own DST. A 2% DST was introduced in the UK in 2020 aimed at 'soft' sales of search engine services, social media advertising and the like, but not consumer Internet sales. eBay chose not to pass this tax on to

Sky Glass is an all-in-one 4K UHD streaming package that does away with a satellite dish and set-top box. It come in various sizes and chassis colours.

Amazon's $1,000 Astro bot is an Alexa on wheels – but for US customers only for the time being.

advertisers, but other tech firms have added it to their bills.

The problem of taxing profits from online trade is something the OECD has been grappling with for years, as it is only by international co-operation that the issue will finally be settled. In September a multinational agreement was finally hammered out – engineered by the US – to raise corporation tax globally to a minimum 15%, which is less than many countries already levy anyway.

The EU is still considering its own tax policies to address what it calls the 'fair taxation of the digital economy'. Expect more clamouring that high-tech multinationals pay 'the right amount of tax' and news about an EU directive before the year end. Until then, it's business as normal as far as the US tech giants are concerned.

Alexa gets some wheels

With the festive season looming, Amazon has been busy with some intriguing new product launches, many focused on home security. As a sign of things to come, their forthcoming Astro 'household robot for home monitoring' has Alexa built in and includes a 6-month free trial of the property monitoring service Ring Protect Pro. Astro will obey your commands, follow you around, patrol your premises, send an alarm and perform many other useful tasks on the go. It is likely to cost $1,000 and is yet to be listed by Amazon UK. Some early reviewers muse that it might infringe privacy, or fall down stairs! (For more details, see: **https://youtu.be/sj1t3msy8dc**)

The Ring 'Always Home Cam' drone will patrol a single-storey property and relay video.

Amazon.com is also soft-launching its Ring-brand 'Always Home Cam' security camera drone intended for domestic indoor use on a single storey; it flies along custom flight paths that users 'train' it to follow, and (naturally) it plays streaming video on an app. Currently, Always Home Cam is available by invitation only in the US.

Amazon UK introduced Echo Show 15, a 15.6-inch, 1080p Full HD flat panel display and 5MP camera (with built-in privacy shutter) that can be wall-mounted or placed on a counter using an optional stand. It features a redesigned home screen, more customisation and promises all-new Alexa experiences. The self-contained laptop-size screen is optimised for 'family organisation' and could be the next best thing to a smart TV in the kitchen, Amazon reckons, as it supports Prime Video and Amazon's Drop-In video calling. It has debuted at £239.99. Pre-order from **Amazon.co.uk**

Amazon has opened its first '4 Star' store outside the US – in Kent, England.

The company has also chosen Britain to open its first non-foods '4 Star' store outside the US, in Bluewater, Greenhithe, Kent. The store will sell a special selection of products that average an Amazon 4-star rating, but it does not use 'Just Walk Out' technology used in Amazon Fresh stores (see *PE*, August 2021). A new '4-star' option has been glimpsed in Amazon's shopping app showing a QR code that might offer buyers faster in-store checkouts.

Aviation Spirit

In other news, electrically powered flight took a step towards reality on 15 September when Rolls-Royce announced a successful record-breaking test flight of its new all-electric airplane, the Spirit of Innovation (noting that the figurine adorning Rolls-Royce cars is the 'Spirit of Ecstasy', see: **https://bit.ly/pe-dec21-rr1**).

The electric plane first taxied in March and finally left the ground at a UK Ministry of Defence site in Britain last month. Its aerodynamics are redolent of a Rolls-Royce Merlin-powered Spitfire fighter plane, but in place of a Spitfire's aviation-spirit-fuelled piston

The Spirit of Innovation, an electric aircraft produced by Rolls-Royce takes its maiden flight in England.

Mayflower AI is an autonomous, crewless vessel packed with AI technology designed for marine research.

engine is a 400kW powertrain containing the world's most power-dense battery pack ever built for an aircraft, says Rolls-Royce. The Spirit of Innovation forms part of Rolls-Royce's ACCEL programme, short for 'Accelerating the Electrification of Flight'. You can follow progress at: **https://bit.ly/pe-dec21-rr2**

America's GE is also investing in electric flight, partnering with NASA and MagniX USA in a new $260m EPFD (Electric Powertrain Flight Demonstration) project, with commercial passenger transport ultimately in mind.

Speed control

The automotive press has become very excitable about the forthcoming implementation of automatic speed limiter systems in new cars but, happily, *Net Work* readers already know about them! The September 2019 issue (p.13) forewarned that Intelligent Speed Assistance (ISA) could eventually find its way into cars, and ISAs (also known as ASLs) are now mandated for new vehicle sales from July 2022. A combination of GPS or traffic sign recognition cameras may be used to force a vehicle to slow down to comply with prevailing speed restrictions. Despite Brexit, it's expected that the UK will fall in line with these European safety regulations, though it will be many years before ISAs have any impact on casualty rates.

Backed by the resources of IBM working with other marine partners, the crewless *Mayflower AI* ship is an autonomous vessel and proving ground for AI-powered marine research. With no crew to worry about, Mayflower's designers were able to concentrate on packing the vessel's hull with AI technology instead. During some early trials, problems with its hybrid solar-boosted powertrain were highlighted, so Mayflower returned to dry dock in Plymouth, England for improvements. You can follow the vessel's developments and view dashboard data at: **https://mas400.com/**

Our friends in America might be interested in **https://bit.ly/pe-dec21-mf** as, in actual fact, the Pilgrim fathers originally sailed from this (then tiny) inlet port in north-east Lincolnshire, England to Holland. The town recently celebrated 400 years of the Mayflower's voyage.

Artist impression of the T-pylon test line at National Grid's training academy, the first new design for an electricity pylon in Great Britain for nearly a century.

Pylon upgrade

The first new electric pylon design in Britain for more than 100 years has been erected by contractors Balfour Beatty for National Grid in Somerset, England. The new T-Pylon reduces a pylon's footprint compared with traditional lattice towers commonly populating the British countryside. (Landowners and farmers receive an annual 'way leave' rental for hosting pylons and pipelines on their land, in case you ever wondered). The new design is a single pole with T-shaped arms carrying diamond-shaped cable arrays, and some of the new pylons also contain a time capsule laid by local schoolchildren containing, of course, Covid-19 face masks and lateral flow tests for posterity.

Finally, an interesting footnote to my item in the September issue (page 14) about Virgin Orbit's satellite-launching service based on their specially adapted jumbo jets, and the controversial Nord2 gas pipeline running between Russia and Germany (*PE*, October 2021, p.13). A fascinating article published on **Theaviationgeekclub.com** describes a period in the 1990s when the US tried its best to buy three Soviet Tu-160 Blackjack strategic bombers that were being disposed of by the Ukrainian Air Force. The US badly wanted to ensure they did not find their way back to Russia, and US companies had also won contracts for scrapping military hardware that had become a financial burden for Ukraine. It turns out, according to author Dario Leone, that three Tu-160 bombers were pencilled in for purchase by America's Platforms International Corp in 1999 who, it was said, [ostensibly] intended to convert them into launch platforms for Pegasus Launch Vehicles to place satellites into low-earth orbit. The more things change, the more they stay the same: an added irony is that Ukraine needed the money because it was deeply in debt to Russia because of unpaid gas bills. You can read the full article at: **https://bit.ly/pe-dec21-tu160**

The Northrop Grumman Pegasus project pre-dates the Virgin Orbit 747 satellite launcher and Wikipedia has an item at: **https://bit.ly/pe-dec21-ngp**

See you next month for more news and updates from *Net Work!*

The author can be reached at:
alan@epemag.net

All the hard parts are already done for you!

by Charles Kosina

Easy-to-build Digital AM/FM/SW Receiver

Digital radios are very capable, but can be somewhat complicated and costly to build. Not this one, though! It uses the BK1198 digital radio chip which is cheap and readily available, and requires only a handful of discrete components to work. The resulting radio covers the AM and FM broadcast bands, plus shortwave from 2.7 to 22MHz.

The design of radio receivers has changed dramatically in recent years. For decades, the standard AM receiver was a superheterodyne circuit with a mixer stage that combined the incoming signal with a local oscillator.

The resulting intermediate frequency signal was then further amplified and fed into an envelope detector that extracted the required audio component. Finally, sufficient audio amplification was provided to drive a loudspeaker.

When transistors replaced valves, the initial design philosophy remained much the same. Such receivers (and those that preceded them, such as super-regenerative and tuned radio frequency [TRF] receivers) required multiple tuned circuits, many of them adjustable.

But with the advancement of technology, analogue circuits have largely been replaced by digital techniques.

The BK1198 is a good example of this. Its functions are described in the following PDF document from Jaycar: **https://bit.ly/pe-dec21-bk1198**

Jaycar sells the mono version of the BK1198 separately (Cat ZK8829), as part of a prebuilt AM/FM portable radio (AR1458) or in their 'Cardboard Radio' kit (Cat KJ9021).

We reckoned that we could do more with the chip, and build a more capable radio – hence this design.

If you don't mind using an external speaker, it fits into a low-cost Jiffy box. Alternatively, you can use a larger box and include an internal speaker. Either way, it delivers 0.9W to the 8Ω speaker.

The current band, tuning range and frequency are displayed clearly on a backlit character LCD screen.

It also boasts a tone control, volume control, on/off switch and headphone socket.

So basically, it has everything you need for listening to AM, FM and SW broadcasts and not much else, and it's easy to drive. It runs off a 9-12V AC plugpack or 12V DC external battery.

The PCB has been designed with a mixture of SMD and through-hole components; we can't avoid having SMDs since the BK1198 is not available in any through-hole packages (a common situation these days).

That being the case, we decided to use some larger passive SMDs to keep the overall device compact, without making it too hard to put together.

Performance

Performance is reasonable for such a simple design. On the FM band, I found an internal wire length to be quite adequate to pick up many local stations (in my case, the Melbourne area) with good quality. I do have line-of-sight to to local towers, however.

The AM band suffers from interference from various sources, and switch-mode power supplies in the vicinity will create background noise. Moving away from such sources gives reasonable quality.

I got the best results by taking it into my car and running it off the car battery.

On the short wave bands, a 1µV signal is detectable, and 10µV gives a reasonable signal-to-noise ratio.

Circuit description

While the simplest radio designs using the BK1198 require only a few discrete components plus an audio amplifier, my design is rather more ambitious, but thanks to the use of an Arduino Nano, still manageable. The circuit I came up with is shown in Fig.1.

There are two ways of controlling the BK1198 radio chip (IC4), selected by the MODE pin (pin 5). If this pin is tied low, it's controlled by serial data on the SCLK and SDIO pins. While this would appear to be the sensible approach, documentation on how to do this is rather sparse, and the translation from Chinese does leave a lot to be desired.

My design leaves this as a future option, but for now, an analogue tuning approach is used. This means that we have the jumper on LK1 pulling MODE up to 3.3V.

A voltage on the BAND pin (pin 15) selects the band that the BK1198 operates on. There are a total of 18 pre-programmed frequency ranges available, and the simplest way is to have a voltage divider connected to TUNE1 (pin 1), which is the tuning supply voltage and very close to 1.2V. However, I have used a different approach. The required voltages are:

AM 2 (513–1629kHz, 9kHz steps)
300mV

FM 1 (87–108 MHz, 100kHz steps)
33mV

SW10 (2.7–10.25MHz, 5kHz steps)
1033mV

SW11 (9.8-22MHz, 5kHz steps)
1100mV

The appropriate voltage is generated by IC2, an MCP4822 12-bit digital-to-analogue converter (DAC). The user controls the band using 6-position rotary switch S2.

Why six position? I decided to split up each of the shortwave bands into two (more on why I did this later).

The frequency tuning voltage is generated by another DAC, the DAC8551 (IC6), which has 16-bit resolution. It needs to be more accurate than the band selection voltage, hence the higher resolution.

The reference voltage for this DAC is the 1.2V on pin 1 of IC4 (TUNE1). This ratiometric approach ensures that an accurate voltage will be generated regardless of the BK1198 chip variations you may encounter.

If we take the FM band as an example, there are 210 channels spaced at 100kHz intervals.

The change in channel voltage is thus 1200mV ÷ 210 = 5.7mV. One bit of the 16-bit DAC represents about 18.3µV (1.2V ÷ 2^{16}), so the digital value steps by about 311 to switch from one channel to the next. This is a more-than-an-adequate safety margin in resolution.

It gets a bit tighter on the shortwave bands. There are 2440 channels spaced at 5kHz on the 9.8–22MHz band. This is only 490µV between channels, or a step-change of 27 in the digital data. Again, we have a sufficient safety margin.

Note that a 12-bit DAC would have less than two steps between channels, which would be quite inadequate.

Coverage

AM:	**513-1629kHz**	(1kHz steps)
FM:	**87-108MHz**	(100kHz steps)
SW1:	**6.4-10.25MHz**	(5kHz steps)
SW2:	**2.7-10.25MHz**	(5kHz steps)
SW3:	**9.8-15MHz**	(5kHz steps)
SW4:	**14.0-22MHz**	(5kHz steps)

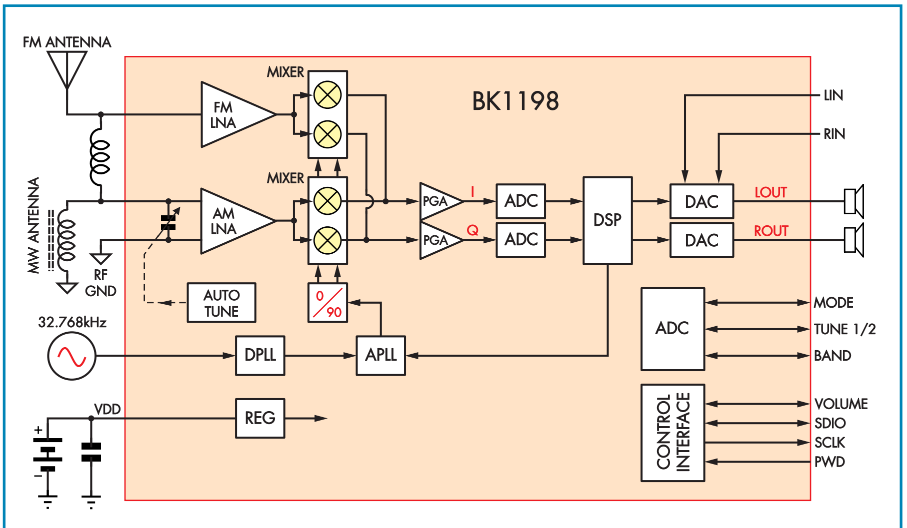
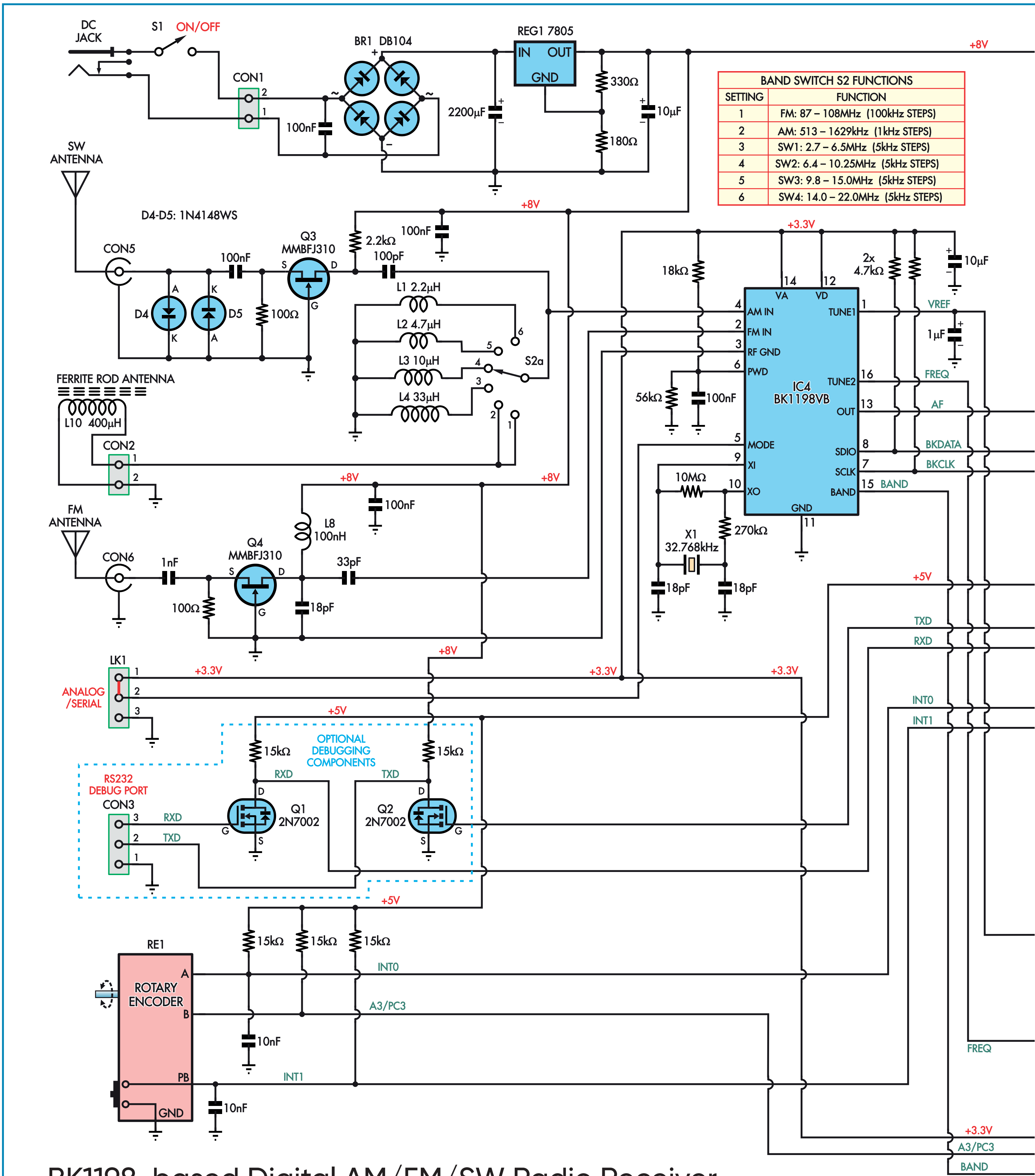


Fig.1: block diagram of the BK1198 radio receiver chip, on which this project is based. All you have to do is tell it which band(s) you want to listen to, display its details and amplify the audio output.



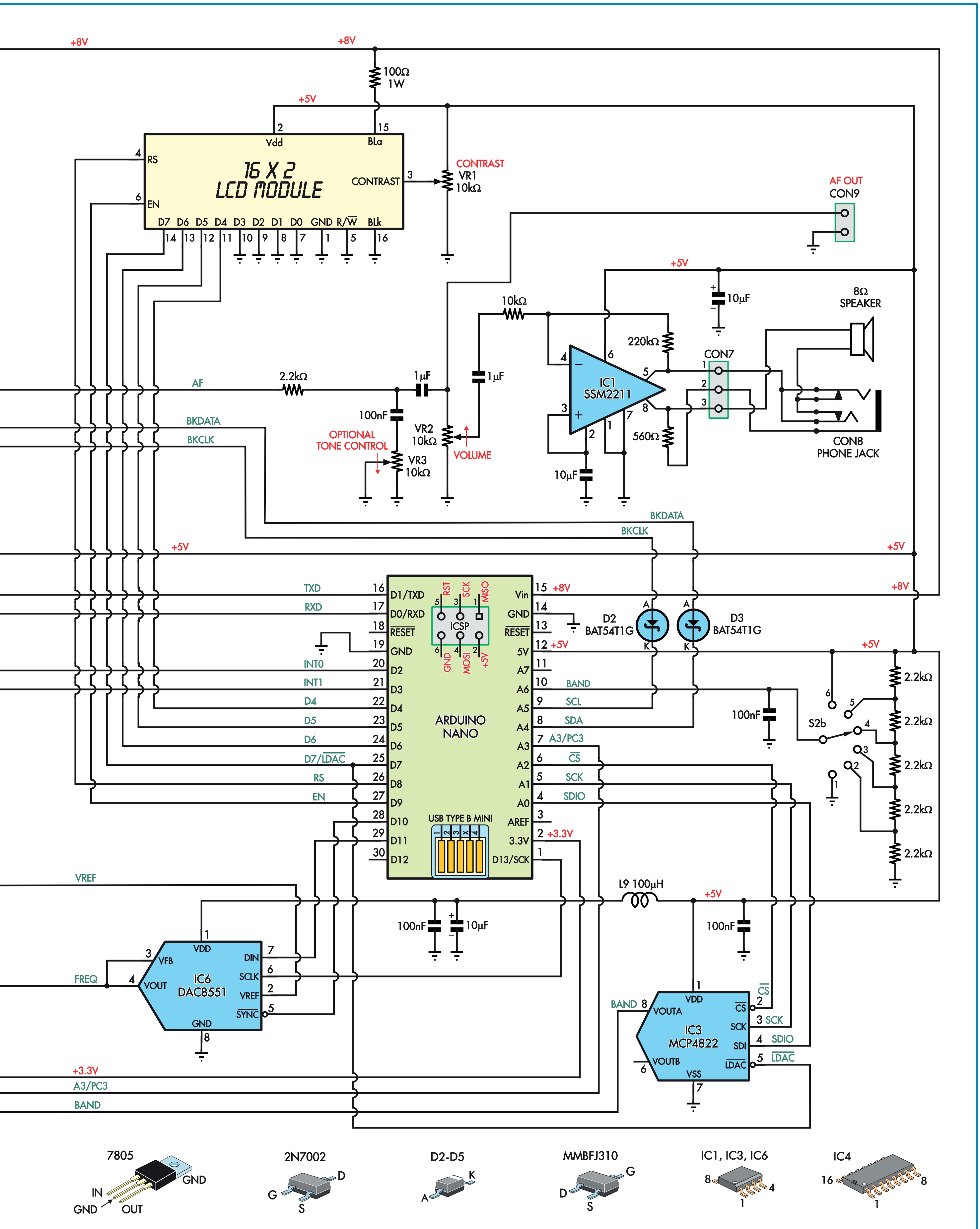
BAND SWITCH S2 FUNCTIONS	
SETTING	FUNCTION
1	FM: 87 – 108MHz (100kHz STEPS)
2	AM: 513 – 1629kHz (1kHz STEPS)
3	SW1: 2.7 – 6.5MHz (5kHz STEPS)
4	SW2: 6.4 – 10.25MHz (5kHz STEPS)
5	SW3: 9.8 – 15.0MHz (5kHz STEPS)
6	SW4: 14.0 – 22.0MHz (5kHz STEPS)

BK1198-based Digital AM/FM/SW Radio Receiver

Fig.2: despite receiving FM and AM in three different bands, the radio circuit is relatively simple thanks to the all-in-one BK1198 digital radio receiver chip (IC4). JFETs Q3 and Q4 provide extra RF gain for shortwave and FM signals respectively, while inductors L1-L4 provide preselection for different shortwave frequency ranges. Tuning and band switching is controlled by the Arduino Nano using DACs IC3 (12-bit, for band selection) and IC6 (16-bit, for tuning). IC1 is the audio amplifier.

There are two RF inputs on the BK1198 chip. It receives the FM signal at pin 2. Reference designs include a preamplifier using an NPN transistor, but I opted to use a grounded-gate JFET as this gives good gain and a high stability margin.

The second RF input is on pin 4, and is for the AM and SW bands. This presented something of a design challenge. For the AM band, a ferrite rod of about 400μH is required. An internal varicap tunes the ferrite rod to the correct frequency. However, there are not many pre-wired ferrite rods



available – the only one Jaycar sells is their Cat LF1020. I found the performance of this one not very satisfactory.

A better option is to use their LF1012 ferrite rod, which is 180mm long and 9mm diameter. With 65 turns of 24AWG (0.5mm diameter) enamelled copper wire, this gives considerably improved performance. The Q of such a coil is not particularly high, and it is preferable to use Litz wire, but it is challenging to strip and tin each strand. Litz wire is used on the LF1020, and it's possible to very carefully remove this winding and slip it on the longer rod, and thus provide an almost-ideal solution. (If you are building this project and don't have 'easy' access to Jaycar then get the spec from the Jaycar online catalogue, source similar parts and experiment.)

Shortwave tuning

I felt that a low-noise preamplifier was desirable for the SW bands, so I chose the J310 JFET for this as well. Since I wanted some degree of tuning on this preamplifier, I used different inductors for the various bands, which brings me back to why I divided up the shortwave bands into two.

My original intention was to use a readily available varicap diode, type BB201, which has a range of about 20–110pF with a tuning voltage of 10–0.5V.

This tuning voltage was to be generated by the second DAC in IC3, and amplified by a rail-to-rail op-amp running off 12V. The varicap range is such that it would cover the appropriate band with the chosen inductor.

By using an appropriate formula, the tuning voltage could be calculated by the micro.

However, this just did not seem to work at all; the best result obtained was with the varicap run at its minimum capacitance, regardless of the band or frequency.

Based on the BK1198 documentation, I gathered that its internal varicap only operated on the AM band. But I suspect that it also works on the SW bands, although the documentation does not describe this. The op amp and varicap of the original prototype were therefore unnecessary, so I removed them in the final design.

You will see that there is a 2.2kΩ resistor from the drain of Q3 to +8V. Originally, this was a 1000µH RF choke, which was fine for the shortwave bands, but it completely killed the AM band because the 100pF capacitor in series resonated within the AM band and formed a very effective series-resonant trap.

By replacing it with a resistor, the HF performance is not significantly affected, and it has a minimal effect on the AM band.

Small-signal diodes D4 and D5 provide some measure of protection against voltage spikes being picked up on the SW antenna, for example, during a thunderstorm. Obviously, they cannot protect against a direct or even nearby strike, but will prevent damage to Q3 from general lightning activity.

The 100pF coupling capacitor, in combination with the inductor L1-L4 selected by rotary switch S2a peaks the shortwave preamp response around the selected frequency band.

Band selection details

Getting back to band selection, S2b selects from equally-spaced voltages between 0 and 5V, generated by a chain of 2.2kΩ resistors between 5V and 0V.

The selected tap is fed to the internal analogue-to-digital converter (ADC) of the AVR ATmega328 chip on the Arduino Nano module. This ADC has a 10-bit resolution, so that the values read are approximately 0, 204, 409, 613, 818 and 1023.

By truncating the last two digits we get 0, 2, 4, 6, 8, and 10. Then dividing by two and adding one gives the selected band number, from one to six. The Arduino code then uses a lookup table to find the value needed to generate the appropriate band select voltage for the BK1198 chip.

This is a more versatile arrangement than using a resistor network to generate the voltage directly, as it can easily be programmed to select any of the different bands available.

Switch positions 3 and 4 both select the 2.7-10.25MHz band, and switch positions 5 and 6 both select the 9.8-22MHz band. However, different inductor values are chosen as part of the SW filter by S2a for each shortwave position.

The Arduino Nano module is available at very low cost and has the advantage of providing regulated 5V and 3.3V outputs, which are needed by other devices in the circuit. Most of its I/O pins are used. The LCD module is the popular 16×2 type that is widely available.

The SCL and SDA lines of the Nano are routed to the BK1198 chip in case someone can work out how the BK1198 serial interface works. The Nano is a 5V device, while the BK1198 runs from 3.3V.

So schottky diodes D2 and D3 are used (along with pull-up resistors to 3.3V) to prevent damage to the BK1198 IC.

Tuning is controlled via incremental rotary encoder RE1. The falling edges of its output pulses generate an interrupt on the INT0 pin (Arduino digital input D2), at which point the state of analogue/digital input A3 is read.

If it is high, the frequency is increased by the appropriate step, and if low, it is decreased. This scheme works with either momentary or level type encoders.

The pushbutton switch integrated with the rotary encoder is connected to INT1 (digital input D3). This is used to toggle between the step sizes on different bands. On the AM band, the spacing in Australia is 9kHz, but the toggle allows for 1kHz step size as well. On the FM band, only a 100kHz step size is used, as it does not take too long to sweep across the band.

All four shortwave bands have step sizes that can be set to 5kHz, 50kHz and 500kHz.

Audio amplification

The audio output section is fairly straightforward. The OUT pin of the BK1198 chip (pin 13) is capacitively coupled to volume control potentiometer VR2. The tone control potentiometer (VR3) at minimum resistance gives a –3dB point of about 700Hz. This works by forming a variable low-pass filter in combination with the 2.2kΩ resistor and 100nF capacitor.

The audio amplifier is an SSM2211 chip which will deliver about 0.9W into 8Ω. The phono jack is configured to cut off the signal to the loudspeaker when phones are inserted. To prevent hearing damage, a 560Ω resistor reduces the output level to the headphones.

Power supply

The original idea was to run the radio from a 12V DC plugpack. There are plenty of switchmode ones available, but they generate so much hash as to make the AM band all but useless.

You could use one which has an iron-cored transformer, but they are almost impossible to buy new now. Fortunately, Jaycar still sells a 9V AC plugpack, the MP3027. We use this and rectify its output using bridge rectifier BR1. The resulting pulsating DC is filtered by a 2200µF capacitor and applied to the input of 7805 regulator REG1.

Don't be fooled though – this regulator is not producing a 5V output. A resistive divider between its output, GND pins and the actual circuit ground (0V) lifts its output to 8V while retaining decent regulation.

The Nano module has a 5V regulator, which powers the ATmega328 micro and also the audio amplifier.

We don't want this regulator to drop too much voltage or else it could overheat. Tests showed that with sustained

Quirks with the BK1198's shortwave tuning

My original prototype had a problem with its SW10 shortwave range; I found it to actually cover 3.1–10.1MHz rather than the expected 2.7-10.25MHz range.

As the ranges are set at the factory by internal programming, this could have been an anomalous chip. Replacing the chip gave me the correct range.

Fortunately, if this happens to you, it is easy to correct by altering just a few numbers in the program code.

maximum audio output, this regulator does not overheat as long as its input voltage is no higher than about 8V. So REG1 is essentially a pre-regulator for the Arduino's own 5V regulator.

Note that you could use a 7808 for REG1, leave out the 330Ω resistor and replace the 180Ω resistor with a wire link or 0Ω resistor. However, 7808s are not as common to find as 7805s are.

By the way, the 100nF capacitor across the input to bridge rectifier BR1 may seem redundant, but it helps to filter out any unwanted RF picked up by the supply leads.

Debugging interface

A simplified RS232 serial interface is provided by transistors Q1 and Q2, which operate as level shifters. This was included purely for debugging purposes in development, operating at 38,400 baud with the usual 8,N,1 encoding. These components (and their 15kΩ drain pull-up resistors) may be omitted if you don't plan to fiddle with the software.

Software

The firmware is written in BASCOM, a versatile BASIC-like language that compiles into native AVR code.

On power-up, the receiver retrieves the last frequency and step size for the set band from EEPROM. The LCD module shows the selected band on the top line and the set frequency on the bottom line. When another frequency is selected by the tuning knob, the new set frequency and current step size is written into the EEPROM after about half a second.

Sourcing the components...

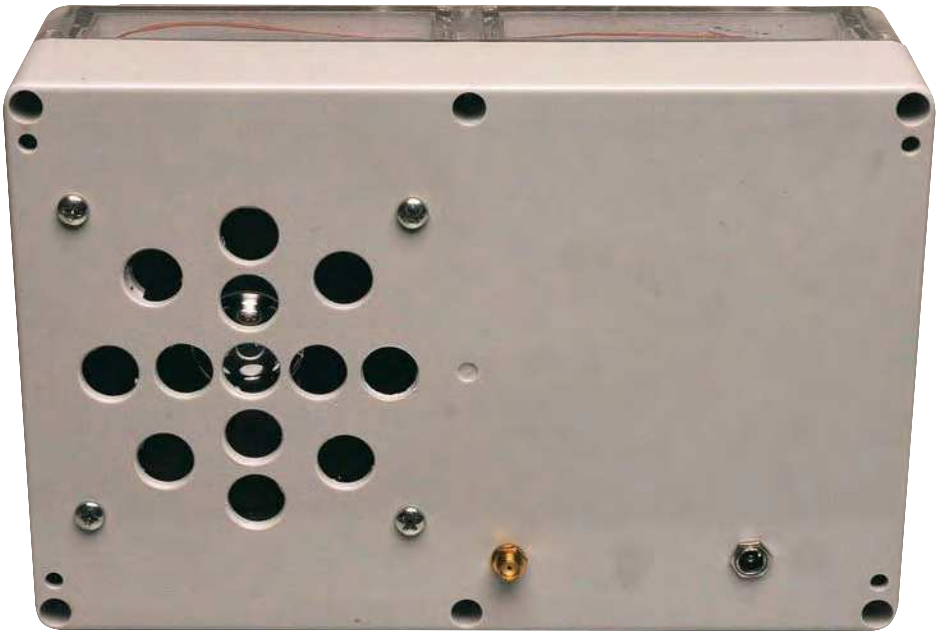
We know that sourcing components can be a challenge, so the ones used in this design were carefully chosen so that they are available from suppliers such as Jaycar, Altronics and element14. In some cases, you might have to buy multiples of the one item.

...but do remember!

Some of these items might be available more cheaply on eBay, AliExpress or Banggood, if you don't mind the longer lead time. For the full details, see the parts list below.

Construction

Refer to the PCB overlay diagram, Fig.3. The BK1198 radio is built on a PCB coded CSE200902A, available from the *PE PCB Service*. It measures 127 × 88mm. If you have some experience soldering surface-mount components, the assembly should not present any problems for you. If you don't, you might want to practice with something simpler first.



Case holes required for the receiver. No diagram is shown for these as none of them are super-critical.

Start by fitting IC6, the 16-bit DAC. It's in an eight-pin fine-pitch (0.65mm) package and does require special care. First, locate its pin 1 dot in the top corner and line it up with the pin 1 indicator on the PCB. Spread some flux paste over the pads, place the chip and carefully tack down one corner pin.

Use a magnifier to verify that the other seven pins are correctly located over their pads. If not, re-melt the solder on that tacked pin and gently nudge it into position.

Repeat until it is precisely located, then solder all the pins and again use a magnifier to check for bridges between pins. If you find any, add extra flux paste and clean up the bridge(s) using solder wick.

The remaining ICs have twice the pin pitch (1.27mm), so they should be fairly easy in comparison. Use a similar technique to fit those, making sure in each case to check the pin 1 orientation before soldering.

Follow with the four small transistors and the four diodes. Don't get the different types of transistors or diodes mixed up. The orientation of each transistor will be obvious, but you will have to check (probably under magnification) for the cathode stripe on the diodes to determine their correct orientations.

The SMD resistors and capacitors are all either 2.0 × 1.2mm or 3.2 × 1.6mm, so again should be fairly easy and they are not polarised. The SMD resistors will be printed with a tiny code on top that identifies their value (eg, 183 [18×10^3] or 1802 [180×10^2] indicates 1.8kΩ) while the capacitors will be unmarked. Make sure each component goes in the correct location as per Fig.3.

Through-hole parts

Next, fit the low-profile through-hole parts: the 1W resistor, axial inductors and the bridge rectifier (watch the orientation – the positive terminal should be marked).

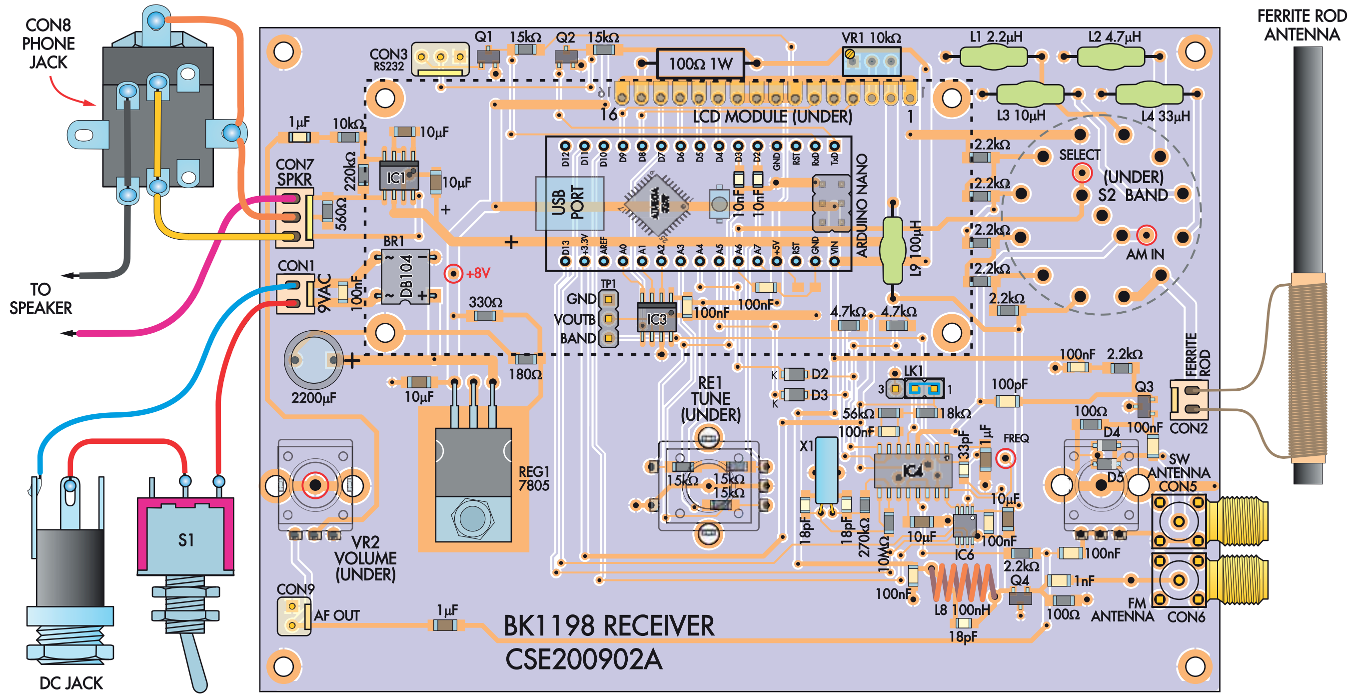
The watch crystal (X1) is laid over on its side and held down with a loop of wire soldered to the board (use a component lead offcut). Be careful bending and soldering its leads because they will be very thin, and you don't want them shorting against each other or the crystal case.

Continue by fitting taller parts like trimpot VR1 (with its adjustment screw towards BR1), polarised headers CON1-CON3, CON7 and CON9 and SMA sockets CON5 and CON6. Also fit the 3-pin header for LK1, and place the shorting block between pins 1 and 2 and the socket strips for the Arduino Nano.

Note that you don't need CON3 unless you plan to use the serial debugging feature, and most of the other headers could be left off if you prefer to solder flying leads straight to the board. That will make the final construction steps a bit more tricky, though. Also, if you live in a strong signal area, you could use FM antenna connector CON6 off the board and just solder a length of wire to its central pad.

Now mount the Arduino Nano module, which can be soldered straight to the board (it's usually supplied with pin header strips) or optionally, plugged in via female sockets soldered to the board.

Either way, make sure that its pinout matches the PCB silkscreen. With that in place, fit the sole electrolytic capacitor, ensuring its longer lead goes to the pad marked with a '+' symbol.



The last part to fit on this side of the board is inductor L8, which is wound using six turns of 0.5mm-diameter enamelled copper wire on a 5mm-diameter former (such as the shaft of a 5mm drill bit).

Space out the windings so that the coil is 7mm long, then cut it to length, strip the enamel off the ends of the wires (using emery paper or a sharp knife), tin the wires and solder the coil to the board where shown.

Underside components

We have seen LCDs with pins 1 (GND) and 2 (+5V) swapped, so check your screen. If pin 2 is GND, you will need to cut the header pins off and add wires to cross these connections over.

The LCD screen mounts on the underside of the board. Solder its header strip in place, then check that it has a pin header attached; if not, solder it now. Plug it into the socket and attach it to the board using the tapped spacers and machine screws.

With the LCD in place, the remaining underside components can be fitted: rotary encoder RE1, rotary switch S1, volume control potentiometer VR2 and tone control potentiometer VR3.

Preparing the ferrite rod antenna

As explained earlier, you probably won't find a 400µH ferrite rod that comes pre-fitted with a coil. The easiest and best solution is to also buy a smaller ferrite rod antenna, such as the Jaycar LF1020, carefully remove the windings from that rod and then gently slip them over the longer rod.

If you can't (or don't want to) do that, instead wind 65 turns of 0.5mm enamelled copper wire onto the rod, and strip and tin the ends, ready for attachment to the PCB via flying leads.

Programming

You can program the Nano module separately, or plugged into the main board, but it's easier before you plug it in.

As the code is written in BASCOM, you can't use the Arduino IDE to program the chip. We suggest a free program called AVRDUDE or (preferably) its Windows graphical version, AVRDUDESS. Download and install it from: **https://bit.ly/pe-dec21-avrdude**

Launch it and find the dropdown under the label 'Presets' in the upper right-hand corner of the window, click the drop-down and select the 'Arduino Nano (ATmega328P)' option. In the upper left-hand corner, modify the COM port number to match your Nano. Once you have plugged it in, you can find its port number in Windows' 'Bluetooth and other devices' Settings page.

Under the 'Flash' heading, click the '...' button and find the radio HEX file (available as a download from the December 2021 page of the *PE* website). Ensure 'Write' is selected just below this and press 'Go'. Messages will appear at the bottom of the window, hopefully indicating that the programming was successful. The most likely cause of any problem is an incorrect port selection.

Finally, unplug the USB cable from the Arduino Nano module and plug it into your radio board. The board assembly is now complete.

Testing

It's a good idea to do a little bit of testing before you put the board in the case, as it is easier to debug and fix in its current state. You will need some sort of antenna connected to verify that the radio is working – at this stage, the FM antenna is probably the easiest to organise. A length of wire might be good enough for initial testing.

You will also probably want to temporarily connect an 8Ω speaker between pins 1 and 3 of CON7.

Position the board so that you can see the LCD and access the controls, and connect a 9V AC or 12V DC power supply to CON1. Verify that the LCD backlight switches on and you get a sensible display on the LCD screen. If you can't see the characters, try adjusting trimpot VR1.

If the backlight doesn't come on, then that points to a power supply problem – check the output of REG1 and verify that it is a steady 8V or so.

If you still don't get any display, then there may be a problem with the programming of the Arduino Nano module, or perhaps the Nano or LCD are not making good contact with their sockets.

Assuming that the display looks OK, rotate S2 to get the unit into FM mode and then try turning RE1 to find a station.

Adjust VR2 to get a sensible volume from the speaker. If you can pick up stations then it's all looking good. If not, you might need a better antenna, or you could have a problem in or around transistor Q4, IC4, crystal X1 or audio amplifier IC1.

If you want to test the other bands, then you will need to connect up a shortwave antenna to CON5 and/or the ferrite rod to CON2.

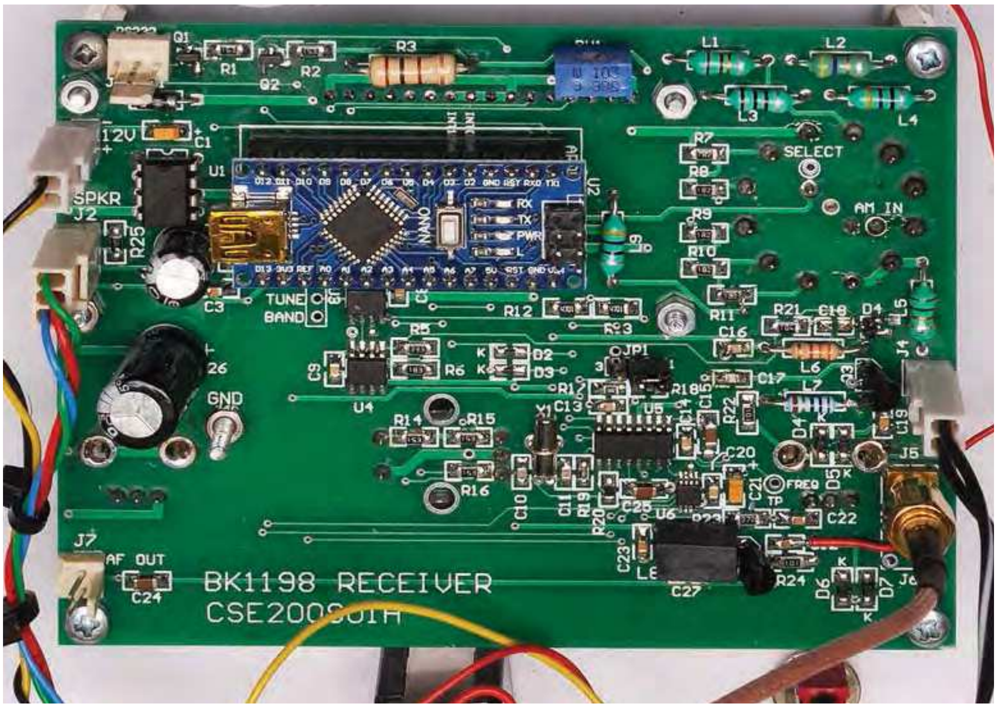


Fig.3 (left): the PCB uses a mix of SMD and through-hole components. Start by fitting the only fine-pitch SMD, IC6, then the remaining SMDs (don't forget the two caps under the Nano!), followed by the top-side through-hole parts and finally, those which mount on the underside (mainly the display and controls).

There are a few optional components, such as the debugging header CON3. This diagram also shows most of the external wiring.

At right, the photo shows the assembled PCB mounted in the case. Note that this is an early prototype board so there are some minor differences between this and the PCB overlay opposite.

Assuming that it all checks out, you can now proceed to finish the build. If you run into problems, it's always a good idea to carefully inspect all of your solder joints, while also verifying that the right parts are in the right locations, and any polarised components have not been soldered in the wrong way around.

Final construction

If you're building the radio into the smaller and cheaper UB2 Jiffy box, you can drill and cut holes in the lid that came with your box.

Fig.4 shows the details of the cut-outs. You could cut a piece of ~3mm thick plastic to this size and make the cut-outs, but it's probably easier to just print this (it's available as a PDF download from the December 2021 page of the *PE* website) and use it as a template on the existing Jiffy box lid.

A laser cutter can't make countersunk holes for the PCB mounting screws, so if you are cutting your own, you will need to use a countersinking tool to profile those four holes on the outside face of the panel.

It's also a good idea to attach a panel label. The artwork we've prepared is available as a PDF download from the December 2021 page of the *PE* website.

Print it onto adhesive paper or print it onto regular paper and laminate it. You can then cut the panel to size and cut out the holes with a sharp hobby knife. But before you glue it to the lid, attach the PCB to the rear so that you can hide the mounting screws.

The radio board attaches to the back of the lid using the 15mm spacers, with countersunk screws through the lid and regular machine screws holding the PCB to the spacers. Once the panel has been glued in place, you can attach the nuts to hold the potentiometer(s), rotary encoder and rotary switch to the panel, then attach the knobs (after cutting down any shafts which are too long).

The power on/off switch (S1) and headphone socket (CON8) mount in the hole provided on the front panel. You will also need to drill a hole somewhere in the side of the box for the barrel power socket. While you're at it, decide where in the case you are going to mount the ferrite rod, and if fitting an internal speaker, that too (you will need to drill sound and mounting holes).

Once you drop the lid into the box, the FM and SW sockets will be accessible via holes in the left-hand side. Temporarily insert the lid into the box and mark out the locations, then drill these holes large enough to get cables onto those connectors.

One of the last steps is to make up the wires and plugs for the ferrite rod, power supply and switch and speaker/headphone socket.

For the ferrite rod, this is simple; you just need to attach a two-way plug to the end of a short piece of shielded cable or twin-lead. The polarity doesn't matter, but it must be long enough to reach CON2 before the lid is attached to the case. Solder this to the primary winding on the ferrite rod.

If you're using a pre-made coil, it might have two pairs of wires, so use the pair with the highest (but non-infinite) resistance reading between them.

The power wiring is slightly more complicated (see Fig.3); one pin of CON1 (it doesn't matter which) goes straight to the outer barrel contact of the socket, while the other pin goes to the central pin contact via switch S1. If your switch has more than two contacts, pick two which are connected when the switch toggle is down but open when up.

One possible pitfall is that barrel sockets often have three solder tabs, one of which is disconnected when a plug is inserted. So make sure the outer barrel contact you solder to is not that one. It's easiest to check by inserting a plug, then soldering to the tab which has continuity to the outer barrel.

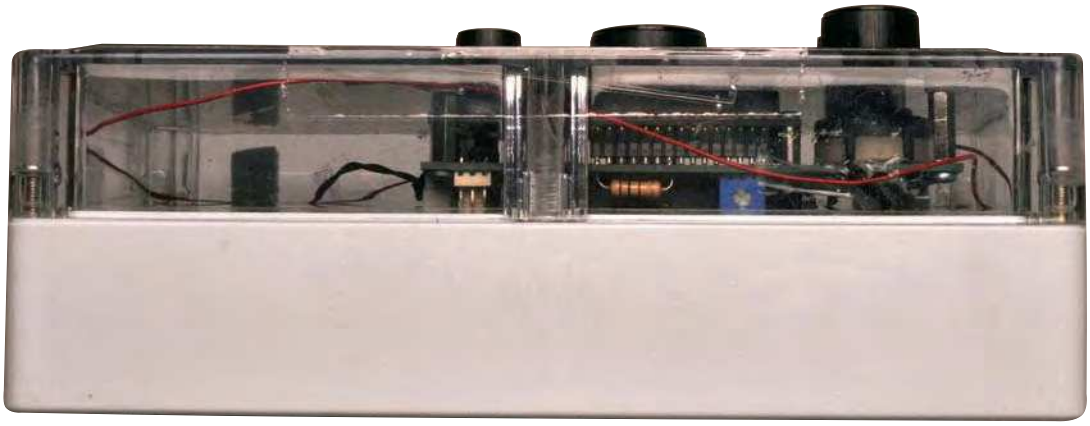
Finally, wire up the headphone socket and speaker as per Fig.1 and Fig.3. Start by identifying the switched and unswitched tip and ring contacts on the socket and joining them together, turning it into a mono socket. Connect the sleeve tab back to the middle pin of the

Radio source code

We will make the source code available for this project, along with the HEX file.

The firmware was written in BASCOM-AVR, a version of the BASIC language that compiles to native Atmel AVR code. So it is quite easy to modify.

BASCOM is commercial software; there is a free demo version available which can produce binaries up to 4KB in size, but the radio software is larger than that. A full license for the software costs around £100 (it's available from a few different online shops). But, do note this is only relevant for those who wish to edit the software. You do not need it to load the HEX file into the chip. There are plenty of free software packages that can do that, like MPLAB IPE and AVR Studio.



The see-through case shows how the electronics mounts to the lid/front panel – and because you can see the 'works', it also adds to the intrigue of this radio!

Parts list – AM/FM/SW Digital Receiver

1 double-sided PCB coded CSE200902A, 127 x 88mm
1 5V Arduino Nano module
1 16x2 blue backlit alphanumeric LCD module
1 220 x 160 x 80mm IP65 sealed ABS enclosure or similar (fits internal speaker), ***OR***
1 UB2 Jiffy box, 197 x 113 x 63mm (no internal speaker)
1 10kΩ single-turn mini vertical (SIL) trimpot (VR1) [eg, element14 9317236]
2 9mm vertical 10kΩ potentiometer (VR2, VR3) [eg, element14 1191725]
1 2.2µH axial RF inductor (L1) [eg, element14 1167666]
1 4.7µH axial RF inductor (L2) [eg, element14 1180375]
1 10µH axial RF inductor (L3) [eg, element14 1180270]
1 33µH axial RF inductor (L4) [eg, element14 1857853]
1 100µH axial RF inductors (L9) [eg, element14 2858897]
1 1m length of 0.5mm diameter enamelled copper wire (L8 and possibly L10)
1 400µH ferrite rod (L10)
1 coil taken from ferrite rod antenna (L10)
1 32768Hz watch crystal (X1) [Jaycar RQ5297]
1 rotary encoder with inbuilt pushbutton (RE1) [eg, element14 2663519]
1 SPST chassis-mount toggle switch (S1)
1 2-pole, 6-position rotary switch (S2) [Jaycar SR1212]
3-4 knobs (to suit VR2, VR3 [if fitted], RE1 and S2)
3 2-pin polarised headers (CON1,CON2,CON9) [Jaycar HM3412]
3 2-pin polarised plugs (for CON1,CON2,CON9) [Jaycar HM3402]
2 3-pin polarised headers (CON3,CON7) [Jaycar HM3413]
2 3-pin polarised plugs (for CON3,CON7) [Jaycar HM3403]
2 right-angle or vertical PCB-mount SMA sockets (CON5,CON6) [eg, element14 2612349]
1 6.35mm switched stereo chassis-mount jack socket (CON8) [Jaycar PS0184 or similar]
2 15-pin female header sockets (for the Nano; can be cut down from longer strips)
1 16-pin female header socket (for the LCD)
1 3-pin header with jumper/shorting block (LK1)
1 2.1mm inner diameter bulkhead barrel socket [Jaycar PS0522 or similar]
1 8Ω 1W full-range speaker driver (eg, 76mm if mounting in a larger box) or an external 8Ω speaker)
4 knobs (size as required)
4 8mm-long M3 tapped spacer (for mounting LCD)
4 15mm-long M3 tapped spacers (for mounting PCB to box)
12 M3 x 5mm panhead machine screws
4 M3 x 10mm countersunk head screws
various lengths of shielded and hookup wire

Semiconductors
1 SSM2211SZ or NCS2211DR2G 1.5W audio power amplifier, SOIC-8 (IC1) [element14 2464727]
1 MCP4822-E/SN dual 12-bit DAC, SOIC-8 (IC3) [element14 1439414]
1 BK1198VB digital radio receiver, SOIC-16 (IC4) [Jaycar ZK8829] – **IMPORTANT**: many vendors (eg, Amazon or AliExpress) sell the SOP (not SOIC) version. This is essentially identical, and you can use it instead.
1 DAC8551IDGKT 16-bit DAC, VSSOP-8 (IC6) [element14 1693841]
1 7805 5V 1A linear regulator (REG1)
2 2N7002 N-channel MOSFETs, SOT-23 (Q1,Q2) [element14 1764537]
2 MMBFJ310LT1G N-channel VHF/UHF JFETs, SOT-23 (Q3,Q4) [element14 1431340]
1 DB104 bridge rectifier, DIP-4 (BR1)
2 BAT54T1G schottky diodes, SOD-123 (D2,D3)
2 1N4148WS signal diodes, SOD-323F (D4,D5)

Capacitors (through-hole)
1 2200µF 16V electrolytic

Capacitors (SMD M3216/1206-size)
4 10µF 25V X7R ceramic
3 1µF 25V X7R ceramic

Capacitors (SMD M2012/0805-size)
1 10µF 25V X7R ceramic
9 100nF 50V X7R ceramic
2 10nF 50V X7R ceramic
1 1nF 50V X7R ceramic
1 100pF 50V C0G/NP0 ceramic
1 33pF 50V C0G/NP0 ceramic
3 18pF 50V C0G/NP0 ceramic

Resistors (all SMD M3216/1206-size 1% thick film unless otherwise specified)

1 10MΩ M2012/0805-size	(code 106)
1 270kΩ M2012/0805-size	(code 274)
1 220kΩ	(code 224)
1 56kΩ	(code 563)
1 18kΩ	(code 183)
5 15kΩ	(code 153)
1 10kΩ	(code 103)
2 4.7kΩ	(code 472)
7 2.2kΩ	(code 222)
1 560Ω	(code 561)
1 330Ω	(code 331)
1 180Ω	(code 181)
2 100Ω	(code 101)
1 100Ω 1W 5% axial	(code brown black brown gold)

UK/EU/US... readers
You don't need to use the exact Altronics/Jaycar parts listed here – they are quoted so you can find local alternatives from the specs provided online.

plug for CON7. The contacts which connect to the ring and sleeve when a plug is inserted then go to pin 1 of CON7.

Then wire the unused pair of headphone socket contacts to one end of the speaker, and the other end of the speaker back to pin 3 of CON7.

Note that if you're building it into the UB2 Jiffy box and using an external speaker, you will have to run a pair of wires out of an extra hole in the case to your external speaker. Alternatively, fit a two pin (or more) connector somewhere on the box, with a matching plug for the external speaker.

A good option for this external speaker is to use an unpowered computer speaker, which usually has a 3.5mm jack plug fitted, then use a 3.5mm jack socket to connect it back to the radio board.

When the wiring is complete, you can plug all the wires into the appropriate headers on the board, then give it all a final test before buttoning it up (ie, attaching the lid to the box). You should be able to do this using the self-tapping screws supplied with the box.

You can now enjoy listening to your new radio!

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An alternative, smaller and slightly cheaper version

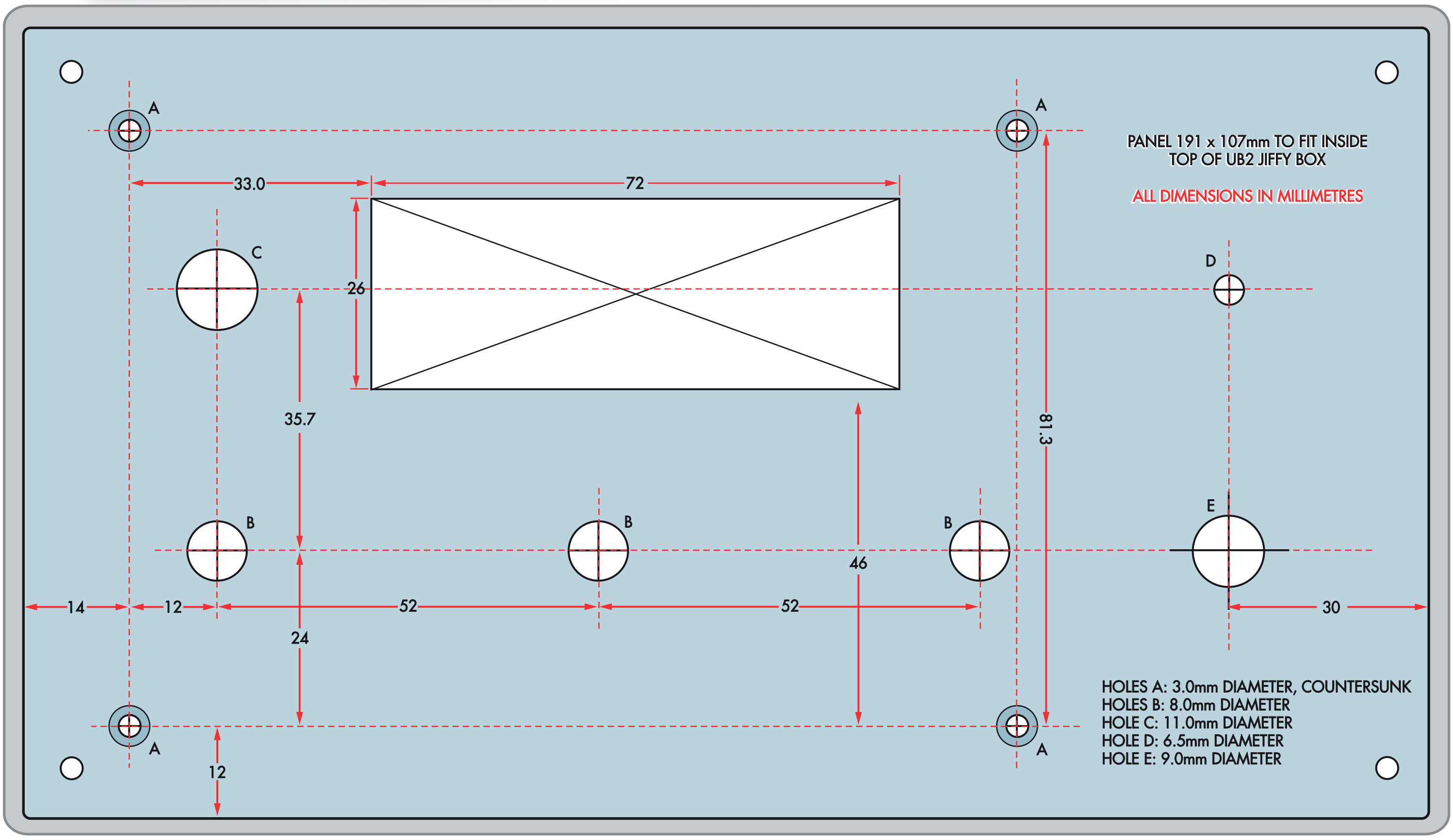
We have also made a second version of the AM/FM/SW receiver which is not only more compact, it is also a little cheaper to build.

It uses the same BK1198 receiver module; in fact, the electronics is virtually identical. The main difference is that it doesn't have an internal speaker, relying instead on headphones or earpieces. (The photo below shows a 3.5mm adapator plugged into a standard 6.35mm socket, so it will take the vast majority of headphone types.)

The other difference is that it uses a standard UB2 jiffy box instead of the more expensive (and larger) ABS case.

Construction is basically the same as the larger version. Like the larger version, the PCB assembly 'hangs' from the case lid, with suitable cutouts for the display, controls and 'phones socket. The photos show how the assembled BK1198 receiver board is an easy fit in the smaller case.

Front panel artwork, as shown in the photo below can be downloaded from the December 2021 page of the *PE* website – it can also be used as a drilling template.



Lid drilling detail for the Jiffy Box version. This, and the front panel artwork is available from the December 2021 page of the PE website.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Balanced Input and Attenuator for the USB SuperCodec

Part 1 – by Phil Prosser

This compact balanced input attenuator is designed to fit into the same instrument case as the *USB SuperCodec* finished last month. It provides four attenuation settings of 0dB, –10dB, –20dB and –40dB and has performance to match the superlative *SuperCodec*. Together, they form a potent recording and/or measurement system.

The SuperCodec USB Sound Card described over the last three issues has excellent recording and playback performance, so it can form the core of a high-performance audio measurement system.

One thing that it lacks compared to our commercial Audio Precision systems is a balanced input. Our AP System One and System Two devices both have balanced and unbalanced inputs, and you can select between them.

There are times where you need those balanced inputs; sometimes, you want to measure the performance of a balanced audio device. However, even with unbalanced devices, it is common to get better results using balanced measurements. That's because it helps to eliminate the common-mode noise inherent in connecting two different devices (the measurement system and the device under test or DUT).

Another thing that the Audio Precision devices have but the *SuperCodec* lacks is input attenuators. The AP systems can measure a wide range of signals from line level (well below 1V RMS) up to the output of multi-hundred-watt amplifiers (50V+ RMS).

You could build our *2-Channel Balanced Input Attenuator for Audio Analysers* (May 2016) and hook it up to the *SuperCodec* inputs. That would solve both problems and give you a test instrument with flexibility approaching that of the AP System Two (and in some senses, exceeding it).

However, then you would have two boxes or three boxes, two different power supplies and cabling connecting them. Clearly, that's less convenient than having a single 'all-in-one' do-everything device.

Also, the May 2016 project only has three attenuator settings (0dB, 20dB and 40dB) and we think that it doesn't quite have the performance to match the *SuperCodec*, for reasons we'll explain shortly.

Hence, we came up with this project. It does a similar job to the May 2016 attenuator, but with the addition of a –10dB attenuator setting and lower impedances for less noise.

Importantly, it has been designed to integrate with the *USB SuperCodec* and fit in the same case, by keeping the PCB assembly compact and designing it to run off the same power supply rails.

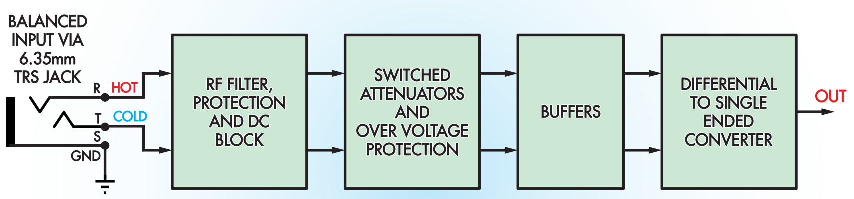


Fig.1: one channel of the *Balanced Input Attenuator*. There is an RF filtering and DC-blocking stage before the relay-switched resistor-based attenuator. After the attenuators are the over-voltage protection stages, buffers and differential-to-single-ended converters before the signals are fed to the ADC inputs on the *SuperCodec* board.

Features and specifications

- Adds stereo balanced inputs (6.35mm TRS sockets) to the front panel of the *USB SuperCodec*
- Balanced inputs replace the rear-panel unbalanced RCA inputs of the original design
- Unbalanced outputs (RCA) remain on rear panel
- Retains the 192kHz/24-bit recording and playback capabilities of the original *SuperCodec*
- Fits into the *SuperCodec* case and uses the same power supply
- 0dB, 10dB, 20dB and 40dB attenuation settings selected via front panel switch
- CMRR: >60dB @ 50-100Hz; >70dB @ 1kHz; >50dB @ 10kHz
- SNR: 114dB @ 0dB, 113dB @ –10dB, 114dB @ –20dB and –40dB
- THD: 0.00010% (-120dB) @ 0dB; 0.00014% (-117dB) @ –10dB; 0.00028% (-111dB) @ –20dB
- Signal handling: 1V RMS @ 0dB; 3.6V RMS @ –10dB; 10V RMS @ –20dB; 50V RMS @ –40dB

So with the addition of this balanced input board and some free or low-cost software, you can build an audio testing system that only a few years ago would have cost thousands.

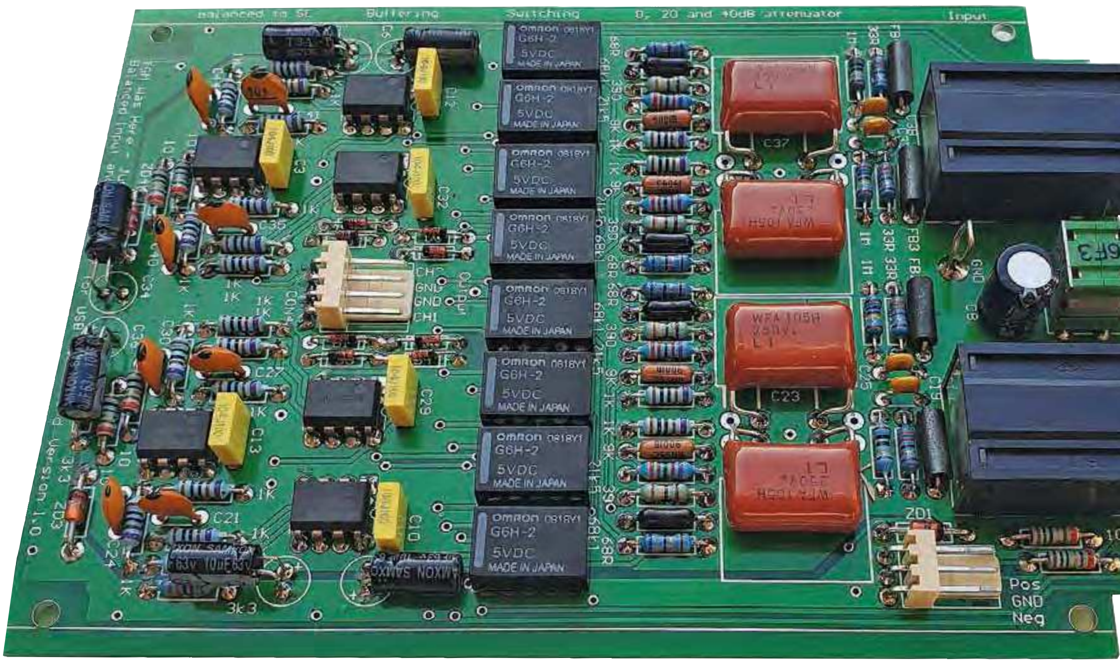
Recording professional audio

Another reason you might want to build the *Balanced Input Attenuator* is to interface the *USB SuperCodec* with professional audio equipment. It gives you much greater recording flexibility, allowing you to use either balanced or unbalanced signals. And with the attenuator, it can handle much 'hotter' signals than the 1V RMS of the original Sound Card design.

The 10dB attenuation setting puts professional +4dBu signals right in the sweet spot of the analogue-to-digital converter (ADC), with good headroom. In this configuration, it can handle up to 3.6V RMS without clipping, or you can switch to the –20dB setting to handle signals up to 10V RMS, with relatively little degradation in performance at 'normal' signal levels.

The design provides very well balanced inputs, with common-mode rejection typically better than 60dB. The attenuation ranges of 0dB, –10dB, –20dB and –40dB allow full-scale inputs of 1V, 3.6V, 10V and 50V RMS, which correspond to 1.4V, 5V, 14V and 71V peak or 2.8V, 10V, 28V and 142V peak-to-peak.

This allows low-level signals, preamplifier outputs and power amplifier outputs to be used as signal sources (among other devices).



Here is the finished add-on board, with low-profile components to fit under the *SuperCodec* PCB. The inputs, RF filtering and AC-coupling components are at right, with the divider resistors in the middle. To their left are the attenuation selection relays, with the buffer op amps next to them, then the balanced-to-single-ended conversion circuitry at far left.

Operating principles

Refer now to the block diagram, Fig.1. If you have a copy of the May 2016 issue, (or a download from the *PE* website) you might also like to read back over the earlier *Balanced Input Attenuator* design, as this design has many similarities.

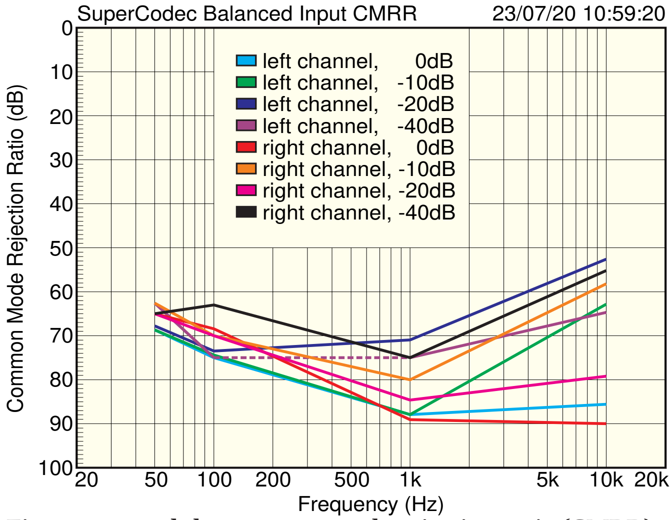


Fig.2: we tested the common-mode rejection ratio (CMRR) for both channels on our prototype, at four different frequencies and all four possible attenuation settings. The resulting plot is a bit messy but gives you an idea of the CMRR spread. A higher CMRR is better since it rejects proportionally more of the hum, buzz and EMI that may be picked up in cables.

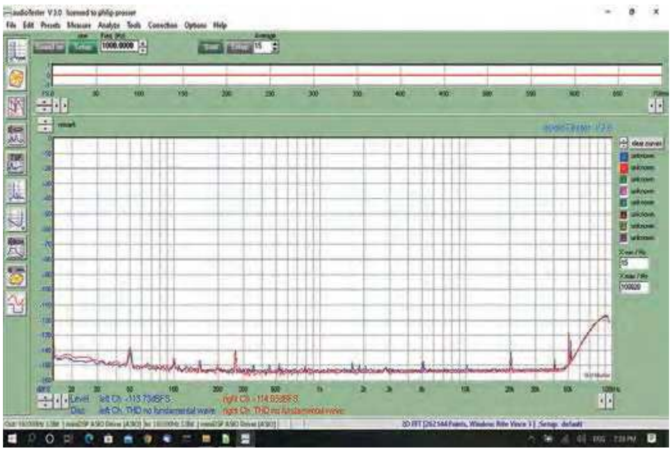


Fig.3: the noise floor of the combined *Balanced Input Attenuator* and *SuperCodec* ADC with the *Attenuator* set to 0dB and the inputs shorted out. This shows that the new board adds minimal noise to the overall system.

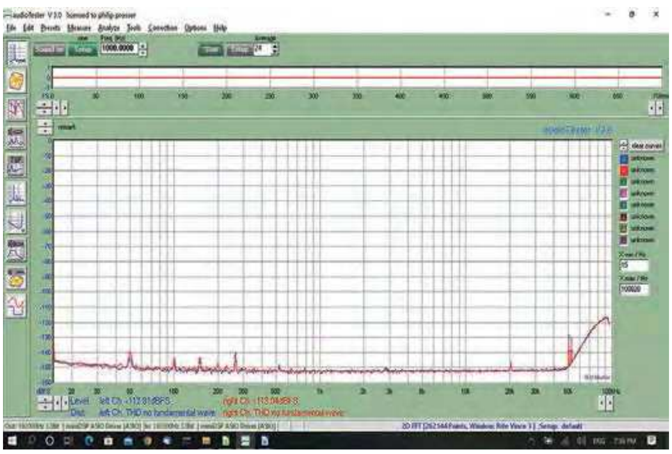


Fig.4: the same plot as Fig.3 but here the *Attenuator* has been switched to –10dB. As explained in the text, this is the setting where the Johnson (thermal) noise contribution of the attenuator resistors is highest. Despite this, the noise floor has only increased by around 1dB compared to Fig.3.

The balanced input is via a 1/4-inch (6.35mm) standard tip-ring-sleeve (TRS) type connector (also often referred to as a 'jack socket'). This was chosen over an XLR connector to save space, so that it will fit in the *SuperCodec* case. 6.35mm TRS is bog-standard, and often used for balanced signals, which makes this a versatile choice. We're sticking with the standard TRS pinout of tip = 'Hot' or positive, ring = 'Cold' or negative and sleeve for signal ground/screen.

The balanced signals pass through an RF filter and DC-blocking capacitors, then into the resistor and relay-based switched attenuator. After that, they pass through a clipping stage to provide over-voltage protection before going onto a set of buffer op amps.

The buffered signals are then converted from balanced to single-ended signals, which are then fed to the inputs of the *USB Sound Card* already described.

Performance

We thoroughly tested the performance of the *Balanced Input Attenuator* to make sure it was up to *SuperCodec* standards. Fig.2 shows the measured common-mode rejection ratio (CMRR) value for both channels of the prototype, at all four attenuation settings and measured at four different frequencies.

As you can see, the CMRR is between 71dB and 89dB at 1kHz for both inputs, and at all attenuation settings. Those are pretty good figures, and 1kHz is a typical test frequency. CMRR is slightly worse at lower and higher frequencies, but is better than 63dB at all tested frequencies below 1kHz, and better than 53dB at 10kHz.

CMRR will be almost entirely a function of matching of the attenuator and balanced receiver resistors. So if you pay more attention when selecting those resistors, you could beat our prototype figures.

With the 0.1% resistors specified, the attenuation error is less than ±0.1dB across all tested frequencies.

The noise and distortion performance is not significantly worse than the straight *USB Sound Card* with a 10kΩ input impedance (the input impedance options are described below). There is a small increase in THD on the −10dB range for the 100kΩ input impedance version.

Fig.3 shows the output spectrum with the *Attenuator* on the 0dB setting and the inputs shorted to ground. If you compare it to Fig.5 on page 19 of the September 2021 issue, showing the same measurement for the *SuperCodec* alone, you will see that there isn't all that much extra noise being introduced by the *Balanced Attenuator*.

A view inside the 'new' *SuperCodec* with the added PCB at bottom. It is designed to slot into the edge guides in the recommended Hammond 1455N2201BK aluminium case.

Fig.4 shows the same measurement but with the attenuator on the –10dB setting, which is the worst case (as explained below). Overall, the noise has only crept up by about 1dB compared to the 0dB attenuator setting, so that's a good result.

Fig.5 shows the THD+N measurement for a test signal of around 300mV RMS being fed into the *Balanced Input Attenuator* with the attenuation setting at 0dB.

This is virtually unchanged from the measurements we made previously without the *Balanced Input Attenuator* board. You can compare this to Fig.4 on page 19 of the September 2021 issue, but note that the test signal level is slightly different.

Fig.6 shows that the distortion performance on the –10dB setting, with the same signal applied as for the 0dB setting, is barely any worse. So the attenuator does not appear to be introducing any signal distortion.

Similarly, Fig.7 shows the result with the attenuator on the –20dB setting. The THD measurement has risen to 0.0003% / –111dB.

However, note that if the applied signal amplitude were increased to a level that you would need the 20dB of attenuation to measure, the THD level would probably drop quite close to the 0.0001% / –120dB shown in Fig.5.

Circuit details

Refer now to the full circuit diagram, Fig.8, and compare it to the block diagram, Fig.1. Let's consider the left channel signal path, starting at CON1; the right channel is the same.

The input signal goes via a ferrite bead with a 22pF bypass capacitor to filter off the worst of any RF signals on the input. The *USB Sound Card* is AC-coupled, so a DC blocking capacitor is included between the input RF filter and the attenuator.

And here's a view from the opposite end, with the lid removed, showing how the new PCB fits 'upside down' above the existing *SuperCodec* board.

We want a lower cutoff frequency (–3dB point) an order of magnitude below 20Hz; we chose 1.5Hz. This means that non-linearities in the DC-blocking capacitors will not introduce any distortion, so long as they are not gross non-linearities (as with high-K ceramic capacitors, for example).

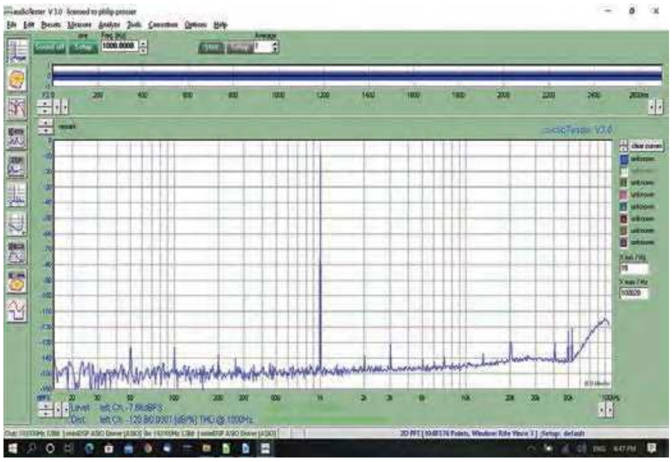


Fig.5: we measured the total harmonic distortion (THD) with a –7.66dBV sinewave fed into the balanced inputs and a 0dB attenuator setting. The result shows very little difference from the same test without the *Balanced Input Attenuator* add-on. So it appears that the added circuitry is not introducing any extra distortion to the signals.

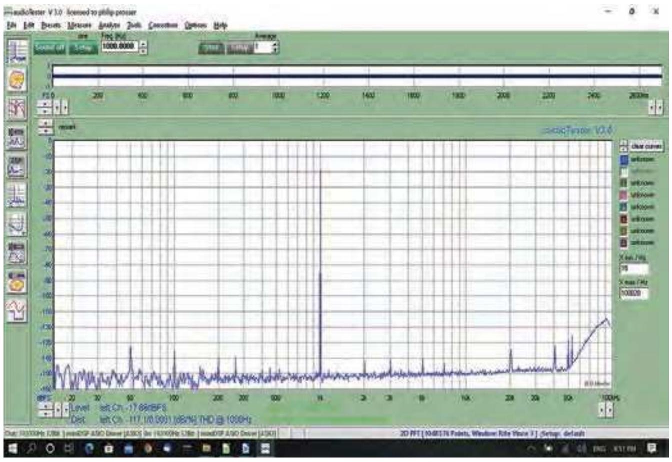


Fig.6: the same test as Fig.5 but with the *Attenuator* set to –10dB. Other than the signal level falling by the expected amount, there isn't much difference. The increase in THD reading is mainly due to the change in signal level; increasing the input signal level by 10dB would likely give the same result as in Fig.5.

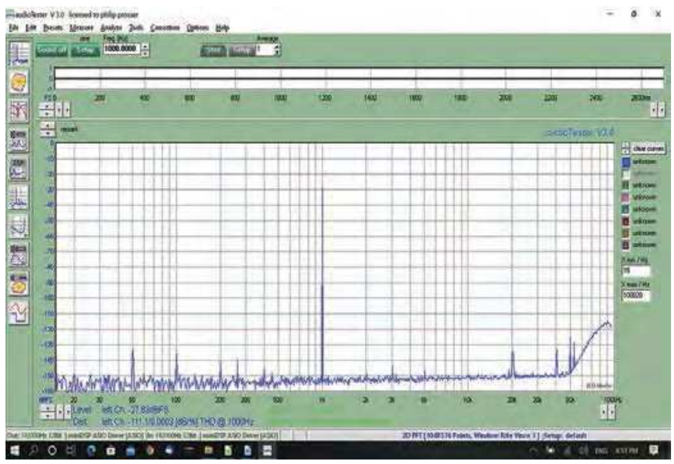
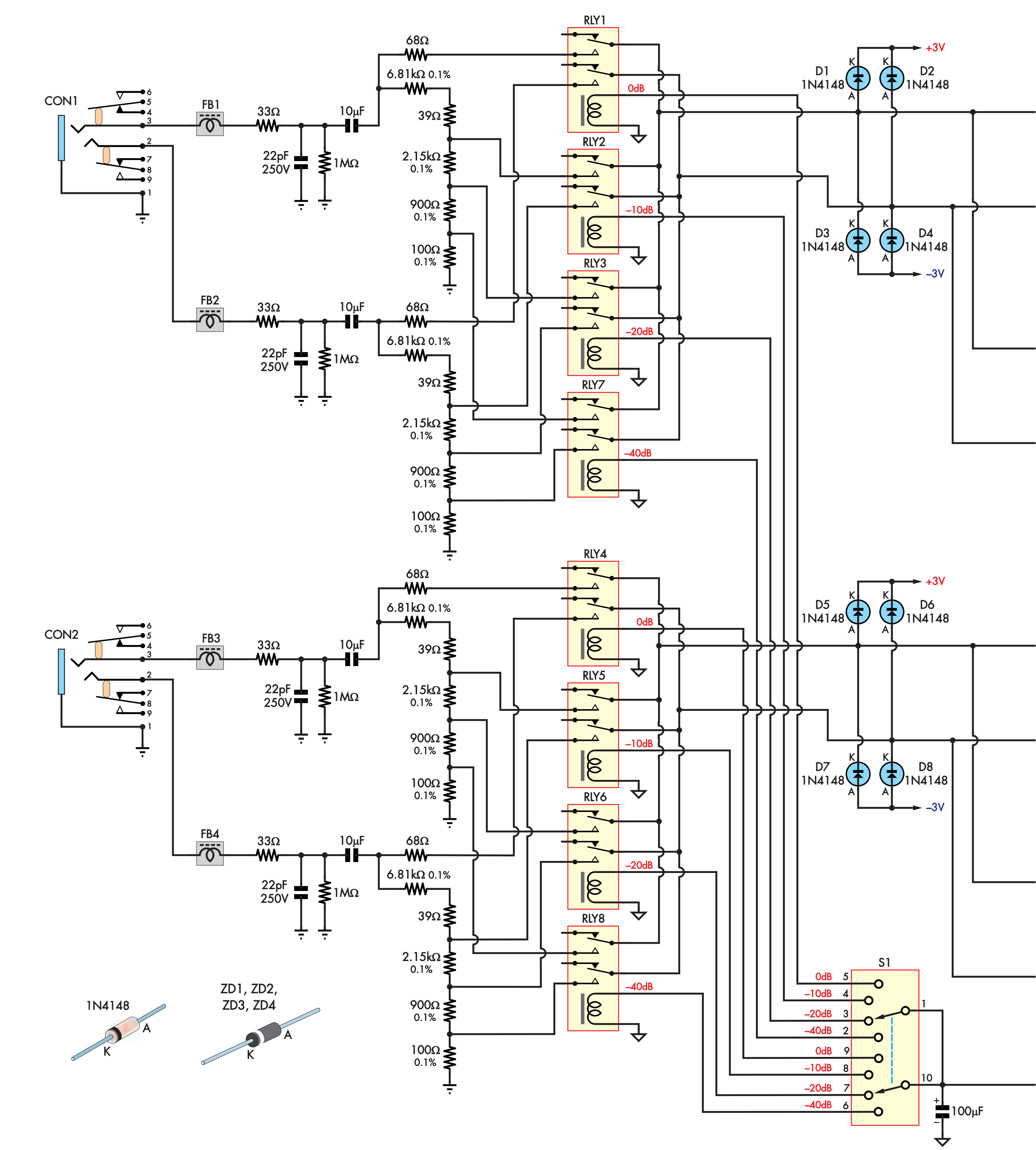


Fig.7: and the same test again with an *Attenuator* setting of –20dB. The same comments as for Fig.6 apply. Note how the signal level drops by very close to 10dB and 20dB in these two tests, showing off the excellent attenuation accuracy.



2-Channel Balanced Input Attenuator

For a 100kΩ input impedance, as used in the May 2016 *Attenuator* design, this demands the DC blocking capacitor be 1μF. But the Johnson noise in a 100kΩ resistance is enough to affect the performance of the *USB SuperCodec*, so we really need a lower input impedance, say 10kΩ. This demands a 10μF DC-blocking capacitor for the same 1.5Hz –3dB point.

The current through these capacitors is extremely low, and pretty much any film capacitor will work well. You could use an electrolytic, but many people don't like the idea of electrolytics in the signal path (even though they work OK for signal coupling). Also, they tend not to last as long as film capacitors. And as mentioned above, ceramic is a poor choice, so plastic film it is.

The switched attenuator

The input attenuator reduces the input signal level by 0, 10, 20 or 40dB. That

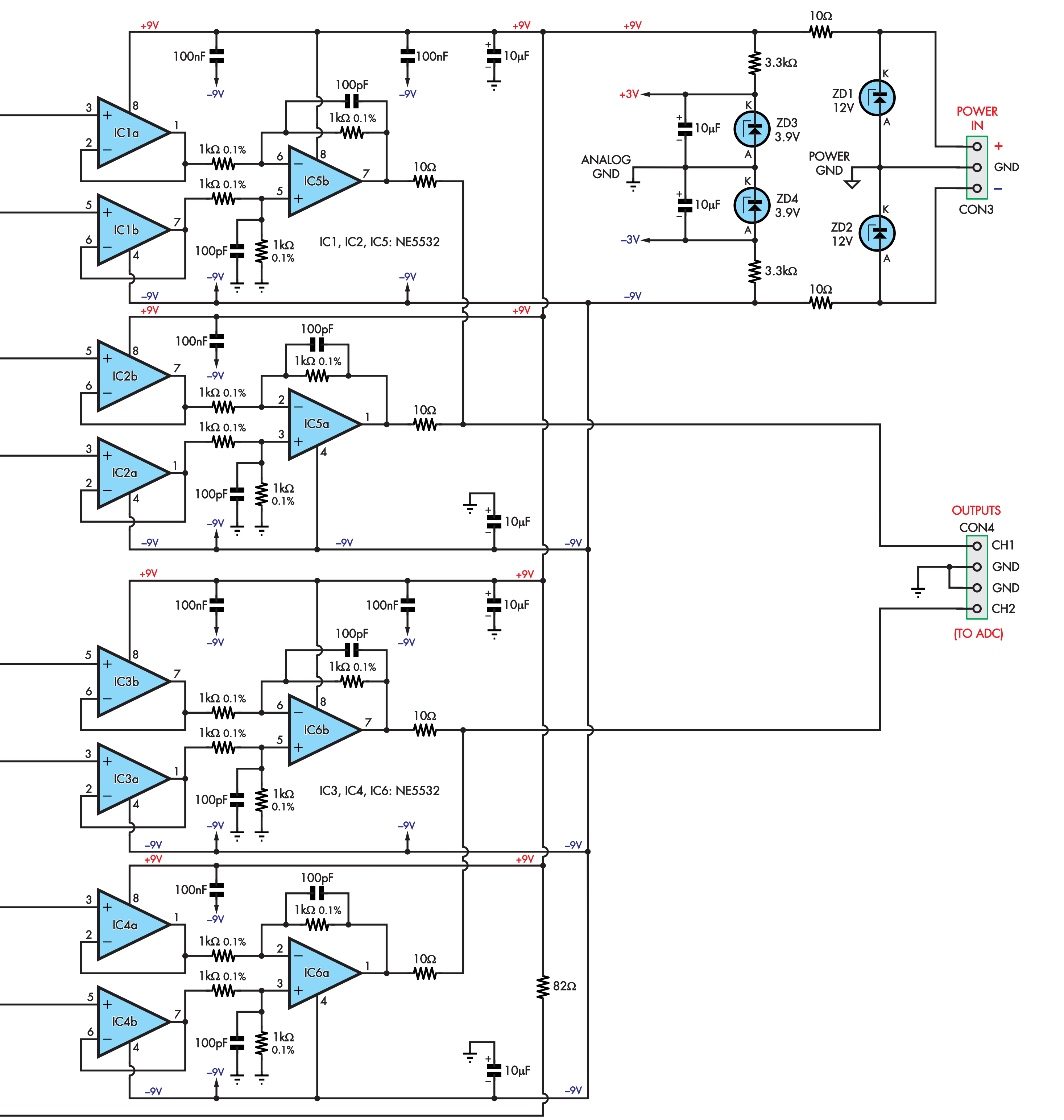


Fig.8: the circuit of the *Balanced Input Attenuator* add-on board. CON1 and CON2 are the new 6.35mm TRS jack socket inputs connectors, while CON3 and CON4 connect to the ±9V supplies and CON4 input header on the *USB SuperCodec Sound Card* board respectively. The attenuator resistor taps are selected via relays RLY1-RLY8, and the signals then pass to op amp buffers IC1-IC4 and the differential-to-single-ended converter stages based on dual op amps IC5 and IC6 before going to the ADC.

means division ratios of 3.16:1, 10:1 and 100:1. We chose these values as 0dB (ie, straight through) gives the best sensitivity and a useful 1V RMS input level. –10dB is well suited to professional audio signal levels.

It is also low enough to be useable with consumer equipment like CD, DVD and Blu-ray players which tend to produce an output signal of around 2.2V RMS. The –20dB and –40dB settings are handy for power amplifier testing.

The attenuator is a simple resistive divider. The total series resistance sets the input impedance of the balanced interface, and as mentioned above, this has an impact on the noise performance and the size of the DC blocking capacitor required.

Thermal noise

The noise impact will depend on the attenuation setting. At 0dB, the divider is effectively bypassed and

Parts list – Balanced Input and Attenuator

1 assembled USB SuperCodec *without* 2x12-pin headers attached or front/rear panels drilled but with loose MCHStreamer module (described in *PE*, Sep – Nov 2021)
1 assembled Balanced Input Attenuator board (see below)
1 set of Test Leads (optional; see below)
2 6x2-pin header sockets, 2mm pitch with pigtails (supplied with MiniDSP MCHStreamer)
1 180mm length of heavy-duty figure-8 shielded audio cable [Altronics W2995, Jaycar WB1502]
1 1m length of red medium-duty hookup wire
1 1m length of black medium-duty hookup wire
1 1m length of green medium-duty hookup wire
1 30cm length of 5mm diameter black or clear heatshrink tubing
1 30cm length of 2.4-2.5mm diameter black or clear heatshrink tubing

Balanced Input Attenuator board
1 double-sided PCB coded 01106202, 99.5 x 141.5mm from the PE PCB Service.
2 6.35mm DPDT switched stereo jack sockets (CON1,CON2) [Altronics P0076, Jaycar PS0180, element14 1267402]
1 right-angle 3-pin polarised header (CON3) [Altronics P5513, Jaycar HM3423]
1 right-angle 4-pin polarised header (CON4) [Altronics P5514, Jaycar HM3424]
4 4-5mm ferrite suppression beads (FB1-FB4) [Altronics L5250A, Jaycar LF1250]
8 2A DPDT 5V DC coil telecom relays (RLY1-RLY8) [Altronics S4128B/S4128C, Mouser 551-EA2-5NU]
1 DP4T right-angle PCB-mount switch (S1) [Altonics S3008]

Semiconductors
6 NE5532AP or NE5532P dual low-noise op amps, DIP-8 (IC1-IC6)
2 12V 1W zener diodes (ZD1,ZD2)
2 3.9V 1W zener diodes (ZD3,ZD4)
8 1N4148 small signal diodes (D1-D8)

Capacitors
1 100µF 16V electrolytic
4 10µF 100V polyester film*, 15mm lead pitch [Mouser 871-B32562J1106K]
6 10µF 35V electrolytic
6 100nF 63V MKT
8 100pF 50V C0G/NP0 ceramic
4 22pF 250V C0G/NP0 ceramic

Resistors (all 0.25W ±1% metal film unless otherwise specified)
4 1MΩ 2 3.3kΩ 1 82Ω 4 68Ω 4 39Ω* 4 33Ω 6 10Ω
4 6.81kΩ* ±0.1% [Mouser 71-CMF556K8100BEEK]
4 2.15kΩ* ±0.1% [Mouser 71-RN55C-B-2.15K]
16 1kΩ ±0.1% [Mouser 71-PTF561K0000BXR6]
4 900Ω* ±0.1% [Mouser 71-CMF55900R00BHEB]
4 100Ω* ±0.1% [Mouser 71-CMF55100R00BEEB]

*** for 100kΩ input impedance, substitute these instead:**
4 1µF 250V polypropylene film, 7.5mm lead pitch [Mouser 667-ECW-F2105HAB]
4 68.1kΩ ±0.1% [Mouser 279-H868K1BYA]
4 21.5kΩ ±0.1% [Mouser 279-YR1B21K5CC]
4 9kΩ ±0.1% [Mouser 71-PTF569K0000BYEK]
4 1kΩ ±0.1% [Mouser 71-PTF561K0000BXR6]
4 390Ω ±1%

Test Lead parts
2 90° 6.35mm TRS line plugs [Altronics P0048 or P0049]
2 1.2m lengths of microphone cable (or length to suit) [Altronics W3024/W3029, Jaycar WB1534]
2 small red alligator clips [Altronics P0110, Jaycar HM3020]
2 small black alligator clips [Altronics P0111, Jaycar HM3020]
2 small green alligator clips [Altronics P0102]
1 30cm length of 6mm diameter black or clear heatshrink tubing
1 30cm length of 3mm diameter black or clear heatshrink tubing
1 30cm length of 2.4-2.5mm diameter black or clear heatshrink tubing

UK/EU/US... readers
You don't need to use the exact Altronics/Jaycar parts listed here – they are quoted so you can find local alternatives from the specs provided online.

so the input impedance has no real effect on the performance.

At the other three settings, the input impedance 'seen' by the *SuperCodec* is the upper and lower halves of the divider, bisected by the selected tap, in parallel.

The worst case is the –10dB setting, at 21.6% of the overall input resistance (ie, 21.6kΩ for the 100kΩ option and 2.16kΩ for the 10kΩ option). For the –20dB setting, it is 9% of the input resistance and for the –40dB setting, it is 1% of the input resistance.

Thermal noise in a resistance is calculated as $\sqrt{(4 \times K \times T \times B \times R)}$ where $K = 1.38 \times 10^{-23}$, T is the temperature in kelvin, B is the bandwidth in Hz and R is the resistance in ohms.

At room temperature (around 300K), for a bandwidth of 20kHz and a resistance of 21.6kΩ, this works out to 2.67µV RMS, which is –111.5dBV. That is a higher level than the inherent noise in the *SuperCodec's* ADC, so it would definitely degrade performance.

A source impedance of 21.6kΩ to the buffer op amps would also increase their distortion contribution slightly.

For 1/10th the resistance, that noise level drops by a factor of $\sqrt{10} = 3.16$, to 845nV RMS or –121.5dBV.

This is usefully below the noise floor of the *SuperCodec*, so it will have little impact on performance at –10dB, and even less on the –20dB and –40dB settings.

In fact, the biggest impact on performance is likely to be EMI pickup due to the higher input impedance in this case.

Consider errors caused by loading the DUT with 10kΩ. A preamp might have a 100Ω resistor in series with its output.

If we measure this preamp with a 10kΩ input impedance balanced line test set, we will introduce a 1% scaling error.

That probably does not matter in most cases, but it does need to be considered. We certainly would not want errors greater than this.

So 10kΩ is the lower practical limit, especially when you consider that film capacitors with values above 10µF are expensive and bulky, and would not fit in the space available.

We also need to consider power dissipation in the divider. With 50V RMS fed into the divider, the power dissipation is 0.25W for a 10kΩ divider. This is spread out through several resistors, but heating in those resistors could lead to some inaccuracies.

The ratings of the divider resistors would allow up to 80V RMS to be fed in, but besides this being possibly unsafe, we prefer not to run them at their limits.

So there is no perfect answer. Hence, we are providing resistor values for the input attenuator that give either a 10kΩ or 100kΩ input impedance. Remember to choose the right value capacitor to go with them. Our inclination is to go with 10kΩ, but we fully understand why others might choose 100kΩ.

Benefits of balanced signals

Professional audio equipment uses balanced signals carried on three conductors: the positive ‘Hot’, negative ‘Cold’ and a screen. Electromagnetic interference picked up in the cable (usually heard as hum or buzz) affects both the Hot and Cold signals similarly. The balanced receiver subtracts the Cold signal from the Hot, resulting in twice the signal with severely attenuated noise.

If the Hot signal is given by: (signal × 1) + noise

And the Cold signal is: (signal × –1) + noise

Then, Hot – Cold is: [(signal × 1) + noise] – [(signal × –1) + noise]
= (signal – – signal) + (noise – noise) = signal × 2

This is a great way to reject noise and hum from things like ground loops, especially on long cable runs.

Besides added complexity in the circuitry, the main disadvantage of this approach is that converting a balanced signal into an unbalanced signal generally introduces a bit of white noise; so while hum and buzz are rejected, the signal-to-noise ratio (SNR) can suffer.

When testing audio equipment, we often need to analyse the signal between two particular points in the device under test (DUT). We certainly want to avoid measuring any voltages within the ground system of the DUT or our test equipment itself.

By using a balanced input in this situation, we can connect the Cold conductor to an appropriate ground reference point in the DUT. The Hot connection is then used to measure the signal of interest. Any noise between the USB Sound Card ground and the DUT ground is subtracted out of this measurement.

When measuring low voltages and exceptionally low distortion levels on signals at moderate voltages, this is extremely important, as sometimes we are looking for microvolt or even nanovolt level distortion signals.

As good as balanced interfaces are, earthing remains essential. To achieve good results below –100dB, you will need to work on the test earthing and layout. You might be surprised how much things like the orientation of the equipment being tested and its proximity to computer equipment and even the operator can affect the results!

We have used relays to switch between the four possible attenuation settings. This is a little bit expensive, as they are a few pounds each, but it makes the design nice and clean in terms of layout and avoids the possibility of noisy, unreliable wafer switches failing. The relays give a satisfying ‘clunk’ as you switch across ranges, suiting such a high-performance device.

Buffers

The voltage divider output impedance varies depending on the range selected. This does not suit the balanced-to-single-ended converter, so buffers are needed.

We use two paralleled op amps to do this, driving two balanced-to-single-ended converters. These are combined at the output to get a 3dB improvement in signal-to-noise ratio compared to using fewer op amps.

The differential-to-single-ended converters subtract the Cold input signal from the Hot input signal. The matching of resistors in these is important, at least within each arm of each converter. Therefore, we have specified 0.1% tolerance 1kΩ resistors here. This tolerance is required to deliver the specified performance.

We have chosen 1kΩ resistors as they have a low enough resistance to add negligible thermal noise to the convertor without loading the op amp outputs too much.

And as many constructors will likely have plenty of 1kΩ 1% resistors, they could select well-matched pairs using just about any DMM and avoid the cost of 0.1% types.

The output of the differential-to-single-ended convertors is combined through 10Ω resistors (necessary to allow for the op amps having different offset voltages), which then feed into the USB Sound Card.

We have included input protection comprising diodes clipping to a 3.9V rail. We have tested that this does not impact distortion performance.

Note though that if you connect this to a high-voltage source on the 0dB range, you will risk damaging this part of the circuit!

There is additional protection on the power supply rails provided by 12V zeners, which again should only operate under extreme fault modes.

Next month

We don’t have room for the construction details this month. That will have to wait for the next issue.

As well as describing the construction, and what you have to do to get the *Balanced Input Attenuator* to fit into the same case as the *USB SuperCodec*, the second and final article in this series will also cover the testing procedure, and how to make some handy balanced test leads.

Mini Digital Volt/ Amp Panel Meters

There are many low-cost digital panel meters available which can display voltage and current at the same time. Quite a few have popped up on the market in the last year or so. So let's take a look at some of the more popular models, see what's inside them and whether they're easy to use.

There are a surprising number of these low-cost digital panel meters currently available. Many are quite similar to each other, but a few are noticeably different.

This article will focus on a few of the more popular and useful models. We'll be looking at the meters designed to measure DC parameters this month (ie, DC voltage and current), with a follow-up article to describe those which make AC measurements.

The first is the DSN-VC288 from the Chinese firm Geekcreit (we'll be seeing more of their products in later articles).

It is available in two versions: one with a 0-10A current range using an internal current shunt, and the other with a 0-50A current range using an external current shunt. Both versions have a 0-100V voltage range.

The 10A version comes with two plug-in connection leads for around £2 from **aliexpress.com**, while the 50A version comes with both the leads and an external 50A current shunt for a similar price from **aliexpress.com**

The DSN-VC288 is quite small, at 48mm wide, 29mm tall and 22mm deep. Some the suppliers describe it as having a 0.56-inch dual LED display, but that is misleading.

The three-digit seven-segment displays used for both voltage (red) and current (blue) are each only 7mm or 0.28in high. Despite this, the displays are quite readable. The display 'window' is 35 × 18mm.

Both versions of the DSN-VC288 can be powered from a supply voltage of 4-30V DC, usually drawing less than 20mA. So if they are to measure voltages in this range, they can be powered from the same voltage source.

The only thing to bear in mind is that the DSN-VC288 can only measure voltages which are positive with respect to its negative rail. That also applies to current measurements.

Inside the DSN-VC288

The circuit of the DSN-VC288 is shown in Fig.1. It's all based on IC1, an STMicro STM8S103F3 8-bit microcontroller. This runs firmware which directs it to take voltage and current measurements every 300ms or so, then show them on volts display DS1 and current display DS2.

Three-pin connector J3 at upper left is used for both the meter's supply input (V+ and V–) and its voltage measurement input (V_{IN}). The V+ supply input connects to the anode of diode D1 and then to the input of REG1, an ME6203 LDO (low drop-out) regulator, which provides a regulated 3.3V supply for the rest of the circuit.

On the other hand, the V_{IN} input from J3 goes to the AN4/PD3 input (pin 20) of IC3 via a 270kΩ/8.2kΩ resistive voltage divider, together with VR1 (the voltage calibration trimpot) and a 100nF filter capacitor across the 8.2kΩ resistor.

The meter's 'current' input is via two-pin connector J4, at lower left. Here pin 1 (–) is connected straight to the meter's negative rail, while pin 2 (+) connects to the non-inverting input of IC2b, via a low-pass filter formed by a 330Ω resistor and 100nF capacitor. IC2b is connected as a DC amplifier with an adjustable gain between 23 and 25 using trimpot VR2, to calibrate the current range.

Resistor R_S connected across the current input pins of J4, shown in red, is the internal current shunt. For the DSN-VC288 version with the 10A current range, R_S is a 7.5mΩ (milliohm) resistor. In contrast, the DSN-VC288 version with a 50A current range has no internal resistor R_S, as the current shunt is external, with a value of 1.5mΩ.

The only other thing to note about Fig.1 is that 'connectors' J1 and J2 are not physical connectors, but actually a row of test points in the case of J1, with the purpose of J2 unexplained. Presumably, J1 is also used to program IC1 at the factory.

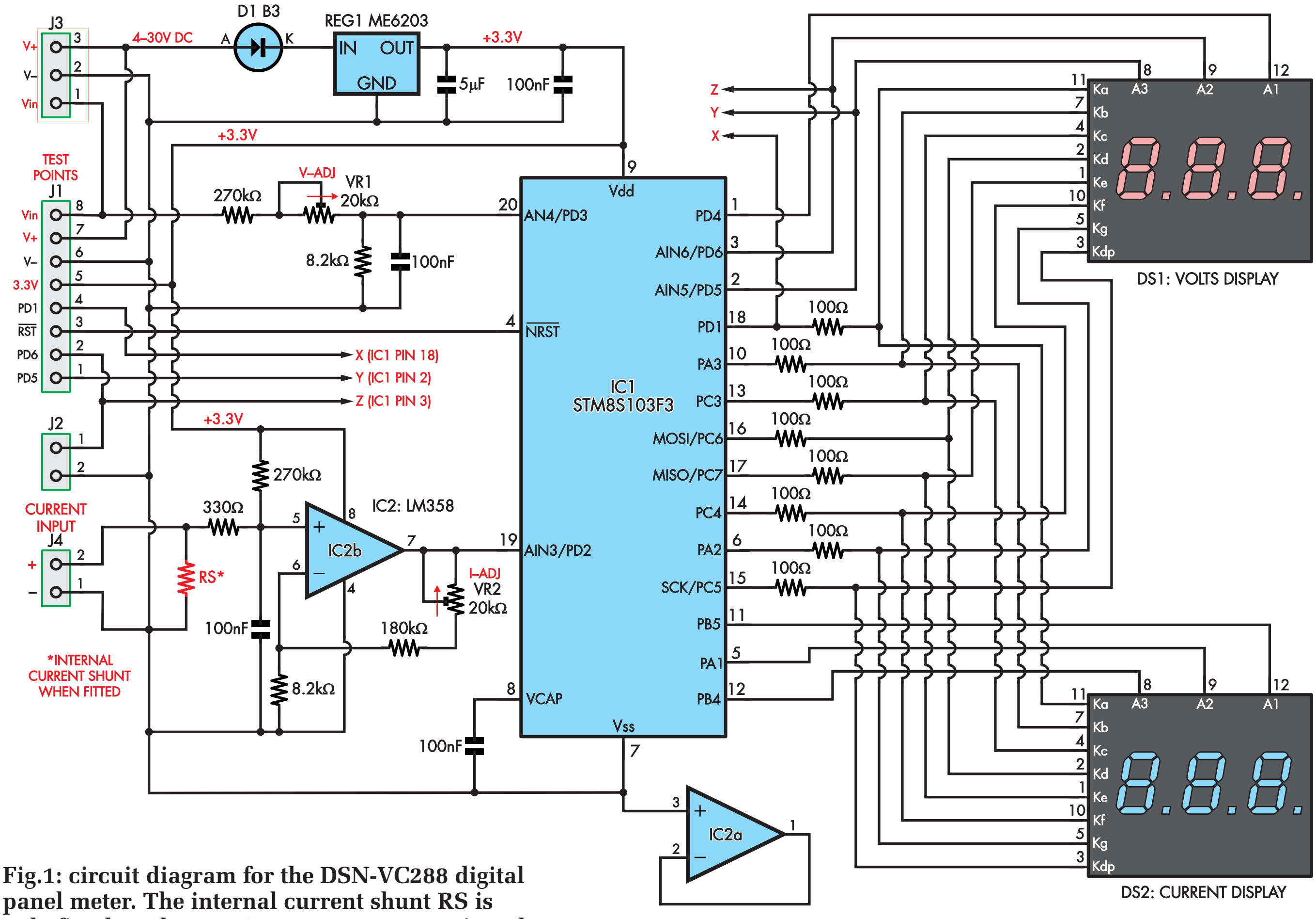


Fig.1: circuit diagram for the DSN-VC288 digital panel meter. The internal current shunt RS is only fitted on the 0-10A current range version, the alternative model with a current range of 0-50A uses an external shunt.

DSN-VC288 Mini Volt/Amp Meter

Using the DSN-VC288

It's easy to put the DSN-VC288 module to use, as shown in Fig.2. The first two diagrams show the connections for the version with the internal 10A current shunt, with (A) showing the connections when the module has a separate power supply, and (B) showing the connections when it shares its power supply with the load. (B) can only be used when the load supply is below 30V.

The other two diagrams show the connections for the DSN-VC288 version with an external 50A shunt. (C) shows the connections when the module has a separate power supply, while (D) shows the connections for a shared power supply. Again, it must be less than 30V.

The two short (150mm) connecting leads which come with the DSN-VC288 are distinguished by both their size and their insulation.

The wires attached to the 3-pin connector that plugs into J3 are thin, while the two wires attached to the larger 2-pin connector that plugs into J4 are thicker.

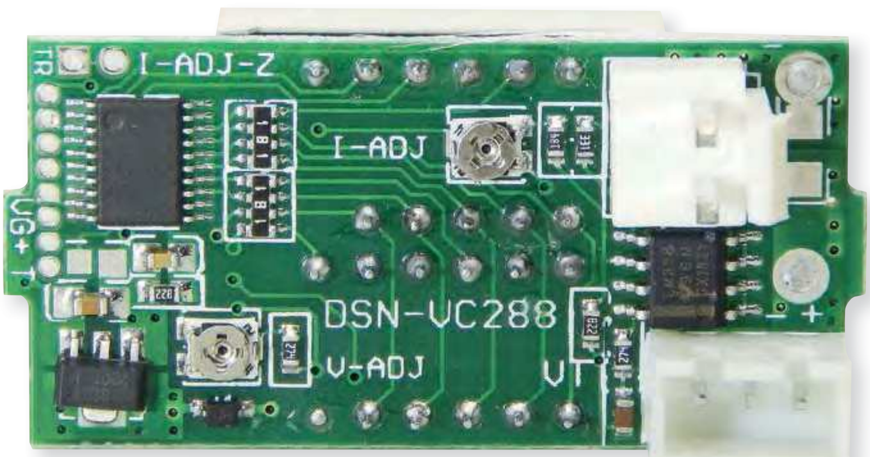
But these four connection options are not the only way that the DSN-VC288 modules can be used. For example, if you want to measure lower currents than their nominal 10A or 50A, you can do that.

Bear in mind that the current range of the DSN-VC288 is really just a 0-75mV voltage range, with the firmware scaling this range to show the current passing through the shunt. So you can get a lower current range by changing the shunt resistor value. This is easier with the version using an external 50A shunt, but it's also possible with the other version if you're careful.

For example, if you'd like to use the 50A version to measure currents between 0 and 50mA, replace the big 50A shunt with a 1.5Ω 0.1% resistor. The meter's scaling will then simply provide current readings from 0-50mA instead of 0-50A.

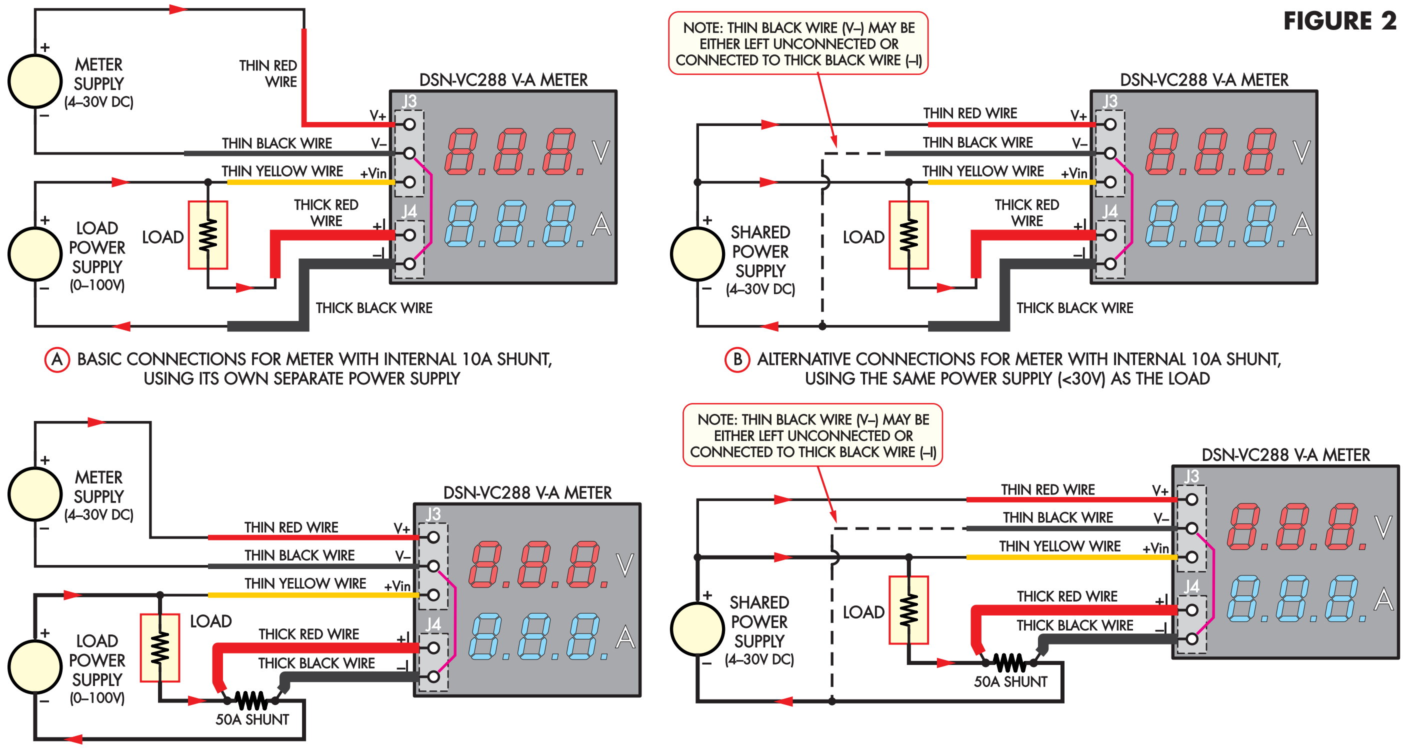
The same approach could be used to give the meter current ranges of 0-500mA or 0-5A, although the decimal point will be in the wrong position. If that doesn't worry you greatly, the shunt values to use would be 150mΩ for 0-500mA, or 15mΩ for 0-5A.

If you have the internal shunt version of the DSN-VC288, to change its current range, you'll need to remove the internal 10A shunt. This is a stout



The underside of the 50A current range version of the DSN-VC288 module.

FIGURE 2



(A) BASIC CONNECTIONS FOR METER WITH INTERNAL 10A SHUNT, USING ITS OWN SEPARATE POWER SUPPLY

(B) ALTERNATIVE CONNECTIONS FOR METER WITH INTERNAL 10A SHUNT, USING THE SAME POWER SUPPLY (<30V) AS THE LOAD

(C) CONNECTIONS FOR METER WITH EXTERNAL 50A SHUNT, USING ITS OWN SEPARATE POWER SUPPLY

(D) CONNECTIONS FOR METER WITH EXTERNAL 50A SHUNT, USING SAME POWER SUPPLY (<30V) AS THE LOAD

U-shaped wire soldered to the meter's PCB just to the right of J4, looking from the rear. This is what you need to desolder to change the meter's current range.

Since the internal 10A shunt has a resistance of 7.5mΩ (providing 75mV when 10A is flowing through it), the scaling firmware in this version will turn 75mV into a reading of '10.0'. So you can change its current range to 0-10mA by replacing the internal shunt with a 7.5Ω resistor (ideally with 0.1% tolerance).

Or again, you could give it a range of 0-100mA by using a 750mΩ shunt, or a range of 0-1A by using a 75mΩ shunt. But in both cases, the decimal point will be in the wrong position.

Testing

I ordered a couple of 50A versions of the DSN-VC288 from Banggood and put them through their paces. Both worked exactly as claimed, with an operating current of 20mA, a voltage measurement accuracy within ±0.1% and a current measurement accuracy of ±1%.

In both cases, the readings could be made 'spot on' compared with my reference instruments using little trimpots VR1 and VR2.

So bearing in mind that the DSN-VC288 is very compact and has relatively small readouts, it is very practical and useful, as well as being great value for money!

The PZEM-051 meter module

The PZEM-051 is one of a range of measurement modules made in China by Ningbo Peacefair Electronic Technology, based in Ningbo City, Zhejiang Province.

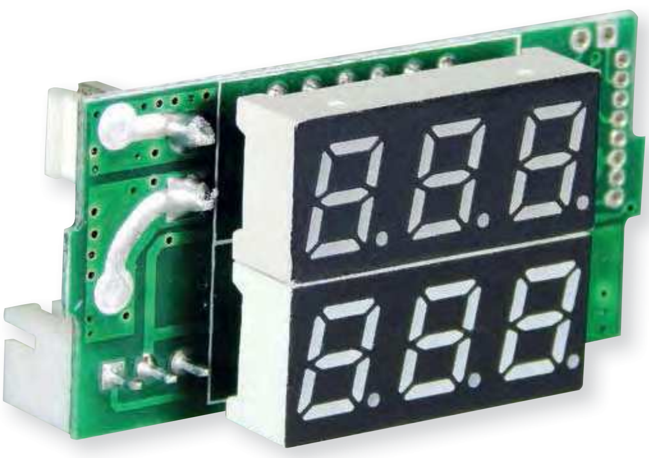
It's available from various suppliers via online markets like AliExpress, eBay and Amazon for between £8 and £12, depending on whether you want the 50A version or the 100A version.

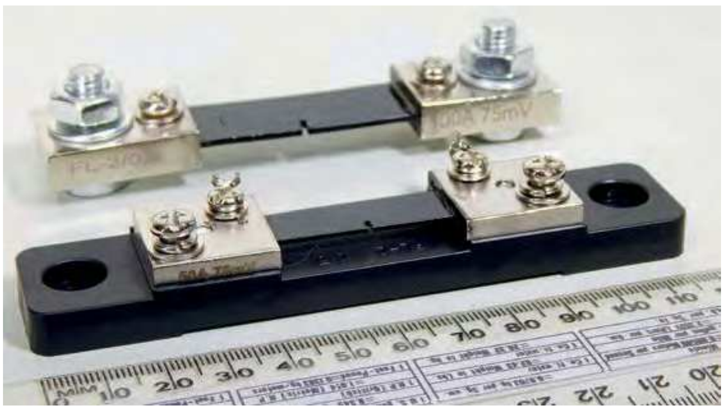
There is a similar module with a 20A current range available from Banggood for around £12, designated the PZEM-031 (**https://bit.ly/pe-dec21-bg1**).

Also, Banggood has another version called the PZEM-015 (**https://bit.ly/pe-dec21-bg3**), with extra displays including a bar chart display and measurements of battery capacity and internal resistance. That one comes with a 50A-300A shunt and costs just over £18. (all the above are (sometimes) plus delivery, which is usually inexpensive when using Chinese suppliers.)

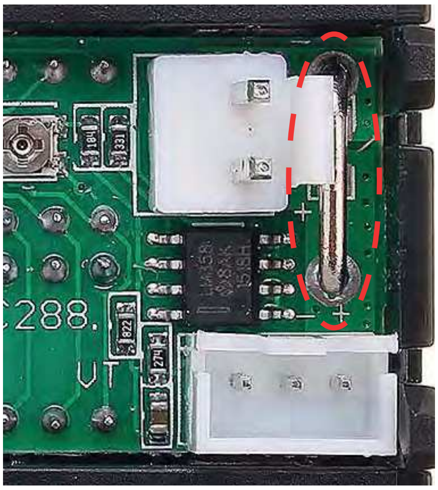
The common PZEM-051 is somewhat larger than the DSN-VC288, at 90mm wide, 50mm high and 25mm deep. It has a display 'window' measuring 50 × 30mm, and the display is an LCD with blue LED backlighting.

As you can see from the photo, it offers four-digit displays of both voltage and current, plus two additional four-digit displays: one for power (in





The external 50A 75mV shunt is in the foreground, with a similar 100A shunt behind.



The stout U-shaped wire (circled in red) is what needs to be removed to change the meter's current range.

either watts or kW) and the other for energy in either watt-hours (Wh) or kilowatt-hours (kWh).

Other features include switching the display backlighting on or off, resetting the energy indication to zero, setting a voltage alarm level and configuring the PZEM-051 for use with either a 50A or 100A current shunt. These functions are changed using the small pushbutton just to the right of the display window, via various long and short button press combinations.

The button is recessed slightly to prevent accidental presses, and can only be pressed intentionally using a small screwdriver or stylus. All of these settings are stored in non-volatile memory, and are retained even when the power is turned off.

The operating voltage range of the PZEM-051 is 6.5-100V DC, and it can measure voltages within the same range. The current measurement range is either 0-49.99A or 0-99.99A, depending on the version and the current shunt. The power measurement range is 0-10kW, with a display format of 0-999.9W for levels below 1kW, or 1000-9999W otherwise. Similarly, the energy measurement range is from 0-9999Wh for levels below 10kWh, or 10-9999kWh for levels of 10kWh and above.

The current shunt story

In the not-too-distant past, voltages and currents were measured using 'moving needle' analogue meters (ie, moving-iron and moving-coil meters). The current shunt was developed to allow these meters to measure currents that were higher than their basic sensitivity.

For example, if a meter needed 1mA to give a full-scale reading (ie, 1mA FSD), it could be used to measure currents up to say 1A by connecting a low resistance 'shunt' across its terminals. The resistance was chosen so that it would carry 99.9% of the current, leaving just 0.1% to flow through the meter itself. This effectively converted the 0-1mA meter into a 0-1A meter.

Similarly, the meter could be used to measure currents up to 10A by shunting it with an even lower value resistor which would carry 99.99% of the current, leaving just 0.01% to flow through the meter itself. The current shunt would conduct all of the current at 10A, except the 1mA needed for the meter to achieve full-scale deflection (FSD).

The name 'shunt' comes from railways, where a train is shunted onto a parallel section of track, just like how the current shunt parallels the pre-existing current path through the meter.

Working out the required resistance of the current shunt was fairly easy, once you knew the resistance of the meter itself, and the fraction of the current which needed to be diverted past it. For example, if the shunt needed to take 999 times the meter current (999mA/1mA), it would need to have a resistance of only 1/999 that of the meter itself.

So if the meter had a resistance of 100Ω, the shunt would need a resistance of 0.1001Ω or 100.1mΩ (100Ω ÷ 999).

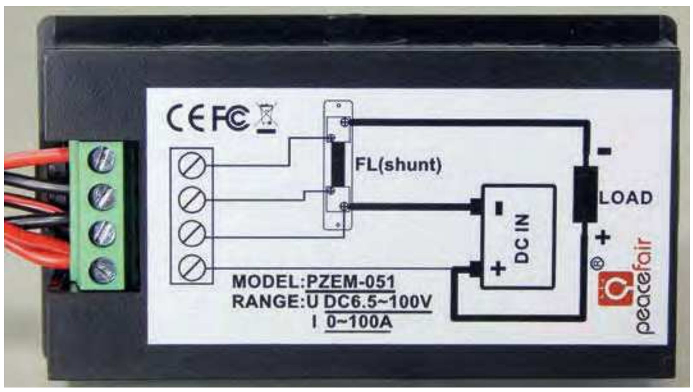
In the same way, to take 9999 times the meter current, the shunt would need to have a resistance of 10.001mΩ (100Ω ÷ 9999).

So that was the purpose of current shunts back in the old 'analogue' days. But things changed with the advent of digital meters. Since these essentially respond to voltage rather than current, the role of current shunts needed to change as well. Instead of just taking the major proportion of the current, they became a current-to-voltage converter.

Their resistance value is chosen to cause minimal disturbance to the circuit in which the current is flowing, while still providing enough voltage drop to allow accurate measurement. And the voltage level chosen was 75mV (millivolts), so most modern digital meters are designed to have this full-scale voltage sensitivity on their current ranges.

It is still relatively easy to work out the resistance value of a shunt for any particular current range. For example, if a meter needs a 0-10A current range, the shunt value required would be V/I or 7.5mΩ (0.075V ÷ 10A), according to Ohm's famous law. Or if you wanted to give the same meter a 0-1A current range, you'd need a current shunt with a value of 75mΩ (0.075V ÷ 1A).

So that's the function of a current shunt nowadays – to provide a small but accurately measurable voltage drop when a particular current is flowing through it.



Front and rear views of the PZEM-051 module. As shown by the label on the back, this meter has a voltage range of 6.5-100V DC and a current range from 0-50A or 0-100A depending on the external shunt used (see opposite).

An inside view of the PZEM-051 module. The main controller for this board is a Mixchips MXM11P62 (U3; lower middle) which is an 8-bit microcontroller.

I couldn't find a circuit diagram for the PZEM-051, but once the 100A version I ordered from AliExpress arrived, I carefully opened its case to take a look inside.

As you can see from the internal photo, there is not a great deal in it. At its heart, there's a Mixchips MXM11P62 8-bit microcontroller (U3) with 14KB of one-time programmable ROM, 256 bytes of SRAM, an ADC with 24-bit resolution, 18 bidirectional I/O pins, three 8-bit timers and a UART.

There's also a Holtek HT1621B LCD interface chip (U2) which links the MCU to the four 4-digit displays on the LCD, and a K24C02 (U4) two-wire serial EEPROM, which is presumably used to store measurement and display settings. So the design of the PZEM-051 is quite elegant.

Trying it out

Using the PZEM-051 is just as easy as the DSN-VC288, as you can see from Fig.3. The two uppermost screw terminals need to be connected to the voltage/power source, while the two lower terminals are connected to the ends of the current shunt. The two inner terminals must be connected to the negative side of the power source and the current shunt, respectively.

Note that the screw terminals are located at the rear of the PZEM-051, at the left-hand end. They're shown at the front in Fig.3 purely for clarity.

I measured the PZEM-051's voltage readings as 0.16% high, while the current readings were just over 2% high. The latter may be due to the current shunt tolerance.

There was a pleasant surprise when I measured the meter's own current draw, which was just below 3mA with the backlight switched on, falling to around 1mA when it was switched off. Therefore, despite its extra functions, the PZEM-051 is much more energy-efficient than the DSN-VC288, due to the use of an LCD rather than LED screen.

To summarise, the PZEM-051 multifunction DC measurement module can be described as both extremely useful and decent value for money.

Coming up

As mentioned earlier, a future follow-up article will describe some of the newer AC-measurement meter modules.

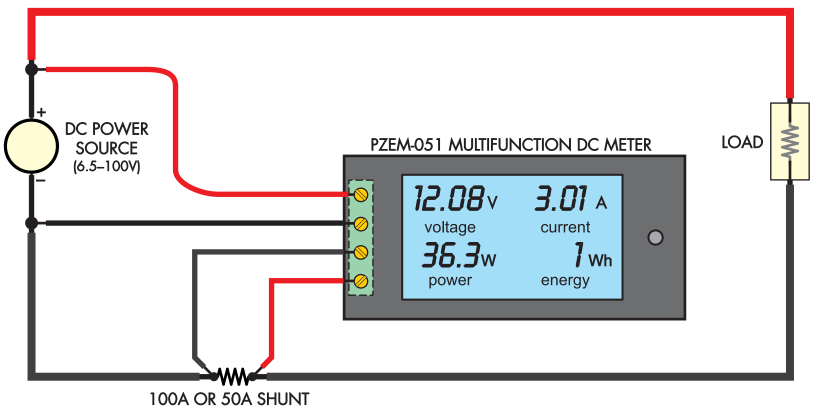


Fig.3: a simple example of how you can use the PZEM-051 meter to measure DC power, voltage, current and energy consumption.

Max's Cool Beans

By Max the Magnificent

Flashing LEDs and drooling engineers – Part 22

Just a couple of days ago – as I pen these words – I received an email from a new subscriber to this illustrious magazine. The gentleman in question was querying the 'Drooling Engineers' portion of the title to our current series of *Cool Beans* columns. I replied that it originated from the fact that I'm prone to proclaim, 'Show me a flashing LED, and I'll show you a man drooling.' I can only assume that the fact I've heard nothing since that time is because he's still rolling on the floor laughing.

Sew a button on your head

You know how you sometimes start a sentence by saying 'So...' and then pause to gather your thoughts before proceeding. Well, many moons ago, I had a friend of the female persuasion who abhorred a conversational vacuum, and who would fill it by saying, 'Sew a button on your head.' I had no idea what this meant, and I used to find it extremely annoying, so... it's ironic that I now tend to find myself doing the same thing to other people.

The reason I mention this here is that I'm eager to embark on a new endeavor. Do you recall my *Pedagogical and Phantasmagorical Inamorata Prognostication Engine* project? It was instrumental in kicking off this Flashing LEDs series of columns in the first place (*PE*, March 2020). The *raison d'etre* of this bodacious beauty, which currently resides in my office, is to predict the mood of my wife (Gina the Gorgeous) and inform me as to which way the wind is blowing before I set off home in the evening. Paradoxically, should Gina ever come to discover the beast's true purpose, I won't need it to predict her mood.

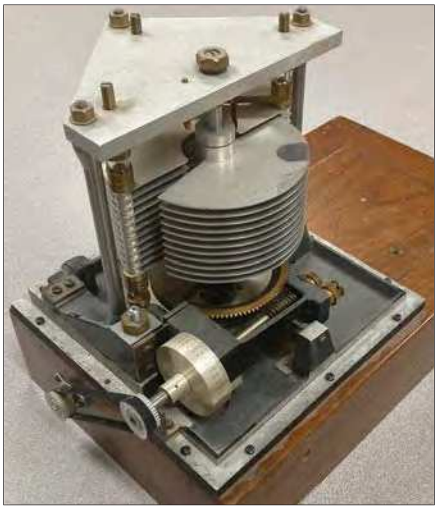


Fig.1. My ginormous variable capacitor – do you have bigger one?!

Everyone who encounters the groundbreaking *Prognostication Engine* is enthralled. Many of my friends have told me that they could do with one themselves. In fact, I am often asked to bring it to events like local hamfests to adorn the booth of a technical company or radio society. The problem is that it's a tad large – it stands taller than me – and is more than a little delicate, so I prefer to leave it where it is.

My new machine, which we will call the *Sewing Engine*, will be much more mobile. It's going to be housed in an antique sewing machine table with a cast iron base, much like the one that appears on the *Olde Good Things* website (**https://bit.ly/3n56Ogz**). Mine is almost identical, except that I certainly didn't pay the $250 the folks at *Olde Good Things* were asking for theirs because – knowing what I was looking for – my chum Carpenter Bob acquired one for a song at an auction out in the country somewhere.

I'm still mulling things over in my head as to the actual implementation. One thing I do know is that I'm going to finally get to use the ginormous variable capacitor that was gifted to me a couple of years ago by my chum Paul Parry of *Bad Dog Designs* (**https://bit.ly/3v5NMtS**). This little scamp (the capacitor, not Paul) is about 30 × 30 × 30 cm (Fig.1). I'll be removing its current wooden box base and repurposing that for something else, but – for the moment – observe the drive belt on the left. Paul removed the end stops that limited the motion of the moving part of the capacitor. This means it's now free to continuously rotate around, which is going to look mega-impressive. I don't like to boast (I take enormous pride in my humility), but I bet my variable capacitor is bigger than yours!

Another thing I know is that the *Sewing Engine* is going to flaunt five humongous vacuum tubes, like those perched on top of the *Prognostication Engine* (the tallest of which is 13-inches from tip to tail). I acquired these tubes, which are no longer functional, for a pittance several years ago from a local electronics store that was going out of business, and I've been waiting for an occasion to use them ever since.

In the case of the *Prognostication Engine*, there is a metal band around the base of each tube (for the *Sewing Engine*, I'll be using cunning 3D printed bands that were designed by my chum Steve Manley). Inside each band is a strip of 30-or-so WS2812 tricolor LEDs. Way back in the mists of time, I started by lighting these LEDs with static values, but the resulting display turned out to be almost impossible to perceive in regular ambient lighting conditions. Next, I experimented with dynamic effects, such as having lit pixels chasing each other around the bands (Fig.2).

The human eye is incredibly sensitive to motion, so the effect is quite startling, to the extent that the structures inside the tubes sometimes appear to be rotating in the opposite direction. To let you see what I'm waffling about, I just took a quick video in my office: **https://bit.ly/3ax6EZu**

In addition to displaying various random sequences, I may also decide to make these LEDs respond to sound,

Fig.2. Using LEDs to give old vacuum tubes a new lease of life.

Fig.3. A cheap-and-cheerful 3-phase 12V motor controller.

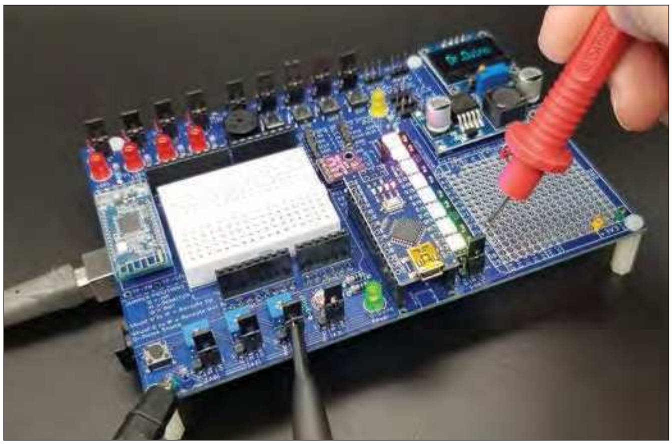


Fig.4. The Dr.Duino Explorer (Image source: Guido Bonelli).

but that will be a story for another day and a future column.

Motoring along

Returning to my variable capacitor, one end of the drive belt is attached to a sprocket on a shaft that drives the capacitor, while the other end is affixed to a sprocket on a shaft driven by a motor that's lurking in the wooden base.

I vaguely remembered Paul telling me that this was a 12V motor, but that was about it, so you can only imagine my surprise when I looked inside the base to find a small gear and motor combo about 1.5 inches in diameter and 4 inches long. Actually, that wasn't the surprise. The surprise was the fact that there were three wires coming out of the motor. 'Ah Ha!' I thought, 'What we have here is a 3-phase brushless motor.'

The advantage of brushless motors is that they are extremely quiet, both physically (audibly) and electrically (in the form of electromagnetic noise). The downside is that they are a right #$%$#$ to control if you wish to build your own controller from the ground up. Fortunately, you can purchase a cheap-and-cheerful controller from eBay (**https://bit.ly/2YLSLUi**), so that's what I did (Fig.3).

I remembered that Paul used four of these motors to drive the drums on the front of his legendary Bombe clock (**https://bit.ly/3p0tH76**), which is a replica of Alan Turing's 'Bombe' that helped British Intelligence officers decipher messages coded by the German Enigma Machine during WWII. I once saw this marvelous machine in action, and you couldn't hear a whisper from the motors.

Is there a doctor in the house?

One of the problems with the control board for the 3-phase motor is that it doesn't appear to be geared up (no pun intended) to be controlled from a microcontroller. The jumper to the right of the far side of the board can be used to control the rotational direction of the motor, while the potentiometer on the lower left-hand side can be used to control its speed. If I wanted to control this using an Arduino Uno, for example, I'm wondering if I can use a regular digital input/output signal to replace the jumper and a resistor-capacitor-smoothed pulse-width modulated (PWM) output to replace the potentiometer.

One of my 'go-to' boards when I'm prototyping something like this is the Dr.Duino Explorer (**https://bit.ly/2YSrIat**), which was created by my chum Guido Bonelli. This is an interesting board in that it can act as a shield that you plug on top of an Arduino Uno, or you can skip the Uno and plug an Arduino Nano into the Explorer, as shown in Fig.4.

Instead of using a regular breadboard and fighting your way through a rat's nest of wires, the Explorer provides most of what you need to prototype a bunch of projects, like my attempt to control my motor controller board, for example. The Explorer provides four pushbutton switches, three potentiometers, a light-dependent resistor (LDR), four red LEDs, and a bunch of current-limiting resistors. The shield also features a piezo buzzer and a stick of eight NeoPixels. Furthermore, there's an organic LED (OLED) display in the upper right-hand corner of the board; a very handy area where you can add discrete components and integrated circuits in the bottom right-hand corner; and a rather meaty voltage regulator just below the OLED display. But wait, there's more, because in addition to a small breadboard, there are pins into which you can plug a variety of I^{2}C-based sensors and actuators (an ultrasonic ranging sensor, not shown here, is also included).

One thing I should perhaps point out is that Dr.Duino Explorer is a kit that you assemble following the step-by-step online instructions that are accompanied by gorgeous high-resolution photos. These are the most comprehensive, intuitive and user-friendly instructions I've ever seen, and I don't say that lightly.

Feeling satisfied?

The old idiom-proverb 'Curiosity killed the cat' is used to warn of the dangers of unnecessary investigation or experimentation. The later addition of, 'but satisfaction brought it back' indicates that the risk would lead to resurrection because of the satisfaction felt after finding out. But none of this is what I wanted to talk about.

I've said it before, and I'll say it again – it's strange how disparate ideas from different sources sometimes seem to come together at the same time. A couple of weeks ago, for example, I received a rather enigmatic image of a curious cat construct from my chum Alvin in the UK (Fig.5). Alvin and I co-authored a couple of books together, including *How Computers Do Math* (**https://amzn.to/3iYNAYH**) and we like to keep each other abreast of our current projects, but this one was new to me, so I asked him to expound, explicate and elucidate.

Alvin responded with a video, which is when I first realised that the eyes appear to move (**https://bit.ly/3DHiMDM**). Alvin went on to explain that he used the OLED displays from an Adafruit Monster Mask (**https://bit.ly/3ayvLen**) to implement the cat's eyes, and that he'd augmented these displays with 40mm convex plastic lenses (**https://bit.ly/3azM7mP**). Alvin tells me that the displays come with software accompanied by a configuration file that allows you to customise them to look like cat, snake, or human eyes. He also picked up

Fig.5. An enigmatic cat (Image source: Alvin Brown).

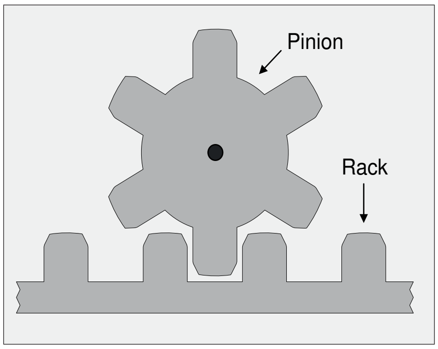


Fig.6. A rack and pinion gear assembly.

a blank cardboard cat mask from Hobbycraft (**https://bit.ly/3AHPJOf**), which he then painted himself. He says the result is approximately 6 × 6 inches in size.

Seeing Alvin's cat's eyes move made me think of the *SMAD* (*Steve and Max's Awesome Display*) eyes on my pseudo robot heads. As I mentioned in my previous column (*PE*, November 2021), Steve and I have been planning on making the *SMADs* appear to look to the left, right, up and down by activating different groups of pixels.

I was happily cogitating and ruminating on this when Alvin sent me one final email saying that he's thinking about future enhancements, including adding a sensor to detect motion and a servo to turn the head towards the detected object. I'd no sooner started to mull over this new piece of intelligence when, much to my surprise...

Robots rising

...I received a call from our illustrious publisher here at *PE*. Yes, the person on the other end of the phone was none other than the man, the myth, the legend (in his own extended lunchtime), Matt Pulzer (cue fanfare of sarrusophones).

I'm not sure if he'd been reading (what I laughingly call) my mind, but Matt said he'd been thinking (I manfully managed to choke back a response) that it would be cool to add some form of motion to my robot heads. In addition to being able to look left, right, up, and down, Matt even suggested the possibility of using some form of linear actuator such as a solenoid or rack-and-pinion assembly to give the *SMAD* eyes the ability to 'pop out' (move forward and backward).

Just to refresh our minds, a solenoid-based linear actuator involves a wire wrapped around a ferromagnetic core. If current is passed through the wire, the core will act like a magnet with north and south poles. The clever part is if the core is only partially inserted into the coil, in which case activating the current will cause the core (officially called the 'plunger,' in this case) to be pulled into the coil. This motion can be used to pull or push a load, like our *SMAD* eyes, for example. When the current is removed from the wire, a spring can be used to return the actuator to its initial position.

By comparison, a rack and pinion assembly can be used to convert the rotary motion of a motor into a corresponding linear action. The way this typically works is that the high-speed, low-torque rotation of the motor is first converted into a lower-speed, higher-torque rotation by means of a gear train. A special gear wheel called the 'pinion' is attached to the shaft coming out of the gear train, and the teeth on the pinion engage with teeth on the rack (Fig.6).

Now, I'm certainly not going to tell Matt that we aren't going to do this (that is, having the eyes move forward and backward). Just to be clear, we aren't going to do this, it's just that I'm not going to tell Matt – it's just our little secret. However, we are going to give our *SMAD* eyes the ability to move left, right, up, and down.

Pan-and-tilt and curved orbs

There are several parts to this puzzle. For example, in order to perform some short-term cheap-and-cheerful experiments, I just purchased two pan-and-tilt mechanisms from Adafruit (**https://bit.ly/3lIjQB1**). Each of these little beauties comes fully assembled and equipped with two SG-90 or SG-92 micro servos that allow the assembly to pan approximately 180° from side-to-side and tilt around 150° forwards and backwards (Fig.7).

We'll discuss the differences between things like servos (analogue and digital) and stepper motors in next month's column. Also, at that time, we will be considering some rather cool 4-axis joysticks that we can use to control our pan-and-tilt mechanisms.

Returning to my existing pseudo robot heads, you may remember that the *SMADs* are used in conjunction with 3D-printed shells. These shells, which are 10mm thick, divide the displays into segments (we use 29-segment and 45-segment shells depending on the effect we're trying to achieve). In front of each shell, we have a thin layer of diffuser material (we're using the white plastic divider sheets you find in file folders). In front of the diffuser, we have a 1mm-thick facia (face plate).

I talked about all of this with my *SMAD* collaborator Steve Manley. The first thing Steve thought of was that we should create new curved facias for our *SMADs* to make them look a little more eye-like (Fig.8). From left to right this image shows the back shell, front shell, diffuser and curved facia. The only reason for splitting the main shell into two 5mm slices is to make it easier to use a spray to paint the inside faces of the segments white (this dramatically increases the brightness of the ensuing display).

Although the curve of the facia is quite subtle (only 5 mm at the center), the result is rather startling. Apart from anything else, the fact that the diffuser is located behind the facia gives the segments a 3D effect all of their own (Fig.9).

Don't forget that, should you wish to join in the fun and frivolity, then *SMADs* are available for purchase from the *PE PCB Service* (**https://bit.ly/3wVUgLq**) for the remarkably low price of only

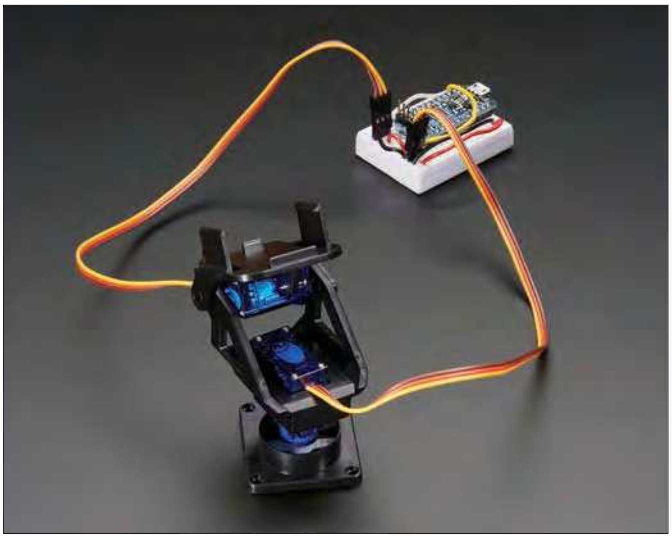


Fig.7. Pan-and-tilt mechanism (Image source: Adafruit).

Fig.8. Exploded view of a 45-segment shell with curved facia (Image source: Steve Manley).

Fig.9. The new curved facias give the segments an interesting ‘depth’ (Image source: Steve Manley).

£11.95 each, which includes shipping in the UK (shipping outside the UK will be quoted separately).

Also, as usual, Steve has very kindly made the 3D print files for this new version of the shells available for anyone who wants to print their own: download file **CB-Dec21-01.zip** from the December 2021 page of the *PE* website at: **https://bit.ly/3oouhbl**

A pain in the neck!

Unfortunately, I fear I’ve unleashed a monster – Steve has leapt into this project with gusto and abandon. In addition to having eyes that can move from side-to-side and up-and-down, Steve wants to extend these capabilities to the entire robot head.

Steve’s already started work on his eyes. I have to say that the solution he has come up with is something I’ve never seen before and that I would not have thought of myself in a million years. Suffice it to say that Steve’s solution puts my simple pan-and-tilt mechanisms to shame.

Every time we chat on FaceTime, Steve’s 3D printer is churning away in the background as he keeps on refining his design. I cannot wait to share all of this with you in future columns.

Sense something strange?

Earlier, I mentioned that one of the ways in which we can control the motion of our *SMAD* eyes and robot heads is by means of some rather cool 4-axis joysticks that we’ll be discussing in my next column.

Another possibility will be to equip our robot heads with some way to sense what’s going on around them and to respond accordingly. Well, by some strange quirk of fate, I was just playing with a brand new VL53L5CX Time-of-Flight 8×8 Multizone Ranging Sensor from STMicroelectronics.

This little beauty is only 6.4 × 3.0 × 1.5 mm, which makes it significantly smaller than the size of a Jellybean (Fig.10). The smaller aperture on the left houses a 940nm invisible light vertical cavity surface emitting laser (VCSEL) and integrated analogue driver. By means of an integrated lens, the laser light spreads out in a three-dimensional 45-degree cone.

The larger aperture on the right holds an 8×8 receiving array of single photon avalanche diodes (SPADs) that detect the laser light reflected from objects up to 4m away. The ‘washboard’ structure in the middle is used to mitigate any laser light that’s reflected if you add a glass or plastic cover on top of the device. Also in the package is a low-power microcontroller that processes all of the data and presents it on demand to a host processor via an I²C bus.

I had a lot of fun playing with this in my office. In fact, I even took a video (**https://bit.ly/3mGOSIA**). The reason I mention this here is that I can easily envisage using one of these sensors to detect the presence of people, monitor their movements, and cause our robot heads and eyes to track them as they move around the room. Of particular interest is that the folks at STMicroelectronics tell me that they are working with Adafruit and SparkFun, and that both of these companies will be bringing out VL53L5CX-based breakout boards (BOBs) in the not-so-distant future. These BOBs will, of course, be accompanied by training materials and example sketches (programs).

-.-- .- -.-- / ... -- .- -.. -.-.--

In 1837, the British physicist and inventor Sir Charles Wheatstone and the British electrical engineer Sir William Fothergill Cooke invented the first British electric telegraph. This instrument made use of five wires, each of which was used to drive a pointer at the receiver to indicate different letters.

Sir Charles was a busy man. For example, among many other things, he took the time to invent the concertina in 1829. I sometimes wonder if Sir Charles invented the concertina because he didn’t have many friends, or if he ended up with few friends because he invented the concertina.

Also, in 1837, the American inventor Samuel Finley Breese Morse developed the first American telegraph. This was based on simple patterns of ‘dots’ and ‘dashes’ (or ‘dits and ‘dahs’), which we now call Morse code (Fig.11), being transmitted over a single wire.

Morse’s system was eventually adopted as the standard technique because it was easier to construct and more reliable than its British counterpart.

Different people can key Morse code at different numbers of words per minute (WPM). However, we can standardise things, because if we say that the length of a dot is one unit of time, then a dash is three units, the space between two parts of the same letter is one unit, the space between letters is three units, and the space between words is seven units. You can experiment with a translator here: **https://morsecode.world**

Of course there’s a reason

The reason I mention all of this here is that I recently received an email from a member of the *PE* community who we will call Simon (because that’s his name). In his message, Simon spake thus: ‘Hi Max, your column in October’s *PE* couldn’t have been timed better. I had in mind a little Arduino project to implement a Morse code trainer and I spent some time

Fig.10. VL53L5CX Time-of-Flight 8×8 Multizone Ranging Sensor (Image source: STMicroelectronics).

A	• ▬	K	▬ • ▬	U	• • ▬	1	• ▬ ▬ ▬ ▬
B	▬ • • •	L	• ▬ • •	V	• • • ▬	2	• • ▬ ▬ ▬
C	▬ • ▬ •	M	▬ ▬	W	• ▬ ▬	3	• • • ▬ ▬
D	▬ • •	N	▬ •	X	▬ • • ▬	4	• • • • ▬
E	•	O	▬ ▬ ▬	Y	▬ • ▬ ▬	5	• • • • •
F	• • ▬ •	P	• ▬ ▬ •	Z	▬ ▬ • •	6	▬ • • • •
G	▬ ▬ •	Q	▬ ▬ • ▬	,	▬ ▬ • • ▬ ▬	7	▬ ▬ • • •
H	• • • •	R	• ▬ •	.	• ▬ • ▬ • ▬	8	▬ ▬ ▬ • •
I	• •	S	• • •	?	• • ▬ ▬ • •	9	▬ ▬ ▬ ▬ •
J	• ▬ ▬ ▬	T	▬	!	▬ • ▬ • ▬ ▬	0	▬ ▬ ▬ ▬ ▬

Fig.11. International Morse code.

pondering how I should format the data in an array. I had come to the conclusion that it would be better to start the data array just as you did with the *SMAD:* declaring the length of data in each row first (see below). I felt somewhat vindicated and relieved that I was on the same track (as it were) when I read your column, so a *big thumbs up* to you!'

Simon went on to say that he had used two `#define` statements as follows, noting that 'the reason for these values is because a 'dah' is three times the length of time of a 'dit' and I use them as the timing structure':

```
#define dit 1
#define dah 3
```

Based on this, Simon defined his Morse code trainer array as follows:

```
uint8_t MorseAlphabet [26][5] =
{
{2, dit, dah},               // a
{4, dah, dit, dit, dit},     // b
{4, dah, dit, dah, dit,}, // c
{4, dah, dit, dit,},         // d
{1, dit},                    // e
etc....
```

Well, I simply couldn't help myself. I decided to create a little program to make my two existing pseudo robot heads have a conversation in Morse code.

I'm not sure how Simon implemented his program (apart from the snippets we just discussed), but I took a different tack, as is my wont. For example, my program commences with two definitions as follows:

```
#define WPM           15
#define UNIT_DELAY 1200
```

My unit delay is for one time unit in milliseconds assuming a transmission rate of 1 WPM. All of the other delay values are calculated as a function of this and the WPM value. Thus, assuming a transmission rate of 15 words per minute, we end up with one unit (a dot) being 1,200 / 15 = 80 milliseconds. I also defined my Morse code dots-and-dashes data array in a different way to Simon, as follows:

```
char *DnD[] =
{
   ".-",      //  0 = A
   "-...",    //  1 = B
   "-.-.",    //  2 = C
   "-..",     //  3 = D
   ".",       //  4 = E
   etc.
```

This is something we haven't discussed before. In this context, the asterisk * character declares our `DnD` variable to be a pointer. Further, since `DnD` is an array of type `char`, this means that `*DnD` is a pointer to an array of strings.

To be honest, explaining the way this works would take longer than we have time for here. The thing is, pointers allow us to do a whole host of cool things. If you want to know more about these little rascals, then there's a wonderful book called *Understanding and Using C Pointers* by Richard Reese, see: **https://amzn.to/3ASgYWI**

In the meantime, you can peruse and ponder my program by downloading the code (file **CB-Dec21-02.txt**) from the December 2021 page of the *PE* website at: **https://bit.ly/3oouhbl**

Finally, for your delectation and delight, I just took a video of all this taking place – see: **https://youtu.be/FmQf1q8dlFQ**

Next time

In my next column we will look at some more *SMAD* display effects. We will also create some simple programs that allow us to use our 4-axis joysticks to control the servos on the pan-and-tit mechanisms, thereby causing our *SMAD* eyes to move around in interesting ways. Until then, as always, I welcome your comments, questions and suggestions.

Cool bean Max Maxfield (Hawaiian shirt, on the right) is emperor of all he surveys at **CliveMaxfield.com** – the go-to site for the latest and greatest in technological geekdom.

Comments or questions? Email Max at: **max@CliveMaxfield.com**

KickStart

by Mike Tooley

Part 6: Exploring DDS

Our *KickStart* series aims to show readers how to use readily available low-cost components and devices to solve a wide range of common problems in the shortest possible time. Each of the examples and projects can be completed in no more than a couple of hours using 'off-the-shelf' parts. As well as briefly explaining the underlying principles and technology used, the series will provide you with a variety of representative solutions and examples, along with just enough information to enable you to adapt and extend them for your own use.

This sixth instalment provides you with an introduction to the technology used for direct digital synthesis (DDS). To help you get started, we've provided some practical circuit arrangements and sample code based on the popular and inexpensive Analog Devices AD9833 DDS chip. This versatile device can form the basis of projects ranging from simple fixed-frequency sources to programmable waveform generators and FSK/PSK generators.

In recent years a range of devices has become available that greatly simplify the task of generating signals and waveforms that are both highly accurate and stable. These handy and increasingly low-cost devices use direct digital synthesis (DDS) where phase-related data is converted into amplitude data before being fed to a digital-to-analogue converter (DAC), and the resulting output is then filtered to produce a sinusoidal analogue signal.

Modern DDS devices are often programmed through a serial peripheral-interface (SPI) and need only an external clock to generate sinusoidal (and other) waveforms. This makes them extremely easy to use and increasingly competitive with alternative solutions based on phase-locked loops and programmable dividers. The latest generation of DDS chips can generate frequencies from less than 1Hz up to 400MHz (based on a 1.2GHz clock) with exceptional resolution. Key features of DDS include:

- Ability to generate signals over a wide range of frequency with a very high degree of accuracy and stability
- The generated frequencies may be changed very quickly without the additional loop settling time associated with phase-locked signal sources, which ensures exceptional frequency agility
- With many of the latest DDS chips, frequency-shift keying (FSK) and phase-shift keying (PSK) can be very easily implemented
- Modern DDS devices built into low-cost, readily available modules offer flexibility and ease of programming using commonly available low-cost platforms such as the Arduino, Micromite or Raspberry Pi (see *Going Further* for examples).

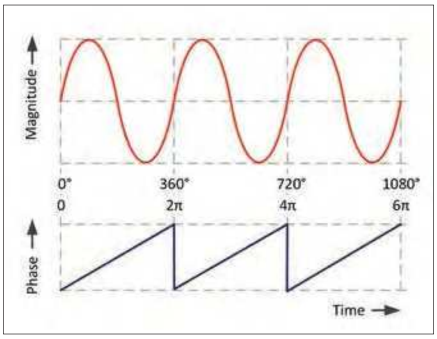


Fig.6.1. How a sinewave's phase angle plot changes linearly with time.

DDS principles

As readers will doubtless be aware, sinusoidal waves repeat on a continuous basis with 360° phase rotation (equivalent to 2π radians) over each cycle, as shown in Fig.6.1. Note how the corresponding phase waveform also repeats every 360° but is *linear* in shape. The underlying principle of DDS generators is simply that this linear change of phase can be translated into a sinusoidal change in voltage. The key to this process is a circuit that can convert a change in phase angle to a change in amplitude, as shown in Fig.6.2.

Fig.6.2 illustrates the basic principle of DDS signal generation. The arrangement is based on four functional blocks: a phase register (or phase accumulator), a phase-to-amplitude converter (PAC), a digital-to-analogue converter (DAC), and a low-pass filter. The phase register stores an n-bit digital word that determines the output frequency, while the PAC is typically a read-only memory (ROM) comprising a look-up table of sinusoidal amplitude data. The output of the PAC is taken to a DAC that usually has a resolution of between 10 and 14 bits.

In a practical DDS arrangement, the phase accumulator is a digital counter that increments its stored data during each clock cycle. The tuning word (M) sets the increment in phase, effectively jumping forward in the data from the counter that's then passed to the PAC. The phase accumulator is designed so that it will overflow when the maximum count is exceeded, thereby *restarting* the count so that the process repeats indefinitely.

The output frequency of the signal generated by the DDS arrangement shown in Fig.6.2 is given by the relationship:

$f_{OUT} = (M \times f_C)/2^n$

f_{OUT}	output frequency of the DDS
M	tuning word
f_C	clock frequency
n	number of bits (resolution) of the phase accumulator.

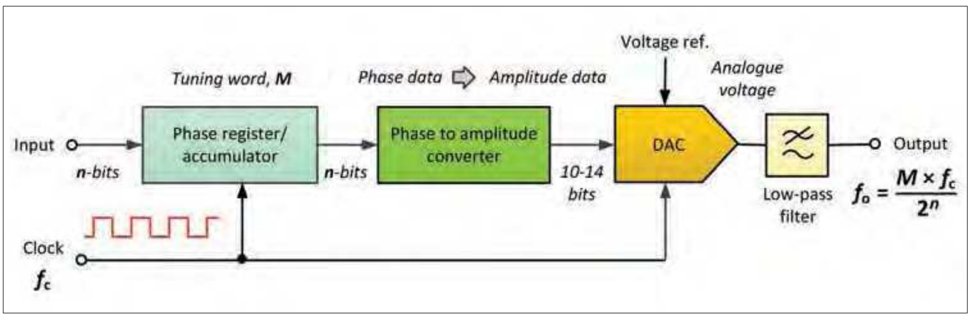


Fig.6.2. Basic principle of DDS signal generation.

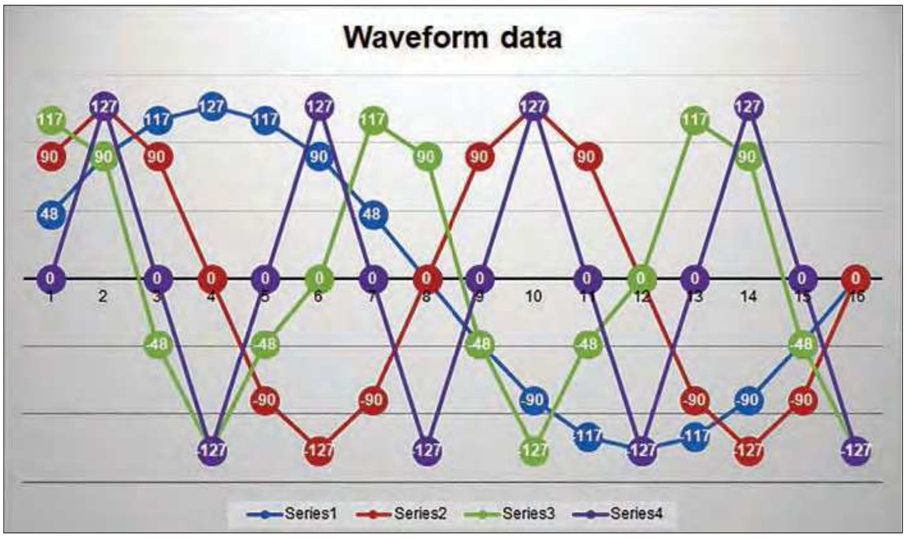


Fig.6.3. Waveform plotted using spreadsheet data generated by Listing 6.1.

Changes to *M* produces an immediate – and importantly – phase-continuous change in output frequency. Plus, as mentioned, there is also no loop settling time which would be incurred with a conventional phase-locked loop.

Note that the phase increment (the constant value determined by the tuning word) is added to the phase accumulator on *each* clock cycle. If the phase increment is large, the PAC will step quickly through the sine look-up table and thus generate a high-frequency sinewave. If the phase increment is small, the PAC will take many more steps, generating a lower frequency sinewave. We can illustrate this important point with some simple software.

Listing 6.1 shows some simple Python code that demonstrates the DDS principle. (This code, and the other two listings (6.2 and 6.3) referenced in this article can be downloaded from the December 2021 page of the *PE* website.) The code uses a lookup table of 16 sinusoidal values and the main loop is executed four times for incremental values ranging from 1 to 4. A list of waveform data is generated on each passage through the loop, and the values produced can then be examined and compared.

On the first passage through the loop the unity increment just produces a list of data values that are the same as those stored in the lookup table. This produces a single cycle of a sinusoidal waveform constructed from the 16 data points. On the second passage through the loop (where the increment is 2) every other data point is used, and the sinusoidal waveform is therefore generated at twice the frequency (but still using 16 data points). On the third and fourth passage through the loop the increment is increased to 3 and 4 respectively. This produces outputs that are respectively three and four times the original frequency.

Do try the Python code (see *Going Further*), it can be very instructive to work through the generated data obtained during each of the four iterations. To help you visualise what's going on, Fig.6.3 shows the waveform data plotted using spreadsheet software. Notice how the blue sinewave uses *all* the stored data points when passing through the loop (Series 1). The red sinewave corresponds to the second pass through the loop corresponding to an increment of 2 (Series 2), while the green and mauve plots correspond to increments of 3 and 4 (Series 3 and Series 4 respectively).

Note how the waveform becomes distinctly less sinusoidal as the increment is increased and fewer data points are used in its generation. Any larger value of increment would result in a very strange waveform because we simply don't have enough data values in the lookup table.

Limitations

As the output frequency is increased, the number of samples per cycle generated by a DDS will decrease proportionately. The Nyquist theorem dictates that *at least* two samples per cycle are required to reconstruct an output waveform, so the theoretical maximum output frequency of a DDS is half that of the maximum clock frequency. However, for practical applications and to produce a waveform of acceptable quality, the output frequency must be limited to significantly less than $f_C/2$. Note also that a low-pass filter must be used in the DAC output to remove spurious signal components present in the output waveform. We will look at this a little later when we describe a practical design example.

The spectral purity of the output of a DDS is expressed in terms of its 'spurious-free dynamic range' (SFDR). This is an important measure of the performance of a DDS system, and it relates to the ratio (measured in dB) between the highest amplitude of the fundamental signal to the highest amplitude of any spurious, signal (including harmonically related components and aliases). SFDR is particularly important in communication applications where the frequency spectrum is being shared with other signals. Fig.6.4 shows an example of determining SFDR from the output spectrum of a DDS system. Note how the indicated SFDR is about 60dB which will be adequate for many applications.

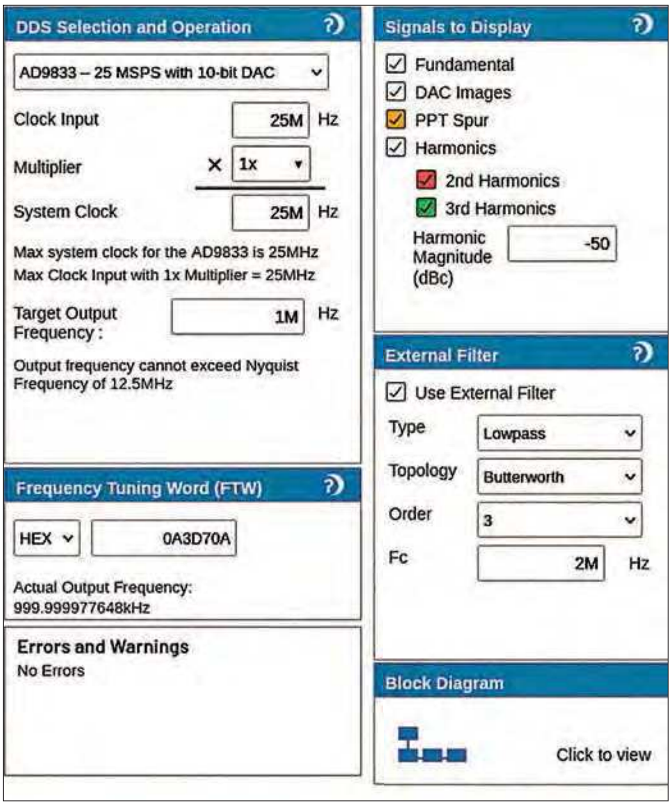
Using a DDS design tool

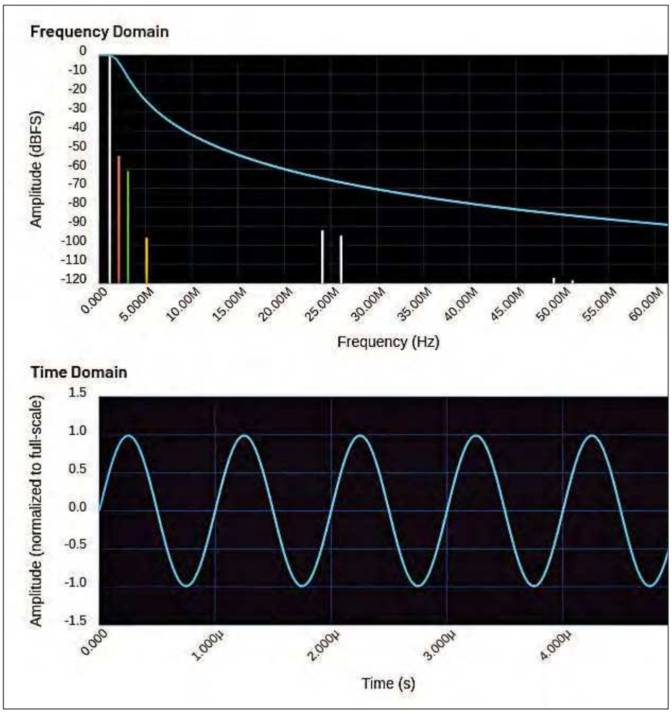
A design tool (see *Going Further*) can be invaluable when attempting to assess the performance of a DDS chip. Fig.6.4 shows the Analog Devices DDS design tool being used to evaluate the performance of a low-cost AD9833 device. This chip operates with a 25MHz clock, and we have set a target output frequency of 1MHz. The design tool has calculated the tuning word which appears as 0A3D70A in hexadecimal (this is the value that we would need to program into the device for the desired 1MHz output frequency). To access this excellent free tool, just go to: **https://bit.ly/pe-dec21-ad3**

In Fig.6.4, the Analog Devices design tool has also calculated the magnitude of the harmonic components relative to the fundamental output. This is shown

Listing 6.1 A simple Python module using a lookup table to demonstrate the DDS principle.

```
# DDS principle using a lookup table
# Sine lookup table with 16 values
sine = [0,48,90,117,127,117,90,48,0,-48,-90,-117,-127,-117,-90,-48]
# Initialise the counter
counter = 0
for increment in range(1,5): # Use four incremental values
   print("Waveform data for increment =",increment)
   for clock in range(0,16):
      counter = counter + increment
      if counter > 15:
         counter = 0
      print(sine[counter])
else:
   print("Done!")
```





(left) Fig.6.4. The excellent DDS design tool from Analog Devices. (above) Fig.6.5. Frequency and time domain plots generated by the Analog Devices DDS design tool.

as –50dB but to provide us with a better impression of the output spectrum, the design tool generates frequency and time domain plots of the output waveform (see Fig.6.5). The response shown in Fig.6.5 also incorporates the low-pass response of the Butterworth filter that we plan to include in the output of the DAC. To provide the desired amount of harmonic attenuation we've set the filter parameters to a third-order response with a cut-off frequency of 2MHz (twice that of the output frequency).

It is important to note that Fig.6.5 indicates the presence of second, third and fifth harmonics (shown in red, green and brown respectively) as well as mixing components at 1MHz either side of the clock frequency (ie, 24MHz and 26MHz).

Filter design

The third-order Butterworth filter can be quickly and easily designed with the aid of an on-line tool like that shown in Fig.6.6 (see *Going Further*). Note that we have used a design impedance of 50Ω for these filter calculations, but this might need to be changed to suit your own particular circumstances. The circuit of the third-order low-pass filter is shown in Fig.6.7, together with its simulated frequency response in Fig.6.8 generated by Tina TI (see *Going Further*). If required, the Analog Devices design tool can also produce tabular data for any major spurious and harmonic components present in the output waveform.

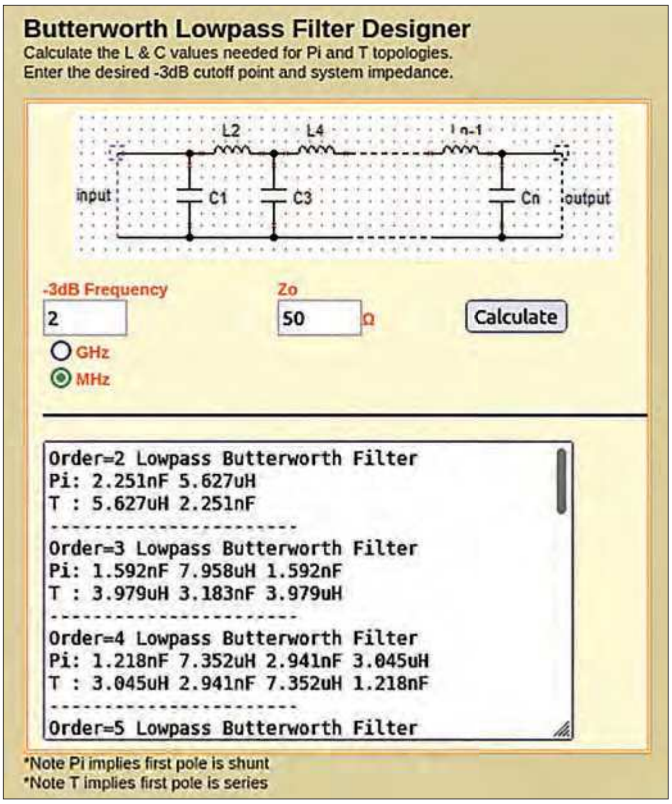


Fig.6.6. On-line design tool to create a simple third-order Butterworth low-pass filter.

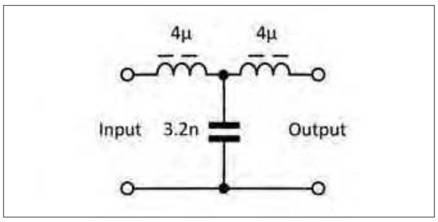


Fig.6.7. Circuit of the third-order Butterworth low-pass filter.

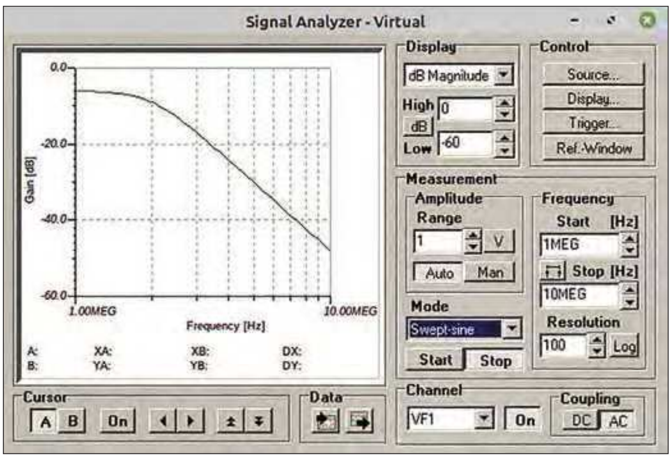


Fig.6.8. Using Tina TI to check the response of the Butterworth low-pass filter.

Fig.6.9. Low-cost DDS module using an AD9833 chip.

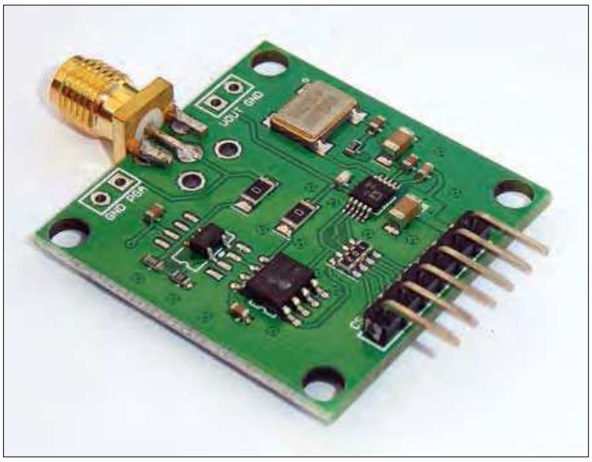


Fig.6.10. An AD9833 module with an enhanced specification (operates at higher frequencies).

Introducing the AD9833 DDS chip

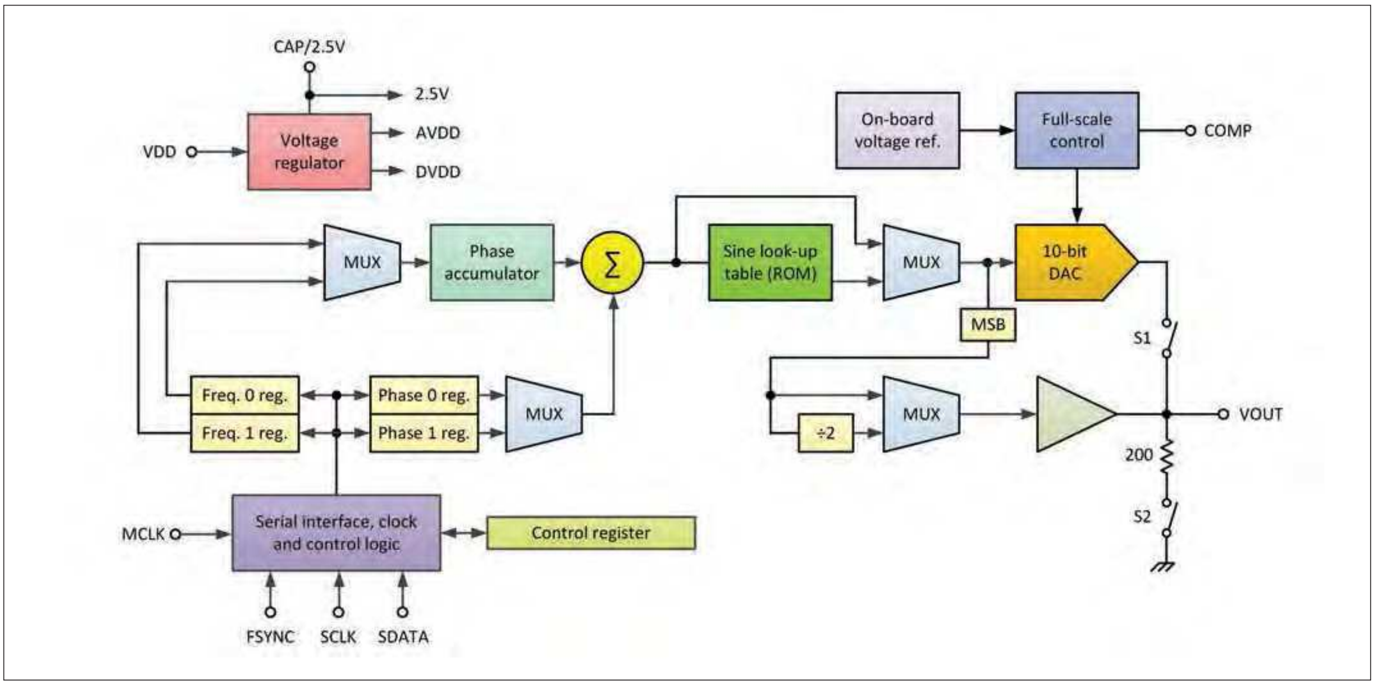
Having explained some of the basic principles behind DDS signal generation it's time to introduce an example of a typical DDS chip. For this, we've chosen the inexpensive but very capable Analog Devices AD9833 device. This device forms the basis of a range of low-cost DDS modules (see Figs.6.9 and 6.10) that can be used in a wide variety of waveform generators and signal sources. Modules are much the easiest, quickest and – surprisingly! – the cheapest way to use the AD9833. The two modules shown in Figs.6.9 and 6.10 are widely available from just a few pounds – see aliexpress.com, eBay and Amazon. Prices do vary enormously, so it definitely pays to shop around.

The AD9833 can produce sine, triangular, and square-wave outputs, and the output frequency and phase are software programmable using a standard serial peripheral interface (SPI). The frequency registers are 28-bits wide and a resolution of 0.1Hz can be obtained with a 25MHz clock. Using a 1MHz clock the device can be tuned to a very impressive resolution of 0.004Hz.

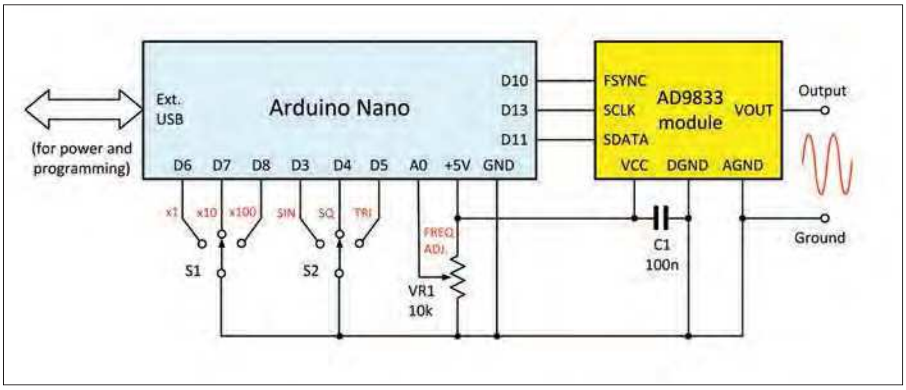
The AD9833 operates from a power supply between 2.3V and 5.5V with a typical power consumption of just 12.65mW at 3V. This makes the AD9833 ideal for use in continuously operating low-power applications.

The internal arrangement of an AD9833 chip is shown in Fig.6.11. Tuning data enters the chip via the serial interface and is loaded into the frequency and phase registers. Note that the frequency and phase registers are duplicated, which makes FSK (frequency-shift keying), and PSK (phase-shift keying) very straightforward.

The phase accumulator is a 28-bit register, the output of which can be combined with either of the two phase registers to provide the digital address input to the sine look-up table ROM. The corresponding stored value from the look-up table is fed to a 10-bit digital-to-analogue converter (DAC).



(above) Fig.6.11. Internal arrangement of an AD9833 DDS chip.



(right) Fig.6.12. Circuit arrangement of the AD9833 function generator.

The output of the chip can be software configured for sine or square-wave operation using internal switches S1 and S2. For square-wave operation only the most-significant bit from the DAC is used, producing an output voltage that is high for half a cycle and low for the other half. For a triangular output the sine ROM can be bypassed so that only the truncated digital output from the phase accumulator is sent to the DAC, which will then produce a 10-bit linear triangular function.

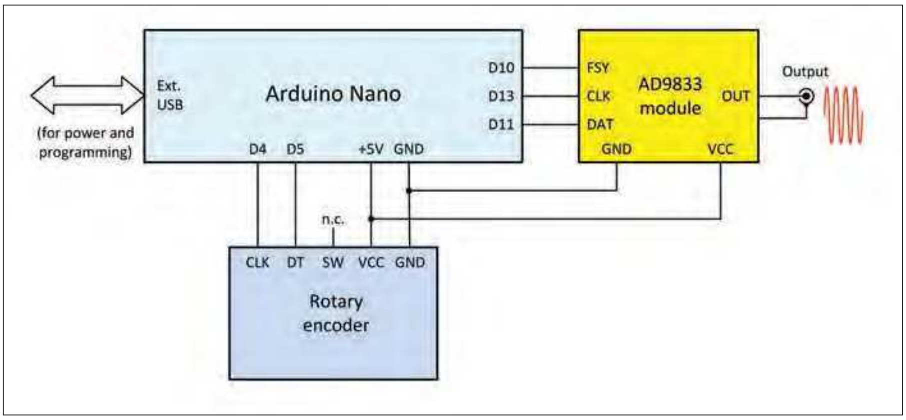


Fig.6.13. Circuit arrangement of the AD9833 variable frequency oscillator (VFO).

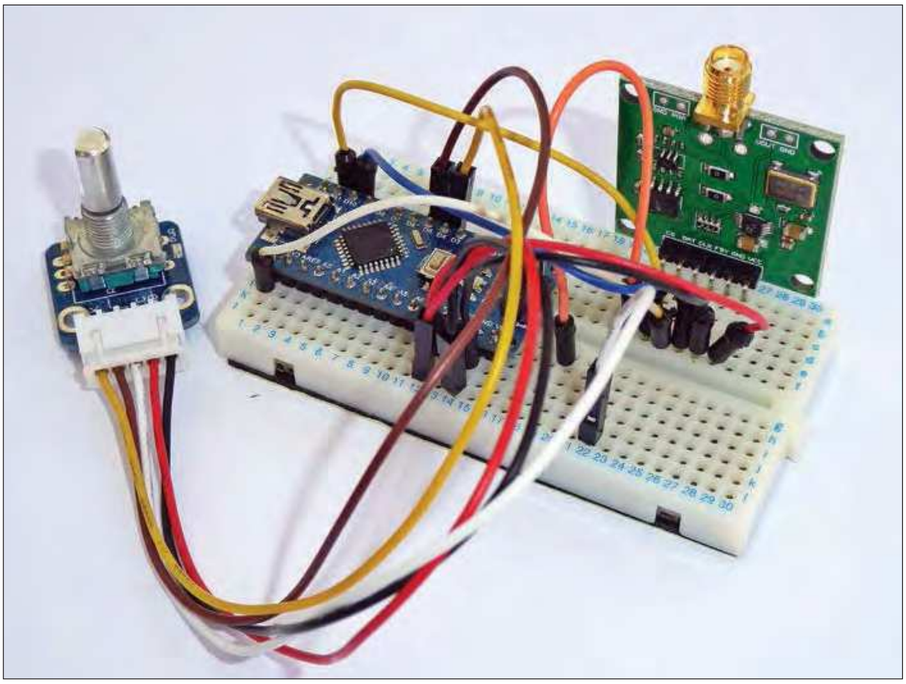


Fig.6.14. Breadboard testing of the AD9833 variable frequency oscillator (VFO).

Fig.6.15. A programmable signal source based on an AD9833 that can form the basis of low-cost test equipment (such as signal, function and sweep generators).

Arduino control

The AD9833 can be very easily controlled using software. As an example, Listing 6.2 is the code for a simple function generator application with sine, square and triangular outputs variable from 1Hz to 100kHz in three switched ranges. The code is designed for use with an Arduino Nano controller using the circuit arrangement shown in Fig.6.12. Note that you will first need to use the Arduino IDE's Library Manager to locate and download the required library file (see *Going Further*) before compiling the code. The total cost of this project is well under £20.

Listing 6.3 provides a further example of AD9833 code in the form of a variable frequency oscillator (VFO) for radio frequency (RF) applications. In this project we've used the enhanced DDS module shown earlier in Fig.6.10 and chosen a rotary encoder (SunFounder type TS0194D) for more precise frequency adjustment than can be obtained with a standard variable potentiometer. The output frequency of the VFO is adjustable over the range 1990kHz to 2000kHz in steps of 100Hz but the tuning limits and steps can be easily altered by modifying the code. The code is for an Arduino Nano controller used in the circuit and prototype configurations shown in Figs.6.13 and 6.14. Once again, it will be necessary to download the required library file before compiling the code (see *Going Further*). As with the previous example, the total cost of this project is under £20.

Micromite control

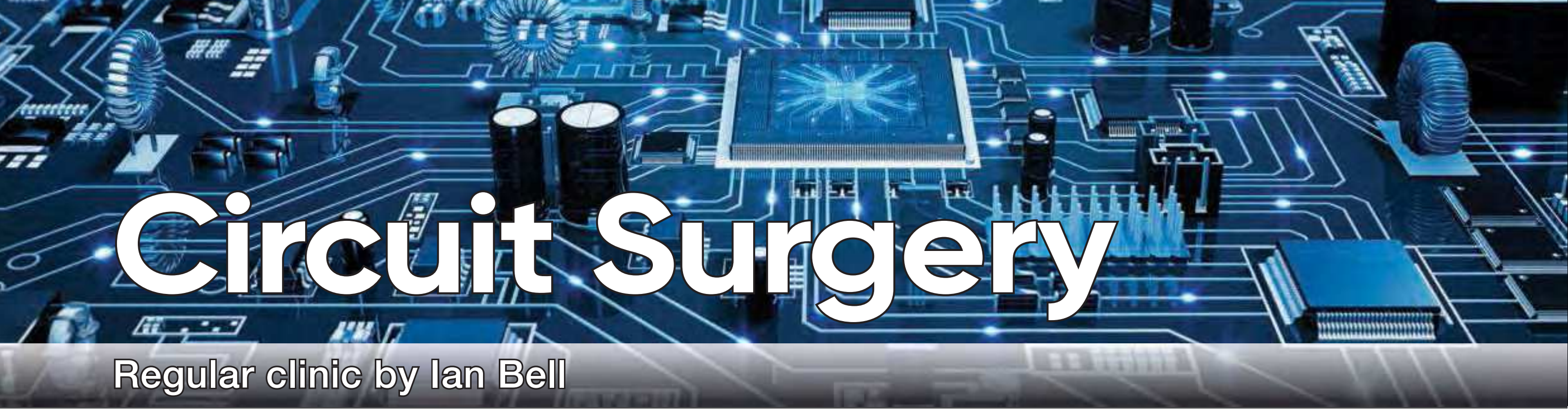
We have covered the combination of the AD9833 and the Micromite in several articles over the last few years – see *Going Further*.

Going further

The table opposite details a variety of sources that will help you find ideas, code and further information that will allow you to understand DDS and make good use of this technology in your own projects. It also provides links to relevant underpinning knowledge and manufacturers' data sheets and online tools.

Table 6.1: Going Further with DDS

Topic	Source	Notes
Under-standing DDS	The main Analog Devices DDS homepage is located at: **www.analog.com/dds** For an in-depth DDS technology tutorial, see: **https://bit.ly/pe-dec21-ad2**	The latest Analog Devices DDS chip selection guide can be found at: **https://bit.ly/pe-dec21-ad1** The excellent Analog Device DDS design tool can be found at: **https://bit.ly/pe-dec21-ad3**
Filter design	The Butterworth low-pass filter on-line design tool can be found at: **http://leleivre.com/rf_butterworth_LPF.html** For the Tina TI circuit analysis tool, go to: **www.ti.com/tool/TINA-TI**	
Python	The Python programming language is available freely for Windows, Linux, Raspberry Pi OS, and macOS – see: **www.python.org**	
Arduino Nano	The official Arduino website provides a variety of resources to support the Nano. Go to: **https://bit.ly/pe-dec21-ard1** The Arduino's integrated development environment (IDE) can be downloaded from: **https://bit.ly/pe-dec21-ard2** *Electronics Teach-In 8 Introducing the Arduino* (available from the *PE* shop) provides a one-stop source of ideas and practical information.	An Arduino Uno can be substituted for the Nano but the board will require a significantly larger enclosure. The code samples can be downloaded from the December 2021 page of the *PE* website. Note that before the code can be successfully compiled you will need to use the Arduino IDE's built-in Library Manager to locate and download the latest **MD-AD9833.h** library file
Micromite	*PE*/*EPE* has covered the Micromite-AD9833 combo in several articles and projects for you to learn and explore further.	For a good introduction to using the AD9833 with the Micromite, see the June 2018 issue. The April 2018 issue ran a *Touchscreen DDS Signal Generator* that generates sine, triangle and square. See the *Superhet IF Alignment using Direct Digital Synthesis* project in the September 2018 issue.
AD9833 DDS module	The AD9833 data sheet can be found at: **https://bit.ly/pe-dec21-ad4**	Inexpensive AD9833 DDS modules can be obtained from on-line suppliers including Amazon and eBay. These can easily form the basis of home-constructed low-cost test equipment (see Fig.6.15).



Op Amp Logarithmic and Exponential Amplifiers – Part 1

This month we will start to look at op amp-based logarithmic and exponential (also called antilog) amplifiers. This was originally inspired by the use of exponential amplifiers in the *MIDI Ultimate Synthesiser* project, which concluded in July 2019 – so it has taken a while to get around to it! Much more recently, in the September 2021 issue of *PE*, we looked at multistage log amplifiers in RF power measurement. These circuits use a cascade of limiting amplifiers with summed outputs to approximate a logarithmic relationship between input and output. That article was inspired by the *Low-cost Wideband Digital RF Power Mete*r by Jim Rowe in the August issue. In both cases the original articles are project-based and are not able to go into a lot of background detail on circuit operation.

As noted in the September *Circuit Surgery* article, using cascaded limiting amplifiers is not the only way to implement a circuit with a logarithmic response (one where the output voltage is related to the logarithm of the input voltage). Logarithmic and exponential amplifiers can also be built using the fact that the base-emitter voltage of a bipolar transistor (or just a diode's forward voltage) is proportional to the logarithm of the current through it. Or conversely, the current through a transistor or diode has an exponential relationship to the applied base-emitter voltage, also called the 'forward' voltage.

Logarithms

Mathematically, the logarithm (or 'log' for short) and exponential are inverse functions – that is, if you take the logarithm of a value then take the exponential of that result you get the original value back, and vice versa.

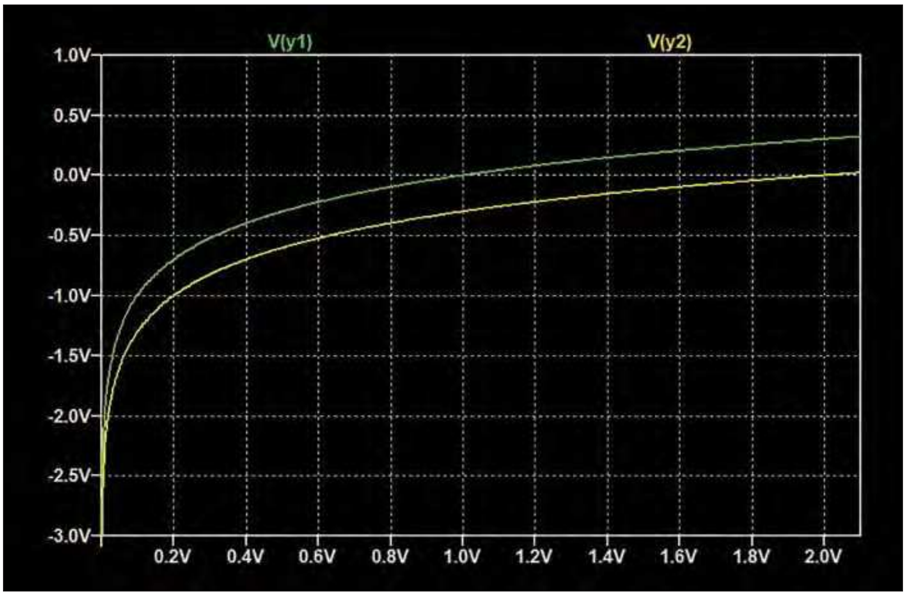


Fig.1. Ideal logarithmic ($\log_{10}$) circuit input-output relationship for unscaled (y_1, green) and scaled by 0.5 (y_2, yellow) input amplitudes.

Logarithmic amplifiers have a range of uses, including measurement of signal levels in decibels, RMS (root mean square) measurements, compression of signal dynamic range (eg, at analogue-to-digital converter (ADC) inputs), and multiplying signals and other mathematical operations.

Adding the log of two numbers and taking the antilog is equivalent to multiplication:

$$a \times b = \text{antilog}(\log(a) + \log(b))$$

Thus, you can make a multiplier using log and antilog circuits (and similarly divide

Fig.2. Ideal logarithmic ($\log_{10}$) circuit input-output relationship for unscaled (y_1, green) and scaled by 2 (y_3, red) output amplitudes.

Simulation files

Most, but not every month, LTSpice is used to support descriptions and analysis in *Circuit Surgery*.
The examples and files are available for download from the *PE* website.

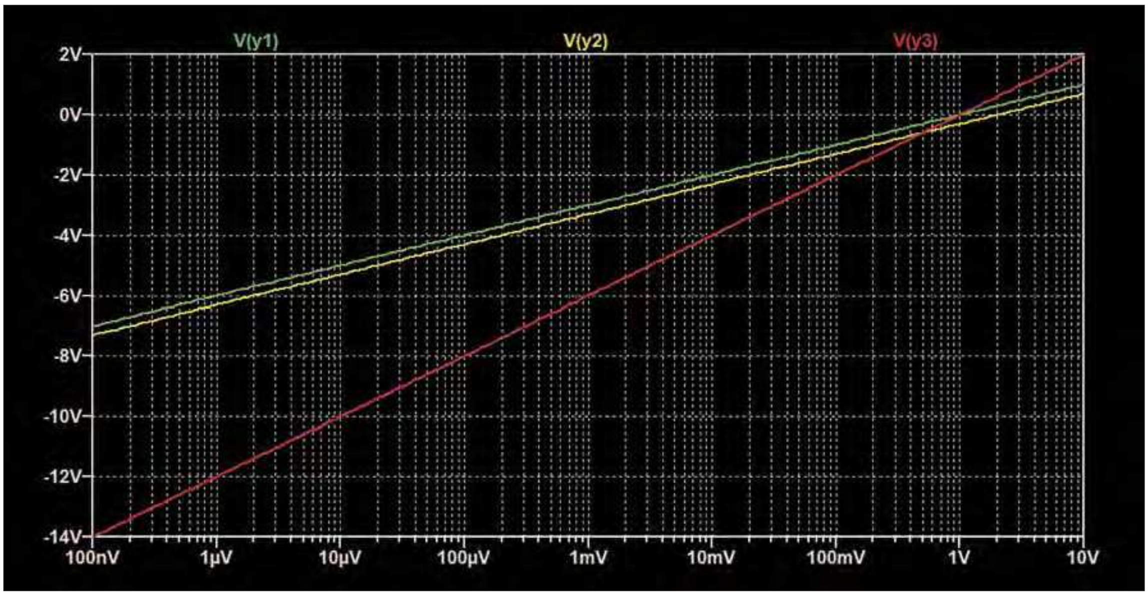


Fig.3. The three logarithmic amplifier responses from Fig.1 and Fig.2 (y_1, y_2, y_3) shown on a logarithmic input axis.

and raise to the power, such as squaring). Multiplication is required in a number of contexts, such as power measurement (multiply current and voltage) and signal processing operations based on multiplying signals together. However, op amp-based logarithmic amplifiers are not necessarily the best way of achieving signal multiplication, as we discussed in the November 2021 *Circuit Surgery* article.

Logarithmic response basics

Before looking at circuit details it is worth getting a feel for what the input-output relationship of a logarithmic amplifier looks like. Fig.1 shows two responses of ideal logarithmic amplifiers to input voltage x, where:

$$y_1 = \log_{10}(x)$$

$$y_2 = \log_{10}(x/2)$$

The shape of both curves illustrates the general behaviour of a logarithmic response. As input amplitude increases, further increases in amplitude result in a diminishing increase in output amplitude – this is the compressing effect of a log response. Small input amplitudes produce large *negative* output amplitudes, tending towards minus infinity for zero input for an ideal logarithmic function. Of course, real logarithmic amplifiers will have a limited output range and may deviate from an accurate logarithmic response for both small and large input amplitudes.

The two responses in Fig.1 show that the effect of scaling the input voltage is to produce an offset (fixed DC difference) in the output voltage. Specifically, for $y = \log(ax)$, where a is a constant scaling factor, the curve shifts up by $\log(a)$ (positive output offset in circuit terms) and for $y = \log(x/a)$ the curve shifts down by $\log(a)$ (negative offset). The example in Fig.1 is for $y_2 = \log_{10}(x/2)$ so the y_2 curve is shifted down by $\log_{10}(2) = 0.3$ with respect to y_1.

For $y = \log(x/a)$ the curves cross the axis ($y = 0$) at $x = a$. For the examples, $y_1 = 0$ for $x = 1$; and $y_2 = 0$ at $x = 2$, as can be seen on Fig.1.

Fig.2 shows the effect of scaling the output of a logarithmic amplifier – it shows two responses of ideal logarithmic amplifiers to input x, where:

$$y_1 = \log_{10}(x)$$

$$y_3 = 2\log_{10}(x)$$

The effect of this scaling is to change the slope of the curve by the scaling factor, but with the curve crossing $y = 0$ at the same point. This can be seen in Fig.2 – the y_3 curve is steeper than the y_1 curve at all points, but both cross $y = 0$ at $x = 1$. The change of slope in the input-output relationship is the same effect as changing the gain of a linear amplifier.

In general, we can write the input (V_{in}) to output (V_{out}) of a logarithmic voltage amplifier as:

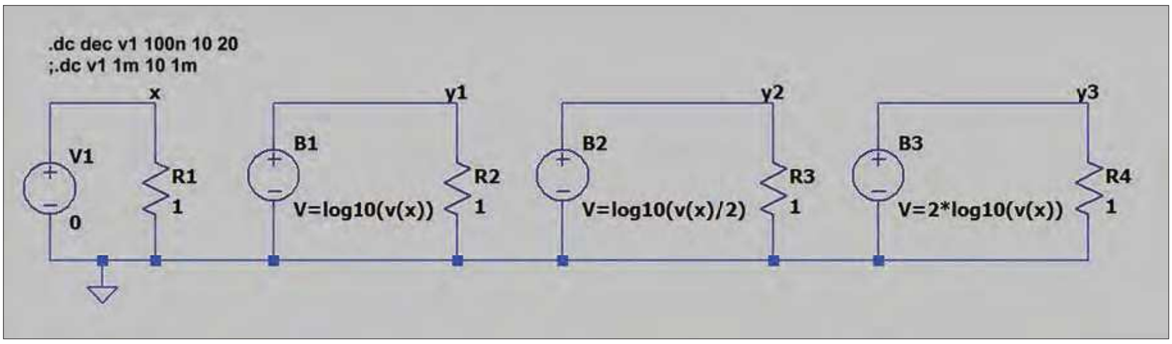
$$V_{out} = V_b \log_{10}\left(\frac{V_{in}}{V_a}\right)$$

Here, V_a and V_b are constants determined by the circuit configuration. Both these scaling values are voltages (for a logarithmic voltage amplifier). This is to obtain the correct dimensions (physical quantities) in the equation. A logarithm is taken of a pure number, which we get by dividing the input voltage V_{in} by voltage V_a.

V_a is called the *intercept* voltage, because, as discussed above, it determines the point where the input-output curve crosses the axis. The result of the logarithm is a pure number which we multiply by a voltage to get an output voltage. V_b is called the *slope* voltage because it changes the slope of the input-output relationship.

Fig.3 shows the three different amplifier responses from Fig.1 and Fig.2 on the same *logarithmic* axis for the input (the x-axis). This shows the effect of intercept and slope scaling discussed above and provides more information than Fig.1 and Fig.2 on the response at lower voltages (the plot is from 100nV to 10V). For a real circuit, V_a and V_b need be set so that the

Fig.4. LTspice schematic for plotting Fig.1 to Fig.3.



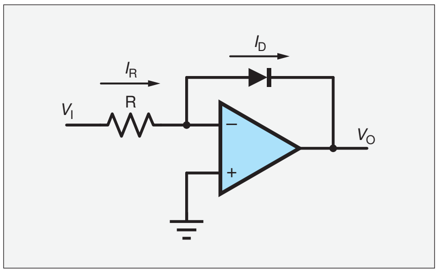


Fig.5. Logarithmic amplifier based on a diode and op amp.

required output range is obtained for the input range of interest.

The graphs in Figs.1 to 3 represent mathematical (idealised circuit) functions rather than real circuit responses. They were obtained using LTspice behavioural voltage sources and DC sweep simulations – see Fig.4.

Exponential diode response

As mentioned above, logarithmic and exponential amplifiers can be based on the exponential current-voltage relationship of the diode. A simplified version of the diode equation (for forward bias) is:

$$I_D = I_S \exp\left(\frac{V_D}{V_T}\right)$$

Here, V_D is the voltage across the diode and I_D is the current through it. I_S is the diode saturation current – a parameter specific to the particular diode or transistor. V_T is the thermal voltage, which commonly occurs in semiconductor equations. V_T depends on physical constants (the charge on an electron and Boltzmann's constant) and temperature. It has a value of about 25 to 26mV at room temperature (specifically 25.85mV at 27°C = 300K (kelvin)). The diode equation is commonly written in the exponential form shown above, but we can rearrange it to show the voltage as a function of the current, which is a logarithmic function (we have to use the inverse function of the exponential to make V_D the subject) – specifically:

$$V_D = V_T \ln\left(\frac{I_D}{I_S}\right)$$

This is similar in form to the general logarithmic amplifier equation above, except that the 'input' and 'intercept' parameters are currents. Also, we have the natural logarithm (ln) rather than the base ten logarithm ($\log_{10}$).

All logarithms are based on a particular number base. For base 10 (the number base we use for counting in everyday life), if $y = \log_{10}(x)$ then we can find x from y using $x = 10^y$, that is 10 to the power y. Natural logarithms use base e, where $e = 2.71828$ (approximately). The function $\exp(a)$ means e^a, so if $y = \ln(x)$ then $x = e^y = \exp(y)$. e is also known as Euler's number after the mathematician Leonhard Euler (1707 – 1783). It is an important mathematical constant and the ln() and exp() functions have many interesting properties. The concepts of ideal logarithmic amplifiers discussed above are the same for different log bases. To get a base-10 log from a natural log we can use:

$$\log_{10}(x) = \ln(x)/\ln(10) \approx \ln(x)/2.303$$

It terms of the generic circuit discussion above, a change of base is related to the slope voltage (we are scaling the result from the logarithm function). This makes it straightforward to obtain an output related to $\log_{10}$ despite the diode function being a natural logarithm.

Op amp circuit

A diode on its own has a logarithmic relationship between a current and applied voltage. Using an op amp allows us to make a circuit with a logarithmic relationship between two voltages – a logarithmic amplifier. Such a circuit is shown in Fig.5. The op amp has negative feedback applied via the diode. The op amp's non-inverting input is grounded (at 0V) which means that the feedback will adjust the output voltage to try to maintain 0V at the other input (inverting input). The non-inverting input behaves as if it is at 0V – that is, as if it is grounded or earthed. This is known as a 'virtual earth'.

With the diode in Fig.5 forward biased, the anode is connected to the virtual earth and the cathode is connected to the op amp output. The op amp output

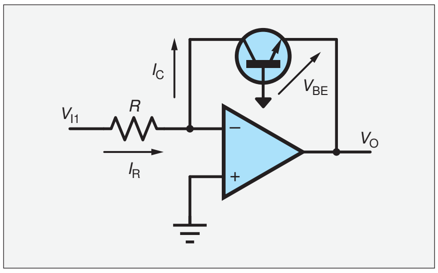


Fig.6. Logarithmic amplifier based on an NPN bipolar transistor and op amp.

voltage (V_O) must be negative and equal to the diode voltage for a current of I_D:

$$V_O = -V_T \ln\left(\frac{I_D}{I_S}\right)$$

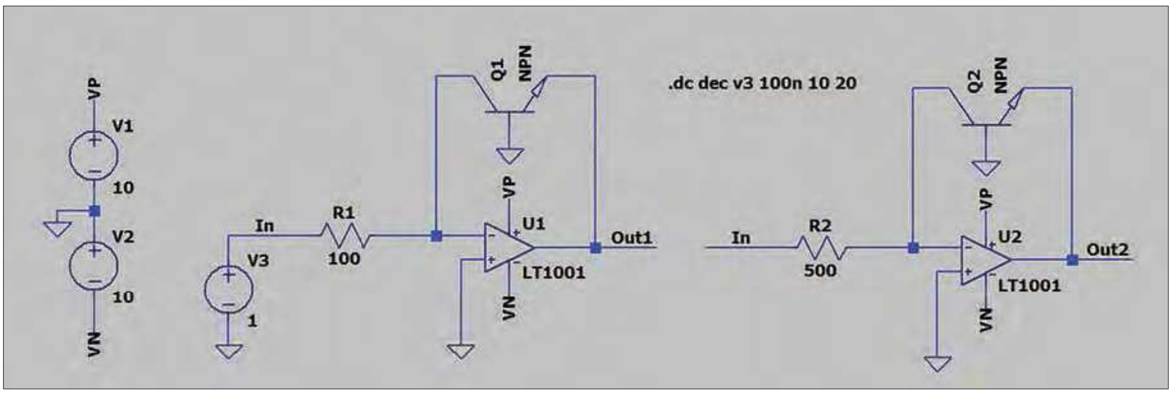
Assuming an ideal op amp, no current will flow into the op amps inputs (assume it has infinite input impedance and requires zero external bias current). This means that all the current in the diode must flow through the resistor, so $I_D = I_R$. The resistor is connected between the input and virtual earth, so the voltage across it is equal to the input voltage (V_I) and from Ohm's law the current is $I_D = I_R = V_I/R$. Substituting I_D with V_I/R in the equation for V_O we get:

$$V_O = -V_T \ln\left(\frac{V_I}{I_S R}\right)$$

This equation is of the same form as the generic logarithmic voltage amplifier discussed above, with $V_a = I_S R$ and $V_b = -V_T$. The choice of resistor will have some effect on V_a, but V_b is fixed by V_T. We should also note that with V_T being the thermal voltage, the circuit's output is very much dependent on temperature. Furthermore, the diode saturation voltage also varies significantly with temperature, so both the slope and intercept voltages are temperature dependent, which will certainly be a problem in some applications.

The circuit can be improved by using a bipolar transistor instead of a diode, as shown in Fig.6. This uses the transistor's base-emitter junction instead of the diode drop to set the output voltage. The transistor's base is connected directly to ground which forces the output voltage

Fig.7. LTspice schematic for investigating the circuit in Fig.6.



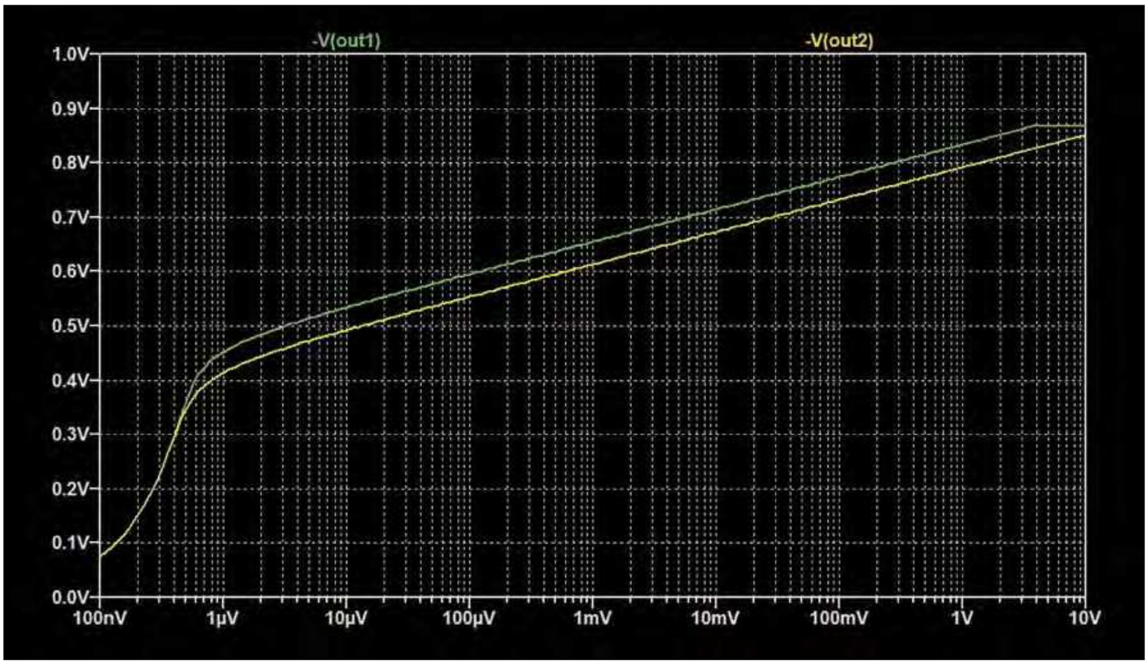


Fig.8. Results from simulating the LTspice circuit in Fig.7.

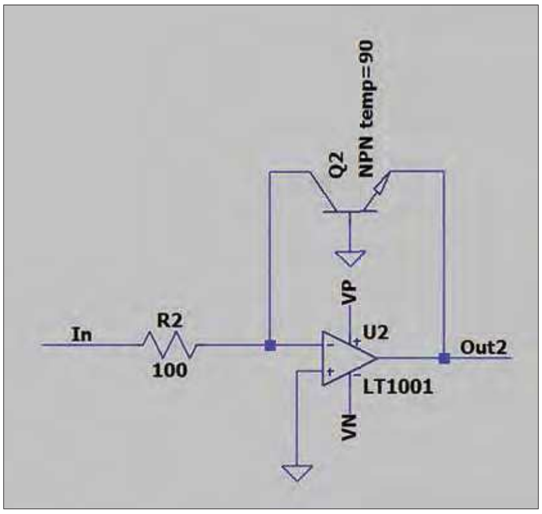


Fig.9. Modification of part of the schematic of Fig.7 to show the effect of transistor temperature.

to be exactly equal to the base-emitter voltage: $V_O = -V_{BE}$.

The relationship between the collector current (I_C) and base-emitter voltage (V_{BE}) of a bipolar transistor also follows the diode equation:

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_{ES}}\right)$$

Here, I_{ES} is the saturation current of the transistor's base-emitter junction. The collector current all flows through the resistor, as just discussed for the diode current. So, with $V_O = -V_{BE}$ and $I_C = I_R = V_I/R$ dropped into the above equation, we get:

$$V_O = -V_T \ln\left(\frac{V_I}{I_{ES}R}\right)$$

This equation is very similar to the diode version, but the transistor version is a better circuit because a transistor's base-emitter junction provides a more ideal diode behaviour than an individual diode. The transistor circuit also reduces the effects of offset voltages at the op amp's inputs, which (in real circuits) shift the diode voltage with respect to V_O, but do not affect V_{BE} in the transistor version by virtue of the directly grounded base. The transistor version has the same problem with temperature dependence as the diode version.

Fig.7 shows an LTspice schematic of the circuit in Fig.6. There are copies of the circuit with different resistors values to observe the effect of changing R in Fig.6. Two values of R are used: `R1 = 100` and `R2 = 500`; the circuits are otherwise identical. The op amp is an arbitrarily selected precision op amp, and the transistor is a generic (LTspice default) NPN. A DC sweep simulation is performed, changing the input voltage from source `V3` from 100nV to 10V logarithmically, with 20 data points per decade of voltage.

The results are shown in Fig.8, in which `–V(out)` is plotted so that the graph is more visually similar to Fig.3 than a direct plot of the negative output voltages. Noting that $I_{ES}R$ corresponds with V_a in the generic response plotted in Fig.3, we would expect changing the resistor (with everything else equal) to shift the response in a similar way to `V(y1)` and `V(y2)` in Fig.3, which is what we see. However, in comparison with Fig.3 we observe that the circuit does not provide an ideal logarithmic response over the entire input voltage range.

The `V(out1)` output levels off at high input voltages and both versions cease to provide a logarithmic response below about 1µV input. A limitation of range is to be expected from a real circuit. The value of `R1` was chosen to show the high voltage levelling off in this example, but in real designs the input resistor is likely to be much larger for handling this level of input voltage, which produces a 100mA current in the circuit in Fig.7. The circuit produces a logarithmic response over an approximately 1µV to 1V range – which is 120dB. The simulation uses a real op amp model, but overall is still somewhat idealised; for example, in a real circuit noise will have a significant effect for very small input voltages.

Temperature considerations

LTspice can be used to observe the effect of temperature. LTspice uses a default temperature of 27°C, but the temperature of the whole simulation or individual components can be changed. The circuit in Fig.7 was modified so that the transistor in the `V(out2)` circuit was at a different temperature. Fig.9 shows the modified `V(out2)` circuit in which the resistor is the same as in the `V(out1)` circuit, but the transistor temperature is set to 90°C. Fig.10 shows the simulation results in which we see a shift in offset and change of slope. This is because a change of temperature alters the value of both V_T and $I_{ES}R$, corresponding to both slope (V_b) and intercept (V_a) voltages in the generic logarithmic amplifier response.

If it possible to compensate for the effect of I_{ES} varying with temperature by using two logarithmic amplifiers with matched transistors – they must have the same characteristics (and hence I_{ES} value) and temperature for this to work. With discrete transistors, matching can be a challenge, but it is relatively

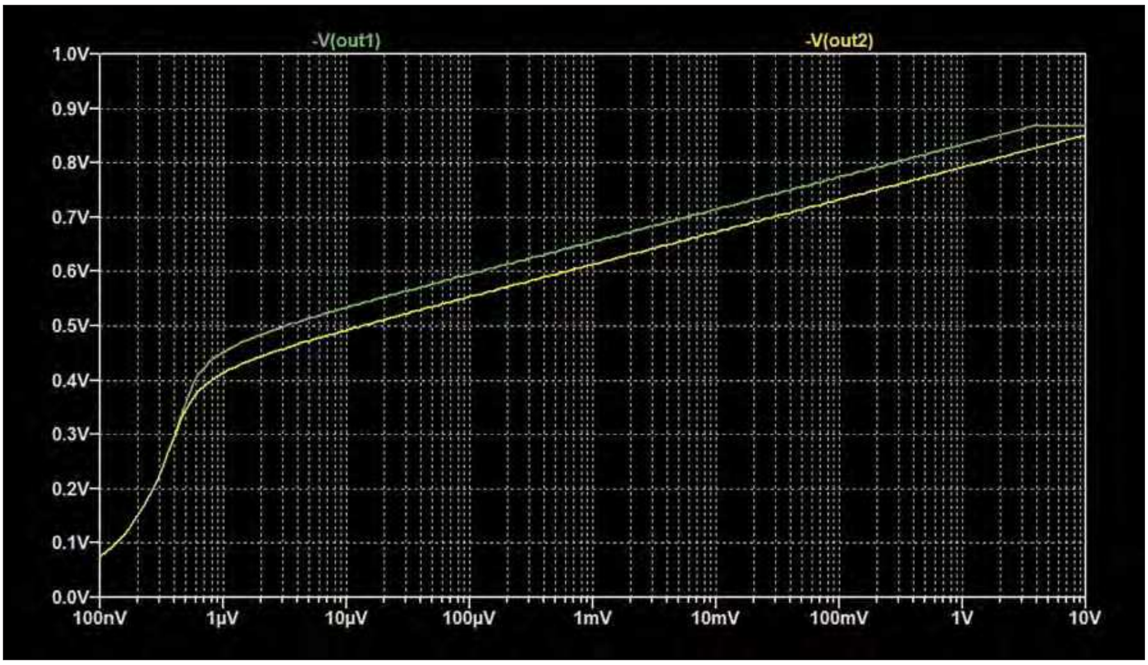


Fig.10. Results of the temperature-effect simulation.

straightforward for IC designers. If we take the difference between two copies of the circuit in Fig.6 we get:

$$V_{OUT} = V_{O1} - V_{O2} = -V_T \ln\left(\frac{V_{I1}}{I_{ES}R}\right) - -V_T \ln\left(\frac{V_{I2}}{I_{ES}R}\right)$$

Recalling that subtracting logarithms is equivalent to dividing the values inside the logarithm we get:

$$V_{OUT} = -V_T \ln\left(\frac{V_{I1}}{I_{ES}R} \Big/ \frac{V_{I2}}{I_{ES}R}\right) = -V_T \ln\left(\frac{V_{I1}}{V_{I2}}\right)$$

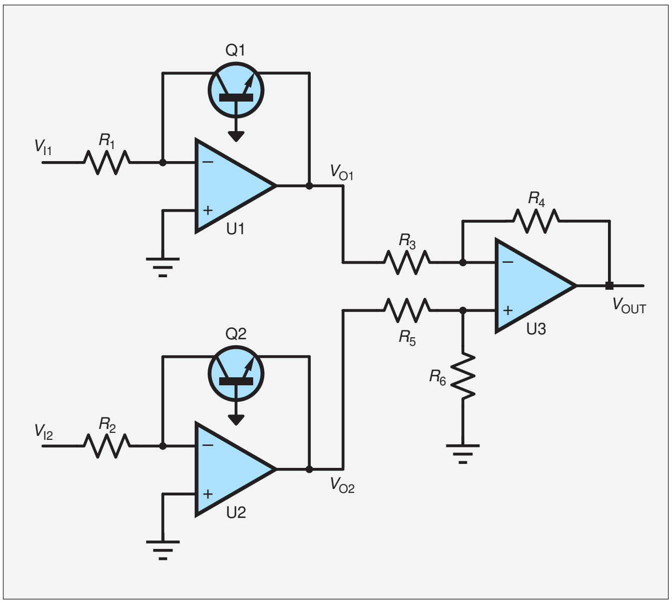


Fig.11. Logarithmic amplifier with compensation for the temperature dependence of transistor I_{ES}.

The I_{ES} values cancel if they are the same for the two transistors. This approach has the added advantage that V_{I2} can be used to control the intercept voltage. Alternatively, the second input can be from a reference signal source (eg, from a sensor, as is done in some light intensity measurements using photodiodes). An implementation of this idea is shown in Fig.11. The difference between the two logarithmic amplifiers is obtained using a standard op amp differential amplifier configuration, for which the gain is R_4/R_3, and $R_3 = R_5$ and $R_4 = R_6$. The pairs of resistors must have very closely matched values for good performance.

The dependence on V_T is not removed by this approach, but as this effect is simply proportional to absolute temperature it is relatively easy to add another amplifier stage with an equal and opposite temperature coefficient using a suitable temperature-dependent resistor in the gain setting.

The MAX4206 Precision Transimpedance Logarithmic Amplifier IC from Maxim Integrated is an example of a chip based on the differencing circuit. It does not have the input resistors built in, so it has current inputs (hence 'transimpedance' in the name).

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AUDIO OUT

By Jake Rothman

Analogue Vocoder – Part 2

Last month, in Part 1, we introduced our brand-new design for an *Analogue Vocoder*, which creates a unique and fascinating vocal effect – human speech is superimposed on a musical instrument.

Before we look in more detail at the design, first a quick conclusion to the discussion of the 'analysis' (multiple channel) filters discussed at the end of last month's article.

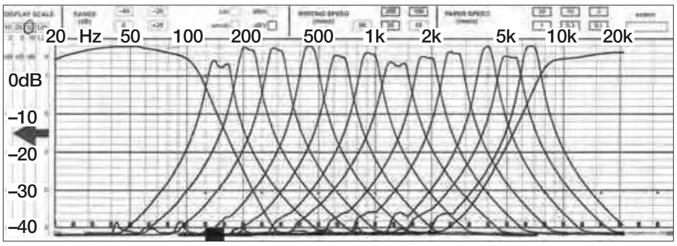


Fig.13. Plot of the analysis filters of the prototype. A little uneven due to the use of 5% capacitors. For musical applications this is of little consequence – we are not building precision test gear. Often the upper and lower band-pass filters are made with a wider bandwidth than the ones in the middle, where the speech information is most concentrated.

Pretty curves

A plot of the speech (or 'analysis') filters is shown in Fig.13. The output/synthesis filters should have exactly the same response, but are harder to measure (and hence produce plots for) because there are VCAs in-between both sections. The high-pass and low-pass curves have a much wider bandwidth with 24dB/oct slopes. This is because nearly all speech information is in the midrange from around 200Hz to 5kHz.

In general, filters should always use 1% tolerance resistors, which fortunately are now cheap. The problem components are the capacitors, which are often only available in 5% tolerance. Occasionally, 2% polystyrene and silvered-mica types are available. These are the best capacitors for filters, but they tend to be larger and much pricier compared to the cheaper and easy-to-find polyester types.

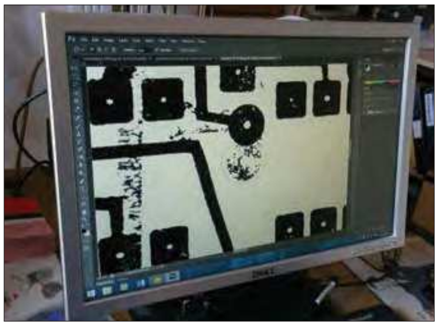


Fig.14. The rough photocopied board layouts in J M Hawkes' student project report were smoothed into a form suitable for etching using Photoshop.

Board stiff

Life is too short to make a 14-channel vocoder prototype on Veroboard! So, to make the prototype shown in Fig.5 (see last month's *Audio Out*) I started off with

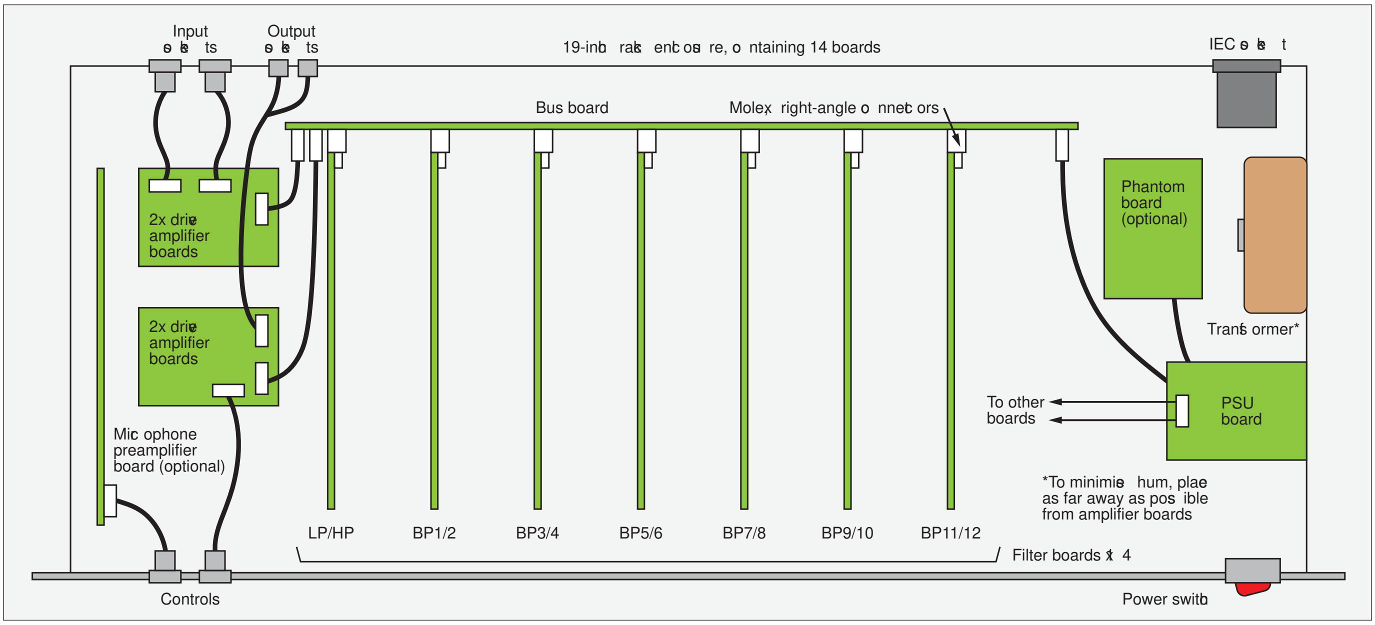


Fig.15. The *Analogue Vocoder* consists of many interconnected boards. The microphone preamplifier, driver, summer/output and power supply boards are all useful audio building blocks in themselves. Putting all the circuits together on one big board is not a good idea since it inhibits experimentation and reduces versatility. (Commercial production would of course dictate much greater integration to reduce labour intensive wiring, but we don't face that pressure.)

Fig.16. Since all the channel connections are wired in parallel (the 'bus') a long piece of stripboard was originally used to connect them all together on the prototype. However, in the design we will be building over the next few months, a proper PCB bus board will be used. It has plated-through holes for extra strength.

an edited version of JM Hawkes' PCBs. Unfortunately, all I had were scratchy photocopies of taped artwork. These were soon cleaned up in Photoshop (shown in Fig.14) and printed out for etching.

Once I had made my own tweaks and produced a working system I got my PCB guru, Mike Grindle, to design a professional set of PCBs. The vocoder comprises 14 boards, including an optional microphone preamplifier, two driver boards, 12 band-pass channels on six boards, an optional low-pass/high-pass channel board and two summing/output amplifiers. These are shown in Fig.15. The vocoder channels are all plugged into a bus board using right-angle connectors, as shown in Fig.16.

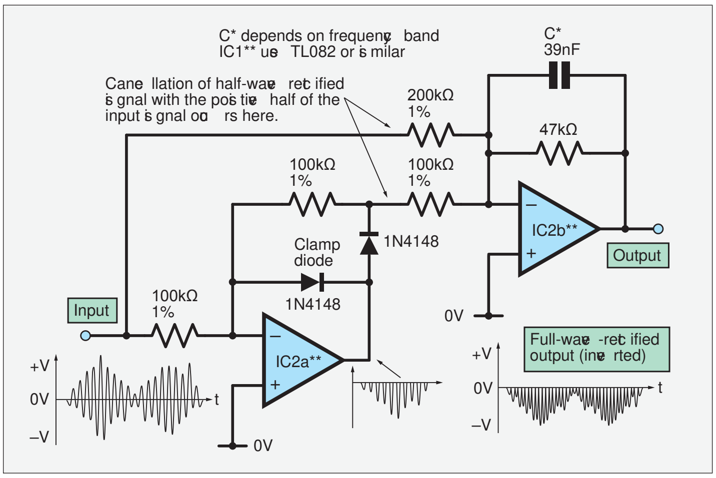


Fig.17. A precision full-wave rectifier circuit is used to generate DC from the output of each speech analysis filter. The circuit depends on accurate subtraction of a half-wave rectified signal from the rectifier input. Note that 1% resistors are needed.

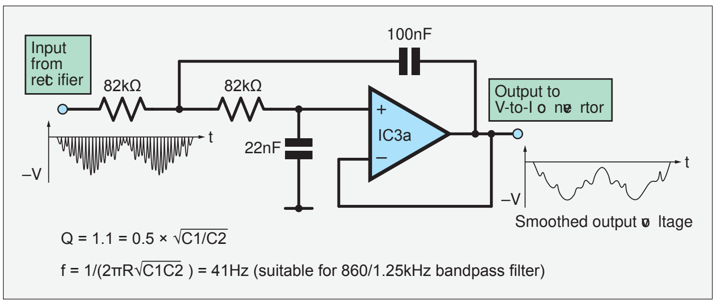


Fig.18. The output from the rectifier is smoothed by a low-pass filter. These filters need different values for each frequency band.

Control signals

The output of the filters are fed into precision full-wave rectifiers (Fig.17) which are smoothed by second-order low-pass filters (Fig.18) whose cut off frequency is proportional to each frequency band. If the smoothing frequency is too high, the effect is 'spittiness' and distortion. If too slow, the intelligibility of the speech is impaired. The idea is to get a general trend of the energy fluctuations in each particular frequency band. The cut-off frequency should be around 5 to 20-times less than the lower frequency of the band-pass filter, with a Q of about 1. The tolerances for these filters are uncritical and 10% tolerance capacitors are fine.

A linear voltage-to-current converter using an op amp and transistor (shown in Fig.19) is used to feed the control pin of the VCA's transconductance amplifiers. This ensures better tracking at low levels because the (PNP) transistor provides a much higher drive impedance than just a resistor.

Chips and VCAs

The transconductance VCAs are the biggest source of noise in the whole system. However, this is masked by the musical sounds generated. Interestingly, it does not detract from the overall effect, the slight roughness introduced makes it sound more 'vocal' and 'breathy', which is a positive effect for this system.

My prototype shown in Fig.16 used the classic CA3080 transconductance amplifier, which ceased production in 2005. Later vocoders and this design use the LM13600/700 which is effectively two 3080s with added Darlington buffers. Linearising diodes are also added for distortion

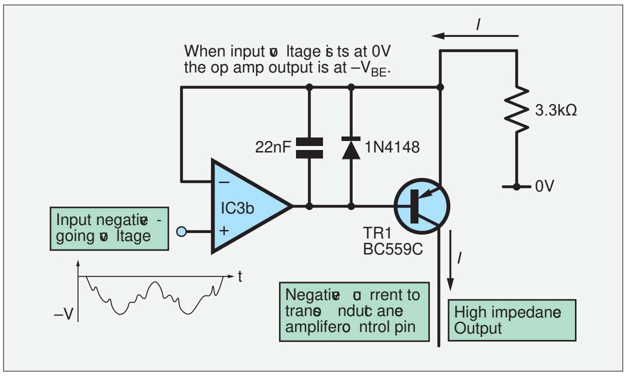


Fig.19. The voltage-to-current converter controls the transconductance op amp to form a VCA. The V_{BE} of the transistor is cancelled with negative feedback. This circuit is a design from Jacob Moskowitz's article, *Current-compensated op amp improves OTA linearity*, Jan 1977. I can't trace the original publication, but it is available on **ResearchGate.net**. I've made minor improvements consisting of a diode to protect the base-emitter junction from reverse bias and a capacitor to prevent HF instability has been added.

Fig.20. Suitable transconductance VCA chips for vocoders. Here we see, the classic CA3080, the LM13600/700, the oddballs NE571 and CA3060 – plus the most recently developed and best, the CA3280. Only the LM13700 and 'That Blackmer Corp' topology 2180 chips are still in production, although the DIL version of the LM13700 will soon be discontinued by Texas Instruments (TI). All are available from the AO shop – see page 59.

cancellation, allowing a higher drive level, and thereby giving lower noise. This is activated by installing R25 (see Fig.21). There is no difference in practice between the LM13600 and LM13700. Originally, the LM13600 provided a link between the control current and the Darlington input to obtain both a high impedance and a high maximum current output over the full range of control currents. The LM13700 is a later version where better processing gave higher current gain in the Darlingtons, allowing this link to be dispensed with. The LM13700 is currently the only transconductance amplifier IC in production, and I use the surface-mount version in my Dubreq Theremin. The CA3280 is the best choice, but is hard to find. It also has linearising diodes, but no buffer stages. Using dual devices, such as the LM13600 means that two vocoder filter channels have to be placed on one board.

There is also the NE571 telephone compander chip that includes a couple of full-wave rectifiers, in addition to two VCAs. The Paia 6710 eight-band vocoder kit uses these. Another odd ball is the CA3060, which has three 3080s on one chip. All these VCA chips are shown in the IC rogues' gallery of Fig.20.

Transconductance amplifiers are voltage in / current out devices. However, here we are using a gain-controlled transconductance amplifier with an additional linear current-driven gain control pin. There are even more complicated VCAs available, such as the 2180 from That Corp. These have logarithmic control characteristic, which complicates the circuits excessively. Also, their Hi-Fi specification is not necessary, possibly making the vocoder too clean sounding! I suspect the soft clipping produced by non-linearised transconductance

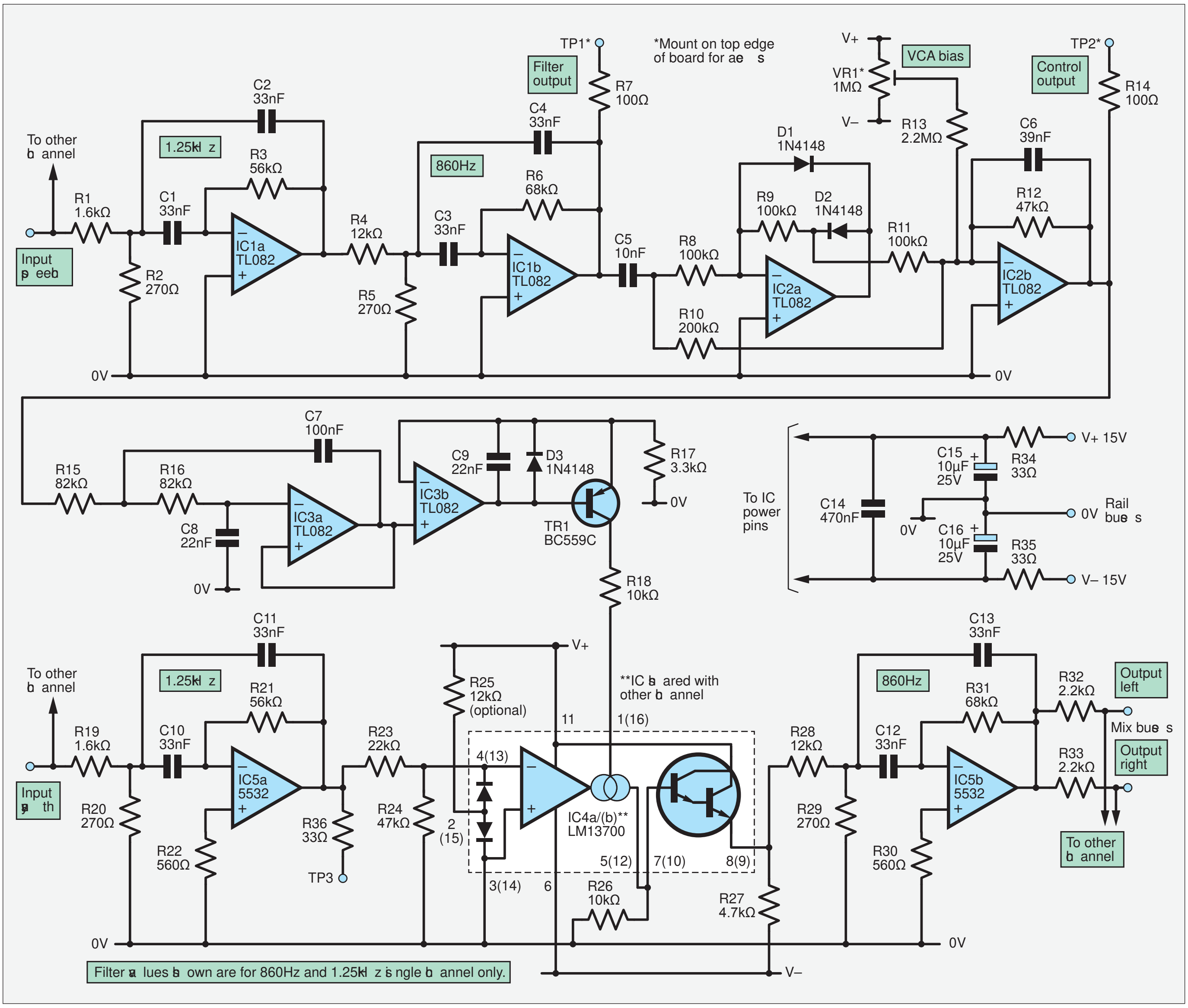


Fig.21. Assembling all the building blocks to form a complete vocoder channel. We will build two channels per PCB – see Fig.15.

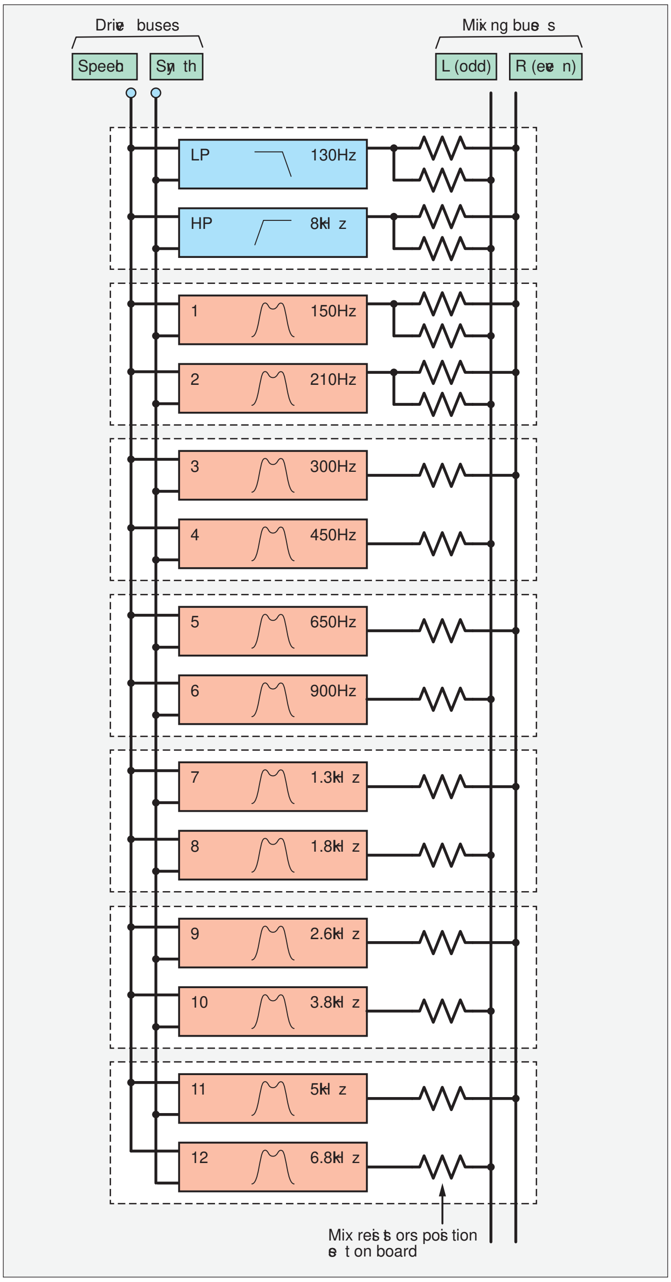


Fig.22. I use a special mixing trick in all my vocoders to give a stereo effect. The outputs of the channels are panned alternately to the left and right outputs apart from the lower bands, which are mono to ensure an even power distribution between left and right.

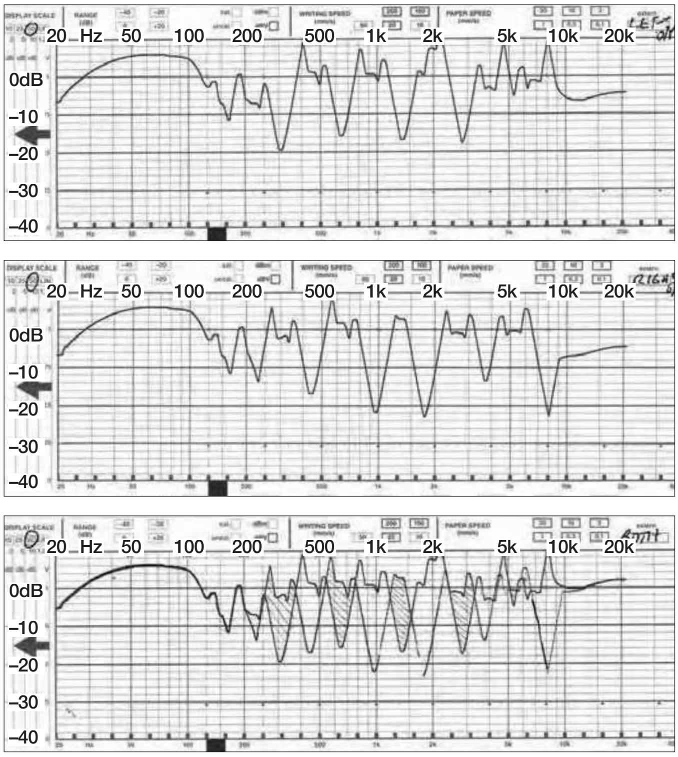


Fig.23. The total frequency response of the stereo output of the vocoder is produced using the left channel (top) and right channel (middle) – here plotted on top of each other (bottom). The shaded area in the bottom plot highlights the difference between left and right channels. This produces a unique musical effect.

amplifiers is actually musically beneficial. I suggest leaving R25 out in your first build.

All the circuit elements described in the vocoder channel block diagram shown in Fig.4 (see last month) are assembled in the complete circuit diagram for a single vocoder band-pass module in Fig.21.

Driving

The total input impedance of all 14 filters is of the order of 130Ω, which is too low for a single op amp to drive (one section of a 5532 can drive 600Ω). This means a small power amplifier or multiple op amps are required. This can be achieved by adding a current-boosting push-pull emitter follower stage to an op amp. This amplifier will also drive output transformers.

Summing up

The outputs of the channels can either all be mixed together into mono or alternatively a stereo mix can be created. In Tim Orr's vocoder designs, the phase of each alternate filter was inverted before being summed to mono to give a smoother response. This is because there is a phase cancellation where the final 12dB/oct filter slopes crossover. In the design we are building I don't do this, which gives a more spacious stereo at the expense of slightly duller sound in mono. The low-pass filter, the two lowest band-pass filters and the high-pass filter are fed into both output channels to maintain essential mono compatibility in the bass. The remaining bandpass filters are then fed alternately into the left and right channels. A block diagram is shown in Fig.22. Thus, the frequency responses of the left and right channels are opposite, where one goes down the other goes up, as shown in Fig.23. This gives a lovely stereo spread between the two speakers. This special mixing is accomplished in the driver PCBs.

Next month

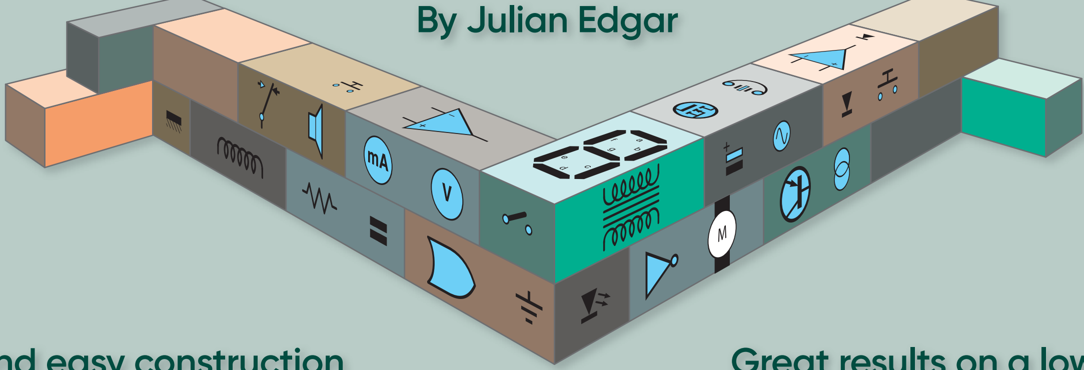
Now that we have described the system, we'll start constructing th driver amplifier PCB next month. This will be a useful module in its own right for feeding headphones, spring-lines, transformers and enabling amplifier bridging. The other boards will follow later.

Acknowledgements

An excellent reference on filter designs is *The Filter Handbook* by Stefan Niewiadomski (a previous contributor to *Practical Electronics*). Also, *The Active Filter Cookbook* by Don Lancaster. Vocoder principles were taught by senior lecturer Tim Orr at the London College of Furniture in 1985. Yes, I did study electronics at a furniture college! (now the London Metropolitan University). He wrote many articles in *Electronics Today International* magazine on electronics for music. These culminated in the *ETI* vocoder of September and October 1980, marketed as a kit for £175 + VAT by Powertran Electronics. He later expanded on the filter design in *Band-pass and beyond* (*ETI*, December 1980). This design was also based on a student HND project report from around 1982 by JM Hawkes. Where is he now, does anyone know?

Electronic Building Blocks

By Julian Edgar



Quick and easy construction

Great results on a low budget

Standalone programmable stepper motor controller

Here's a stepper motor controller that is truly standalone – it doesn't even need to be connected to a PC for programming! The controller board measures just 100 × 55mm. It costs about £20 – cheaper when on special – and is available from a range of sources including Banggood and AliExpress (search under 'DC8V-27V Programmable Stepper Motor Driver Controller Board Step/Angle/Direction/Speed/Time Adjustable 42/57 Phase').

The board has no less than five seven-segment LED displays, nine momentary push buttons and two individual LEDs. It is a bipolar driver, so has four connections to the stepper motor. However, it can also work with six-wire stepper motors, with the central connections of each winding unused (see Fig.1 for the stepper motor wiring connections). The board will work on a wide range of voltages (8 – 27V) and can supply up to 2A.

But it's the programming (all achieved via the push buttons) that's quite fascinating – see Fig.2. From left to right, the small buttons, and their associated LED displays, are:

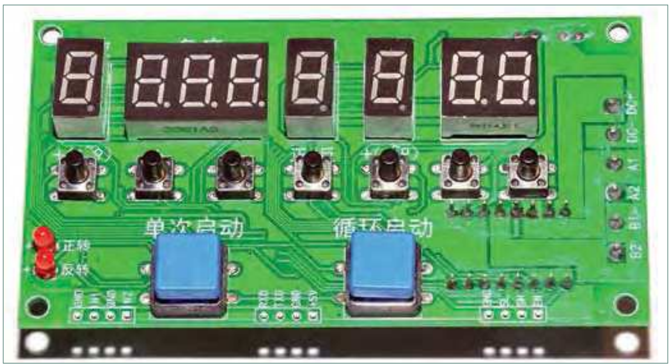
1. Memory sequence (up button)
2. Rotational angle (up/down buttons)
3. Forward/reverse (toggle button)
4. Speed (up button)
5. Delay timer (up/down buttons)

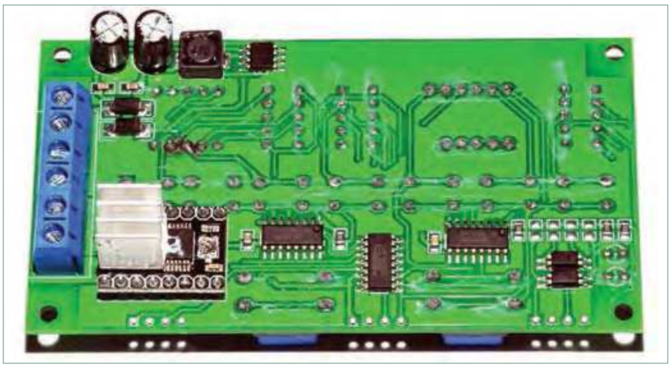
The two large lower buttons are (left) single trigger and (right) continuous loop.

This standalone programmable controller is a very easy way of getting a stepper motor up and running. Speed, direction and rotational angle can all be set, and the module has the ability to store nine programs that can be run automatically in sequence.

On-board programming

Let's look now at the programming. (We'll leave out the 'memory sequence' for now – just set it to 1 in initial testing.) The 'rotational angle' display and up/down buttons set the rotation that the stepper motor will undergo when the system is run in single-trigger mode. The instructions (mostly not in English) suggest that this display shows degrees (ie, 360° in a full circle) but testing at different speeds and with different stepper motors showed that this didn't always match reality. However, for a given rotational speed and stepper motor, the buttons can be used to set the rotational angle of the motor with





Left: The module works from 8-27V and can deliver 2A. Note that even when not turning, stepper motors use current (that is, in their 'hold' position). Thus, it's important when using a stepper motor for which no specifications are available (eg, a salvaged motor) to ensure that neither the stepper motor nor the board's output driver (located on the back of the board, with a small attached heatsink) get overly warm when the motor is being driven – even when it is not turning. **Right:** The rear of the board. Note the terminal strip for the power and stepper motor connections. The small heatsink at left is just stuck on – it can easily be swapped for a larger one.

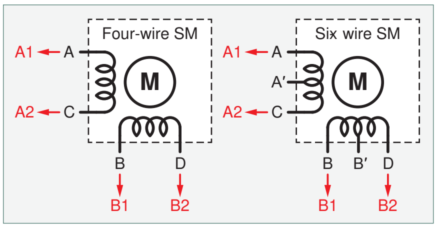


Fig.1. Use this diagram to work out how to connect 4- and 6-wire stepper motors to the module. Note that in 6-wire designs, two of the connections are unused. If you have a stepper for which no wiring details are available, use you multimeter to work out which wire is which – the maximum resistance across any two leads indicates the two ends of a winding. Swapping A1 with A2 or B1 with B2 just causes the motor to reverse – no damage will occur.

good repeatability. (That is, just adjust the display so that you get in testing the rotational angle you want to achieve, and that angle will occur each time.)

The next button toggles between forward and reverse. '0' on the display indicates forward and '1' indicates reverse. Two LEDs at the edge of the board light when the motor is turning – the upper one for forward and the lower one for reverse.

The next button – speed – allows the speed of the motor's rotation to be set at nine different levels. Oddly, the higher the number, the slower the motor's rotational speed. At its slowest speed, the motor turns very slowly – some motors with a distinct cogging action and others quite smoothly.

Finally, the far-right display shows seconds delay, with the up/down buttons allowing timed delays from 0-99 seconds.

So, let's imagine we have the stepper and power connected to the board. We have the rotational angle set to 45, forward/reverse to 1 (forward), speed to 6 and delay to zero. Now when we press the single trigger button at left, the stepper motor will moderately quickly turn through about 45°. Set the speed to 1 and it will turn very quickly.

OK, so what about the delay function? Let's now set that to 5 – ie, a five-seconds delay. Now a press of the single trigger button will cause the stepper to turn, but the timer deactivates the operation of this button until – in this case – five seconds has passed. Ah, but what if instead of pressing the single trigger button, you press the continuous loop button? Now, every five seconds, the stepper motor will rotate by about 45°.

Memory sequence control

You can see that we now have control over direction, speed, rotational angle and, in a continuous loop, the pause before it repeats. Now let's add LED display 1 to the mix – the memory sequence control. Pressing its associated button causes the digit to flash 1, 2, 3, up to 9. When the digit is flashing, whatever you set the other buttons to (ie, direction, speed, angle and timing) are memorised as a program. So if the first digit is flashing '1', the program created by the other buttons is stored as '1'. You can create up to nine programs, and then when the continuous loop button is pressed, the programs are served in sequence. So you can see that you can have up to nine sequences of movements, each having possibly different speeds, directions and rotational angles.

The programs are retained in memory with the power off, but when power is re-applied they need to be triggered by pressing the continuous loop button to start the sequence (ie, the sequence doesn't immediately start when power is turned on).

Position feedback? Nope…

When using this controller with a stepper motor, it's important to note that there's no position feedback. That is, if the motor stalls (eg, because something jams) then the controller won't be able to correct for this. Therefore, in practical terms, the motor and driving current need to be sized so that the load can be easily handled.

Uses

Well, what can we use this module and a stepper motor to achieve? First, it's an ideal board for beginners who want to easily drive a stepper motor. Since no code is needed, someone with very little knowledge can quickly get a stepper motor up and running – cleaning a model car windscreen with an oscillating wiper or even just spinning a personalised sign back and forth! I can also see the controller being used to rotate a display item on a shelf – turning a special piece of jewellery or a fossil by 5° every 90 seconds, for example.

But my pick is its use in a model railway layout or similar. The amusement rides in a model fairground – eg, the rides that swing back and forth like giant seesaws – could be easily driven by a tiny, toothed belt from a stepper motor located under the baseboard. The module allows easy programming of the angle of rotation, direction and speed of movement – perfect in this application. It would even be easy to use the sequence of programs so that the swinging of the ride gradually got bigger and bigger after it was started.

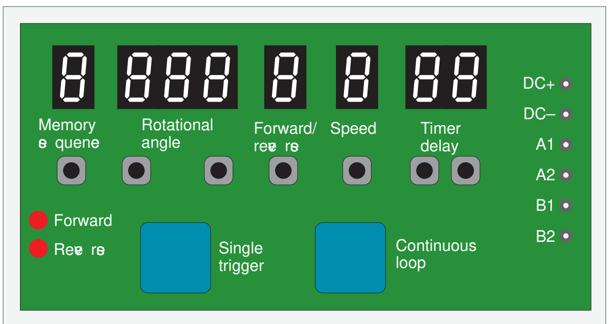


Fig.2. Function of the single/seven-segment LEDs and buttons.

While stepper motors are widely available new, they can also be easily obtained from a range of discarded consumer goods – from air-conditioners to printers. Salvaged steppers often come with reduction geartrains, as pictured here.

Stepper motors

A few other things to note. Stepper motors are salvageable from a wide range of discarded consumer goods – from air conditioners (they move the internal cooling vanes on oscillating models) to printers. So, if you're working to a tight budget, collect those discards! If you do this, you'll also find that many of the stepper motors have geartrains attached. These reduce the rotational output speed (ie, they gear-down the stepper motor speed) which will give both more torque (twisting force) at the output and allow you to use a faster programmed stepper motor speed, so smoothing its action. (Don't forget when programming the module that the angle of rotation of the output will also be a lot less with the geartrain in place.)

Cheap but very cheerful

Look, this module is not perfect. It would be very useful if the timed period were longer than 90 seconds (an additional mode going to 90 hours would be very handy). Also, because it doesn't have any specific tuning controls for different stepper motors, the controller won't work as smoothly with all steppers as a properly optimised control system would – and in fact, with one small stepper motor, I found it wouldn't work at all. However, if you can see yourself using a stepper motor in your next project, this is the easiest and quickest way of getting it up and running!

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Jim Gatenby

Python is the leading programming language, easy to learn and widely used by professional programmers. This book uses MicroPython, a version of Python adapted for the BBC Micro:bit.

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This book is written using plain English, avoids technical jargon wherever possible and covers many of the coding instructions and methods which are common to most programming languages. It should be helpful to beginners of any age, whether planning a career in computing or writing code as an enjoyable hobby.

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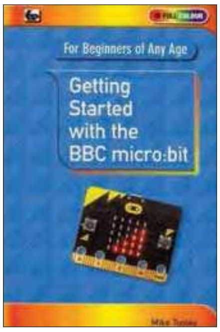

GETTING STARTED WITH THE BBC MICRO:BIT
Mike Tooley

Not just an educational resource for teaching youngsters coding, the BBC micro:bit is a tiny low cost, low-profile ARM-based single-board computer. The board measures 43mm × 52mm but despite its diminutive footprint it has all the features of a fully fledged microcontroller together with a simple LED matrix display, two buttons, an accelerometer and a magnetometer.

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Each chapter concludes with a simple practical project that puts into practice what the reader has learned. The featured projects include an electronic direction finder, frost alarm, reaction tester, battery checker, thermostatic controller and a passive infrared (PIR) security alarm.

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ARDUINO

ARDUINO FOR DUMMIES
John Nussey

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Always check price and availability in the latest issue or online. A large number of older boards are listed for ordering on our website.

In most cases we do not supply kits or components for our projects. For older projects it is important to check the availability of all components before purchasing PCBs.

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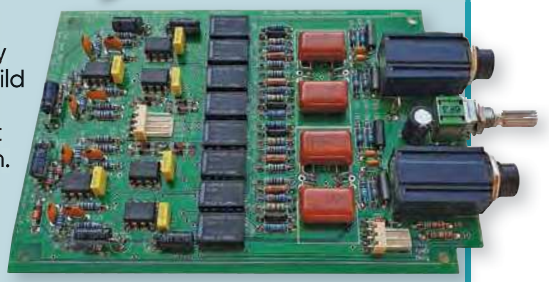
Next Month – in the January issue



Vintage Battery Radio Li-ion Power Supply

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MiniHEART

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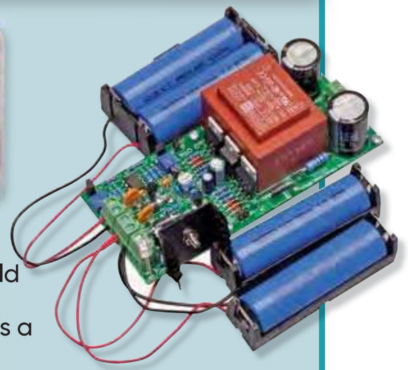

Balanced Input & Attenuator for the USB SuperCodec – Part 2

This add-on board for the USB SuperCodec provides two balanced inputs with four attenuation options. It will fit in with the SuperCodec in the same instrument case, resulting in a sleek all-in-one recording and measurement instrument. Next month, we'll get building it!

Busy Loo Door Warning

'I'm busy – go away!' OK, it's a bit tongue-in-cheek… but the Busy Loo Door Warning could have other, more serious, uses. It flashes a bright LED light on the door when you, ahem, don't want someone barging in. When you leave and open the door the light goes out! It's a simple idea with a nice simple circuit – it makes a superb beginner's project.

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