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Construtional Project

PIC MAGICK MUSICK

JOHN BECKER

Conjure music from thin air at the mere untouching gesture of a finger-tip.

Having enchanted and puzzled his intimate audience with close-up magic, the lone magician raised his hands and made a grand sweeping gesture of departure, punctuated by the downwards glissando of an ethereal harp, conjured as though from thin air.

Later in conversation with the author, the hotel's magical entertainer showed off the splendid capabilities of his Yamaha keyboard. A superb (and probably very expensive) piece of equipment, it seemed an ideal instrument through which to further spell-bind an audience.

Then, with a less dramatic gesture, he passed his hand over a small hole in the top of the keyboard – again the descending scales of a harp were heard. On being questioned, though, all the magician would say was “there’s a magic beam”!

INTRIGUED by the foregoing wizardry, the author continued to puzzle for several days about what had actually been meant by the magician’s cryptic reply. He did not have an assistant. Was the triggering done by a laser beam being intercepted? Infra-red? Ultrasonics? Quite naturally, thoughts turned to how a similar effect plus individual note playing could be achieved as a hobbyist electronics project.

This, then, was the inspiration for PIC Magick Musick, and the following discussion tells how it is achieved (without, we hope, triggering the wrath of the Magic Circle)!

HOW TO PERFORM MAGIC?

At first, optical techniques in the form of laser or infra-red diodes and detectors seemed attractive.

It soon became apparent, however, that whilst these could be used to readily trigger a preset series of consecutive notes, it would be extremely difficult to use them if individual notes were to be triggered according to the height at which the optical beam was intercepted.

Theoretically, it is possible to measure the time lag between a light beam being emitted and its reflected return from a passing hand. Regrettably, though, the speed of light is too Einsteinian-fast for its delayed reflection to be timed by the electronic components typically available to the average hobbyist.

The speed of light is generally taken to be 300,000 kilometres per second (186,000 miles per second). To time its transition across one metre, therefore, would require a detector and timing circuit that could respond in at least 1/300,000,000 of a second.

The response time would need to be even greater if distances varying by only a centimetre or two were to be differentiated. No, such cosmic speeds are beyond hobbyist monitoring!

Optically measuring distance can also be done by sensing the amount of light reflected when a beam of known intensity is emitted. This, though, would require the target to have a known and constant reflectivity. Hands, by their very human nature, have widely differing reflective qualities. The target’s angle to the source would also be critical so that none of the beam’s intensity became reflected away from the detector. This rules out a waving hand as the target.

What about interferometry, measuring the phase difference between emitted and reflected light beams? Huh! Who’s going to pack that amount of equipment into a box portable enough for gigging stage work? Not even the National Physical Laboratory, that’s for sure!

Ultrasonics, then – what about that? Ah, now we’re getting somewhere reasonable. Sound travels at a mere 332 metres per second, roughly. It’s far more easy to measure short distances using ultrasonic transmitters and receivers. It has been proved in EPE several times, using pulsing timing techniques in the author’s Ultrasonic Tape Measure (Nov ‘98), for instance, and phase differences in the rain sensing circuit of his EPE Met Office (Dec ’95/Jan ’96).

Magick Musick can drive almost any sound output, large or small.

www.epemag.com
ULTRASONIC ECHOS

In pulse timing techniques, allowance has to be made for the fact that the mutual proximity of transmitting and receiving transducers causes a “ringing” in the latter during transmission. Even so, with careful hardware or software design it is possible to “mask-out” the ringing and detect only the echo pulses. Distances as close as a few centimetres can be readily measured using this method.

This is the technique used in PIC Magick Musick. A 40kHz ultrasonic transmitter constantly emits six square wave pulses approximately every 140 milliseconds, about seven batches per second (7Hz). After each batch, and following the conclusion of a “masking” period, the return of an echo signal is timed using a synchronised counter. The count value is then related to a look-up table which allocates a particular note frequency to be generated.

For each new note value allocated, an envelope shaper is triggered, which causes the note to be emitted by a loudspeaker or headphones, or sent to a normal domestic amplifier. It starts at full required signal strength and progressively decays in amplitude until it finally ceases. If the next pulse detects a distance significantly different to the previous one, another note is similarly played.

The circuit is designed so that the detection range starts about 20 centimetres above the transmitter and extends for about a further half metre. There are 15 trigger “zones” within that range—allowing two octaves to be covered in eight steps per octave (just the “white” notes on a keyboard – there are no sharps or flats), from C to C′ (131Hz to 523Hz). Approximately two centimetres separate each note.

By inserting a hand or other object into the transmission beam at different heights, different notes can be triggered. Triggering occurs not only vertically above the transmitters, but also within a “cone of sensitivity”. This means that adjacent notes can be triggered even though the hand remains at the same height.

Triggering can occur as rapidly as the transmission pulses are generated, even though the envelope shaper has not allowed the previous note to die away fully. Only single notes can be played, however. It is not possible to create chords.

MODE VARIETY

Variety is added to the unit in various ways. The preceding description is for the principal mode, in which all 15 notes can be triggered. A secondary mode allows just four notes per octave (seven across two octaves) in musical order 1, 3, 5, 8 – e.g. C, E, G, C′ (the notes that would make up a major chord on a polyphonic instrument).

Two other modes can be switched in as alternatives. In the first of these, there are four repeating preset sequences of notes which are triggered by a single pass of the hand anywhere within the detector’s range. The first generates a descending 7-note scale. The next hand-pass causes the same 15 notes, but in ascending note order. Next, a descending 7-note scale (C′, G′, E, C′, G, E, C) is triggered. At the fourth triggering the same seven notes are repeated in ascending order. The cycle then repeats.

The other option plays notes determined by values held in the PIC’s data EEPROM (up to 64 notes). There is a pre-loaded sequence created by the author. Readers having PIC programming facilities, such as offered by EPE PIC Toolkits Mk2 and Mk3 (TK3), can create their own sequences as text files and program them into the data EEPROM using the Send Message facility (which leaves the main program itself untouched).

CIRCUIT DESCRIPTION

The circuit diagram for the PIC Magick Musick ultrasonic processing and control system is shown in Fig.1. The first point of interest is that two PIC microcontrollers are used, IC2 and IC3. They operate synchronously at 4MHz as set by crystal X1, which is in circuit with IC2.

Early attempts to use a single PIC to control the ultrasonic signal and generate musical notes simultaneously proved to be unsuccessful. It was decided, therefore, that with PICs being so inexpensive, two would be used. IC2 controls the ultrasonic transmission pulses and performs the timing of their reflected return. It repeatedly transfers the echo delay values to the second PIC, IC3. This generates the required notes in response to the timing values received from IC2.
Pins RA0 and RA1 of IC2 output brief push-pull 40kHz pulses to transmitter TX1. Echoes are received by receiver RX1 and amplified by the serial network comprising op.amps IC1a and IC1b.

The op.amps are biased to a half-rail voltage (2.5V) by the potential divider consisting of resistors R2 and R3. Amplified pulses are output from IC1b pin 1 and the half-wave rectified by diode D1. Capacitor C4 charges to a d.c. level set by the positive-going amplitude of the rectified signals, superimposed on the 2.5V bias.

A preset potentiometer VR1 has two functions: it sets the trigger level to which transistor TR1 responds, buffered by resistor R7, and provides a discharge path for transistor TR1. The voltage at the wiper of VR1 is set to about 0.5V, just below TR1’s turn-on level of about 0.6V.

In the absence of an echo pulse, TR1 stays in a turned-off condition, with its collector voltage falling to a saturation voltage (2.5V) by the potential divider consisting of resistors R15 and R16.

If the count is greater than a software-set value, the pulse is considered to have arrived too late. This prevents the unit from being triggered, for example, by echoes from the ceiling above it.

If the count is in range, it is allocated to one of 15 sub-ranges, as a value between 1 and 15. This is output as a 4-bit binary code from pins RB1-RB4 to the second op.amps, IC3, which receives these via its pins RA1-RA4.

**FREQUENCY GENERATION**

The software for IC3 causes Port B to constantly increment through 63 steps, roll over to zero and step up again. The rate at which it increments varies by 15 sub-routines, each of which has a different rate of increment. The binary code received from IC2 determines which sub-routine is in use, and so does the sub-routine’s rate at which it increments determines the audio tone that is ultimately heard.

The output from Port B is fed as a 6-bit digital-to-analogue converter (DAC) IC4, Texas Instruments type TLC7524, whose bits 6 and 7 are held permanently low. It is configured in the mode most suited to this application in which a binary input value causes an equivalent d.c. voltage (as opposed to current) to appear at its REF (reference) pin. In this mode the DAC has its two “normal” outputs (OUT1 and OUT2) connected to +5V and 0V, respectively (the device’s data sheet, which describes the modes of operation, is downloadable free from www.ti.com).

Because the input digital value is constantly counting upwards and then rolling over and so on, the output from DAC IC4 is a rising sawtooth (ramp) waveform. Its frequency is that of the musical note required, lying between 131Hz and 523Hz (musical notes C to G). The waveform is fed via capacitor C9 and resistor R13 to pin 4 of transconductance amplifier IC6 (see Fig.2).

The reason for using a counter in 6-bit mode is to speed the frequency at which it rolls over (see the later discussion on PIC frequency generation). It also intentionally limits the range of the DAC’s output voltage to about ±1V peak-to-peak.

**ENVELOPE SHAPING**

Transconductance amplifier IC6 is a dual device (of a similar type discussed in Circuit Surgery Dec ‘01) of which only one half is used. It is an extremely versatile device that can be used in many signal control applications. Its data sheet and application notes are well worth studying and using (obtainable via www.nsc.com).

In this application it is used as a voltage controlled amplifier (VCA) that is under pulsed control as an envelope shaper (a term much favoured in the “golden” music project days of the 1970s and early ‘80s). It is controlled by the logic level output from IC3 pin RA0.

On receipt of a value that is greater than zero and different to the previous value received, IC3 briefly sets its pin RA0 high and then returns it low until the next different note value is received from IC2.

The output from RA0 is fed via diode D4 (Fig.2) to capacitor C10. The capacitor charges rapidly, and then its voltage ebbs away via resistor R15 (and R19 – more in a moment) once the pulse from RA0 has ended.

The voltage across C10 is also a ramp, rapidly charging to a peak close to ±3V (+3V – 07V voltage drop across D4), and then decaying exponentially in typical capacitor discharge fashion to close to zero volts.

VCA IC6 allows a signal to pass from its input at pin 4 to its intermediate output at

---

Fig.2. Envelope shaper and audio output stages.

Fig.3. The lower trace shows the ultrasonic transmission pulse. The upper trace shows the "ringing" pulse received during transmission, followed by the required echo pulse, and then by a later, unrequired, minor echo.

Fig.4. Sawtooth waveform created via DAC IC4.

Fig.5. The envelope shaping pulses at capacitor C10.
Everyday Practical Electronics, January 2002

pin 5 at an attenuation level set by the current flowing into its control pin 1, and in relation to the value of resistor R17.

The control current is derived from the voltage across capacitor C10 flowing into resistor R19. When C10 is as fully charged as it can be (at the start of the pulse from RA0) the audio signal at pin 4 appears at output pin 8 at the full level required by this application (about 1V peak-to-peak, centred around the midway bias voltage of +2·5V).

When the pulse ceases and the charge on C10 decays, so does the current flowing into IC6 pin 1. As the current falls, so IC6 progressively attenuates the signal appearing at pin 5 via pin 7. The output is a.c. coupled via capacitor C11 to potentiometer VR2 (which may be a preset or a panel-mounted control, as preferred). This controls the maximum signal strength that can be fed to the mini-power amplifier IC7.

AMPLIFIER STAGE

Amplifier IC7 is capable of outputting about 1W of power and is suitable for coupling into loudspeakers or headphones having impedances as low as 8Ω. The output is a.c. coupled via capacitor C15 and may also be fed into the line-input of a normal domestic amplifier system.

The op.amp has a gain of about x5 and the maximum output level is around 3V peak-to-peak. The inclusion of resistor R25 and capacitor C14 give stability to the op.amp. It is a dual device of which only one half is used.

SWITCHING

Returning to Fig.1, PIC Magick Musick’s modes are selected via switches S1 and S2, as follows:

S1  S2  Effect
Off  Off  15-note hand-triggering
On  On  7-note hand-triggering
On  Off  Automatic scale sequences – cycle of four
On  On  Automatic triggering of user’s own theme

POWER SUPPLY

The circuit is basically run at 5V as regulated by IC5, except for the power amp, which is powered at the full voltage of the power supply. The latter may be any d.c. source between about 7V and 15V. A 9V battery may be used (e.g. PP3). Capacitor C15’s voltage rating should be increased to 25V for voltages above 12V.

Maximum current consumption will depend on the amplitude output from the power amp. In the prototype the current was about 1·45mA with no audio output, rising to about 80mA when driving an 8Ω speaker at full amplitude with IC7 powered at 9V.

CONSTRUCTION

The printed circuit board (p.c.b.) component layout and tracking details are shown in Fig.7. This board is available from the EPE PCB service, code 332. Assemble in any convenient order you prefer, use sockets for the d.i.l. (dual-in-line) i.c.s, and observe the correct orientation for the polarity sensitive components.

Treat all i.c.s as static sensitive and discharge static electricity from your body before handling them (touch a water pipe or the bare metal of a grounded item of

Fig.6. The attack and decay of a note as controlled by the envelope shaper.

Fig.7. Component layout and full-size copper foil master track pattern.
workshop equipment). Do not insert them until the correctness of your 5V power supply has been established. Once this has been done and assembly completed, you are ready for a bit of magic of your own.

The transducers TX1 and RX1 were mounted on 24s.w.g. enamelled wire ‘stalks’ so that they were close to the holes drilled in the lid of the case.

SOFTWARE

Both PICs (IC2 and IC3) are identically programmed. It does not matter which of your two PICs is put into which IC2/IC3 socket. The correct transmission or music generation routines are automatically selected depending on the logic level connection made to pin RA0. With IC2, the connection is to the +5V rail via resistor R10. For IC3 it is to the 0V line via resistor R12.

If programming your own PICs using Toolkits Mk2 or TK3, also send file MagicM04.MSG to the EEPROM via the Send Message option. (It only needs to go to PIC IC2.)

SOFTWARE SOURCES

The software for PIC Magic Music is available on 3·5 inch PC-compatible disk from the EPE Editorial office, for which a nominal handling charge is made. It is available for free download from the EPE ftp site. More details are given on the EPE PCB Service page.

The easiest way into the ftp site, however, is via our UK web site at www.epemag.wimborne.co.uk. From the entry screen click on FTP Site (Downloads) at the top, drill down through folders PUB and PICS and open folder MagicMusic.

There are three main software files, the source code (ASM written in TASM), and code for sending to the PIC in two formats: OBJ (TASM) and HEX (MPASM). PIC code for sending to the PIC in two formats: OBJ (TASM) and HEX (MPASM). PIC programmers can program the PICs while in circuit via pin-headers TB1 (IC2) and TB2 (IC3). Components R9, R11, D2 and D3 prevent programming voltages from dis-connecting the 5V supply line.

TESTING

For initial testing, place the assembled p.c.b. on a flat surface facing the ceiling and switch on the power. Adjust preset VR1 so that a voltage of about 0·5V appears at its wiper (and at the base of transistor TR1). Set VR2 to maximum volume position (fully clockwise). Plug in a loudspeaker or headphones.

With the switches set to normal “hand-control” mode (both Off), slowly move your hand in from the side to about half a metre above the ultrasonic transducers. Let there be music – and hopefully there will be as a note is triggered by a returning echo!

Moving your hand up and down above the transducers, different notes should be played. You should find that there are minimum and maximum hand distances beyond which the notes will not be triggered (see earlier). Experimenting, you should also find that there is a “cone of sensitivity” around the transducers that causes notes to be triggered when it is entered.

Fig.8. Finger-triggered note sequence.

If you don’t achieve immediate success, slightly readjust preset VR1. If the presence of the ceiling is causing triggering (as would be indicated by lifting the board up and down near the bench), reduce VR1’s wiper voltage fractionally. If the triggering range is too small, or non-existent, increase VR1’s wiper voltage a bit – but regard 0·55V as being the practical maximum, otherwise you could be setting it too close to TR1’s trigger threshold.

Interior layout arrangement. The transducers are mounted on ‘stalks’, see text.

| COMPONENTS |
|------------------------|-------------------------|
| Resistors              | See SHOP page |
| R1, R5, R7, R8, R10, R12, R18, R20, R21 | 10k (9 off) |
| R2, R3, R6, R13, R15, R17, R19, R23, R24 | 100k (9 off) |
| R4                     | 1M |
| R9, R11                | 10k |
| R14, R16               | 1k (4 off) |
| R22                    | 22k |
| R25                    | 10Q |
| All 0·25W 5% carbon film or better |

Potentiometers

VR1 10k sub-min preset, round
VR2 10k sub-min preset, round, or 10k log rotary, panel mounting (see text).

Capacitors

C1 to C4
C6, C9, C14 100n ceramic, 5mm pitch (7 off)
C5, C11 to C13 22u radial elect, 16V (4 off)
C7, C8 10p ceramic, 5mm pitch (2 off)
C10 10u radial elect, 16V
C15 2200u radial elect, 16V (see text)

Semiconductors

D1 to D4 1N4148 signal diode (4 off)
TR1 BC549 or similar gen. purpose npn transistor
IC1 LM358 dual op.amp
IC2, IC3 PIC16F84-4P microcontroller (2 off, identically pre-programmed, see text)
IC4 TLC7524 8-bit digital-to-analogue converter
IC5 78L05 +5V 100mA voltage regulator
IC6 LM13800 or LM13700 dual transconductance amplifier
IC7 L272 dual power op.amp

Miscellaneous

RX1, TX1 40kHz ultrasonic transducer matched pair (transmitter plus receiver)
S1, S2 s.p.d.t. min. toggle switch (2 off)
S3 s.p.s.t. or s.p.d.t. min. toggle switch
SK1 3·5mm jack socket
X1 4MHz crystal

Printed circuit board, available from the EPE PCB Service, code 332; 8-pin d.i.l. socket; 14-pin d.i.l. socket; 16-pin d.i.l. socket; 18-pin d.i.l. socket (2 off); 1mm 4-way pin-headers, 0·1in pitch (2 off) (see text); plastic case to suit, 150mm x 80mm x 50mm; 9V battery and clip (see text); enchantable audience (many); connecting wire; solder, etc.

Approx. Cost

Guidance Only

£35

excluding case & batt.
THEME TUNES

Users of EPE PIC Toolkits MH2 and TK3 will find that writing theme tunes for downloading into PIC IC2's data EEPROM is as easy as writing program code — perhaps easier!

Using your preferred text editor, one way is to write a sequence of 64 numbers whose values lie between 0 and 15, as illustrated in file MagicM02.MSG. Save them as a Toolkit Message file (extension .MSG). Then send the file contents to PIC IC3 via Toolkit's Send Message option. Job done! Next time you trigger PIC Magick Musick when switch S1 and S2 are both in the On position, your programmed notes will be generated.

A second melody writing technique is to use alphabet letters relating to the notes required, as illustrated in file MagicM01.MSG. Lower case a-f are the notes for octave 1, upper case A-F for octave 2, and upper case H for top C (C⁰). A further example is in MagicM03.MSG.

But, you may ask, what numbers should I use? Ah, that’s where your talents as a composer come into play! The options are shown in Table 1.

Column 1 shows the value to be written into your MSG text file. Column 2 shows the letter that could be entered instead. Column 3 shows the approximate frequency that should be expected from PIC Magick Musick.

Another option is to use a random melody, created by loading any 64 characters of a text file. This is how the theme pre-installed (MagicM04.MSG) into the PICs is created. It consists of the first 64 characters of the first line in this article (Having enchanted . . .), written in ASCII values of the 15 notes available that they trigger one of the 15 notes available, spaces, punctuation etc. may all be left in. Any resulting zero value simply creates a pause.

Once triggered, the scales and melody run their full course before another hand movement or switch setting comes into effect.

FREQUENCY PRECISION

As the author has discussed in previous PIC controlled music generating designs, such as PIC-olo (Aug '97) and the PIC Musical Sandal (Jun '99), it is impossible to actually program a PIC to generate truly accurate musical notes. A compromise has to be accepted.

Software-generated frequencies depend on the time between a register value being taken high and low. For instance, if bit 0 of a Port register is taken high, held there for half a second, and then taken low for half a second, and the cycle constantly repeated, the resulting output at Port register pin 0 is a 1Hz square wave.

It will be obvious that with a PIC’s oscillator running at a high rate, timing of the pause lengths between the cycle phases of a slow frequency square wave can be very accurately adjusted, because there are many PIC program cycles that take place during them. Frequency adjustment can be made minutely just by increasing or decreasing the count values between each phase by just one cycle.

In the case of a PIC running at an effective rate of 1MHz (i.e. its crystal clock is running at 4MHz), the precise value of a nominal 1Hz output frequency can be adjusted by mere one millionth of a second, the duration of just one command. Look at the other extreme, though. Again suppose the PIC's effective rate is 1MHz and we want to output a frequency via PORTB pin 0 (RB0). The fastest output frequency generating routine is:

```
HERE: INCF PORTB,F
GOTO HERE
```

Two commands are involved, between them taking 2µs, thus to complete a full square wave cycle takes 4µs, an output frequency rate of 250kHz.

This rate cannot be increased without changing the basic clock rate. It can, however, be slowed by the addition of one command, NOP for example. There are now six commands to the square wave cycle, and an output rate of approximately 167kHz. Adding another NOP reduces the rate to 125kHz.

There are no intermediate frequencies that can be generated between either of the above frequency pairs with a 4MHz crystal controlled clock.

LOOPED DELAYS

Although the required output frequencies for a PIC music-generating design are much slower than these examples, a similar principle prevents truly accurate music frequencies being developed.

A simplified example of frequency generation as it is done in PIC Magick Musick is shown in Listing 1.

Listing 1a provides a look-up table in which the PORTA value causes a jump to the correct note generating routine, one of which is shown in Listing 1b. Here the routine is for note G, which has an approximate frequency of 195Hz. LOOPB is loaded with a delay value of 21, and then is decremented to zero. After two additional delaying commands, a jump is made to the OUTIT routine in which PORTB is incremented, and a jump made back to label TONE.
Even though it is known that the PORTA value has not been changed at this time, the seemingly unnecessary jump again to the look-up table helps to keep the frequency generation even.

When PORTB rolls over to zero, PORTA is read for its current value. If the value is the same as the previous sample, note G routine is again repeated. If a new value is found, the table automatically routes to the appropriate delay routine.

Each note’s delay routine has a different LOOPB value, and varying quantities of NOP commands. These help to “tune” the frequency as close as possible to that ideally required.

In the note G example shown, the actual frequency required is 195·998Hz. The prototype produced a frequency of 194·5Hz (measured on PICGEN of July ’00). Deleting one NOP to raise the frequency generated 196·9Hz. Adding one more NOP to slow it, resulted in 192·2Hz.

As illustrated earlier, the higher the required frequency, so it becomes increasingly difficult to tune software to produce it. Where the decision has been marginal, the author has generally erred for a frequency fractionally higher than the ideal.

WAVEFORM SHAPE

It may at first sight seem that the note loops have a low value compared to the frequency expected when using a 4MHz crystal clock. Had just PORTB pin 0 been

...the frequency output source, generating a square wave, much higher loop counts could have been used, allowing much tighter control of the actual frequency being output.

However, the aim with PIC Magick Music was to generate a non-square waveform. Experiments were tried using sine and triangle generating algorithms, but a sawtooth was felt to produce a more interesting sound.

Its generation, though, takes 64 clock cycles steps at PORTB (used as the 6-bit counter referred to earlier), bringing the note delay loop rates down by the same amount. Originally, 256 PORTB steps were tried, but the frequency results were too low to be acceptable.

Using 256 steps (8-bit) also produced a waveform amplitude greater than required to suitably drive the power amp via the envelope shaper. The 6-bit value basically results in a DAC output swing of about 1V peak-to-peak.

WIZARD FUN!

Whilst music “purists” may wonder if some notes have a frequency that might not be fully welcomed in a concert hall, remember that PIC Magick Musick is an inexpensive fun design. Had greater tuning accuracy really been desired, considerably more complex techniques would have been needed – at much greater cost.

When PIC Magick Musick was demonstrated at EPE HQ, the author was delighted by the positive response it received. It is, he has to say proudly, a super little design which can generate lots of fun for anyone using or hearing it. You’ve just got time before the festivities to build one, and maybe even program it with an appropriate jingle. Magick Season’s Greetings from a would-be PIC Wizard!

The waveform “screen dumps” were created via the author’s PIC Dual-Channel Virtual Scope of Oct ’00.