Low-cost watch crystal excites ultrasonic burst generator

by Daniel F. Johnston
University of New Brunswick, Fredericton, N. B., Canada

A small pulse-burst ultrasonic generator having excellent frequency stability can be formed by uniting the miniature quartz-crystal time base found in an electronic wristwatch with an integrated-circuit divider and one logic gate. This circuit will deliver a fixed frequency output of selectable burst width, and it is thus tailor-made for many portable instruments such as underwater location beacons and depth-finding (sonar) devices. The current drawn by the circuit is typically several microamperes.

The generator is shown in the figure. The standard quartz crystal operates at 32.768 kilohertz, is readily purchased, and costs only a few dollars. Crystals from 17 to 150 kHz can be obtained at slightly higher cost if other frequencies are desired.

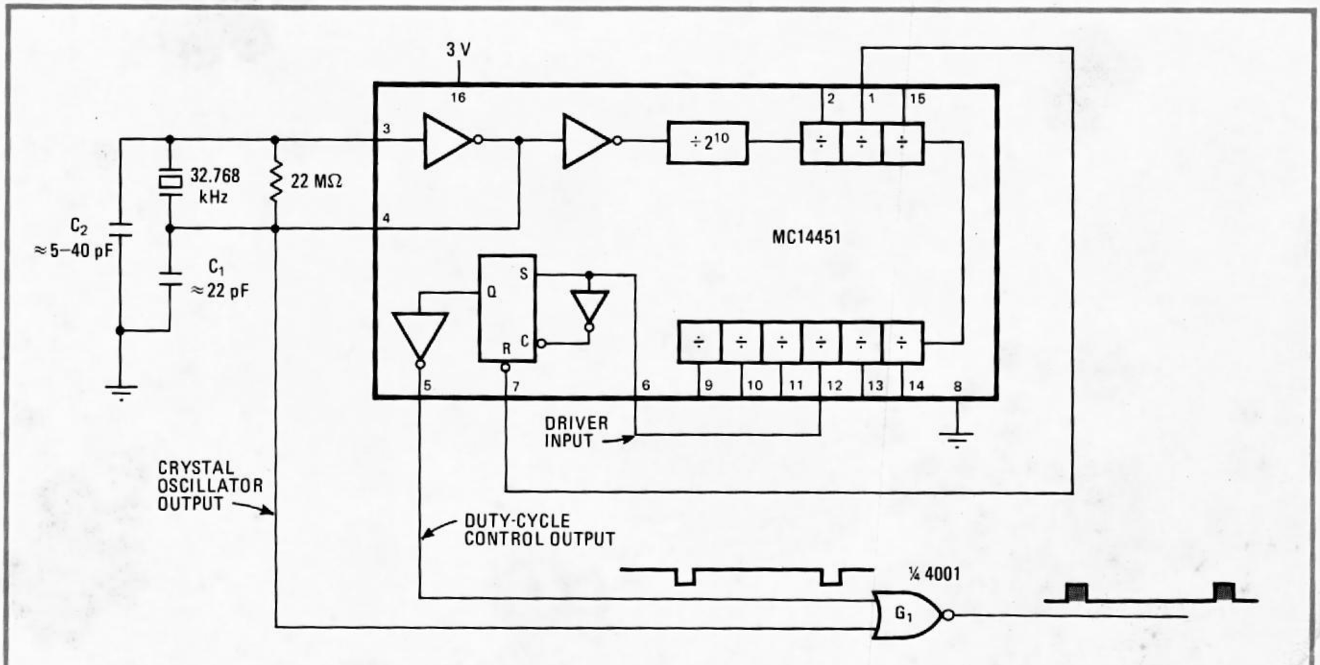
The IC divider is the MC14451, a low-cost divider-and-duty-cycle-controller built with complementary-metal-oxide-semiconductor technology that may be powered by a source of from 1.3 to 3.0 volts. The device contains an 19-stage binary divider (with taps available at any register port from 2^{11} to 2^{19}, inclusive), and a buffered flip-flop circuit for duty-cycle, or burst-width control.

The crystal is placed in a conventional oscillator circuit, as shown, with one inverter of the MC14451 serving as the active positive-feedback element. C_1 and C_2 in the oscillator are trimmed to achieve the required accuracy and are on the order of 22 picofarads for C_1 and 5 to 40 pF for C_2. The output of the oscillator is simultaneously fed to the MC14451 and G_1.

The crystal oscillator signal appearing at the output of G_1 is gated by the duty-cycle control output of the MC14451. To select the burst-width repetition rate, the appropriate buffered output of the divider must be connected to the driver input of the duty-cycle flip-flop, pin 6. Another buffered output, whose output period corresponds to twice the required burst width, must be connected to the duty cycle reset port, pin 7. The duty-cycle control output will toggle as required, switching low for the interval specified by the reset line at a rate controlled by the driver-port signal. The output from G_1 will therefore be a burst of a constant frequency.

Current consumption of the circuit is only 5 μA when a 32-kHz crystal is used and only twice that for a 65-kHz crystal. Thus the circuit can be powered by a small-capacity battery. □

Designer's casebook is a regular feature in *Electronics*. We invite readers to submit original and unpublished circuit ideas and solutions to design problems. Explain briefly but thoroughly the circuit's operating principle and purpose. We'll pay $50 for each item published.



Portable. Programmable-burst ultrasonic generator is small, is low in cost, and draws only a few microamperes. Burst-width repetition rate is selected by connecting the appropriate buffered output of the tapped binary divider in the MC14451 to pin 6. Burst width, adjustable from about 31 milliseconds to more than 1 second, is selected by connecting a second buffered output to pin 7 of the device.

ULTRASONIC SWITCH

Switch from afar with this novel project. Another Hobby Electronics project.

INVISIBLE RAYS have always exerted a considerable fascination on man down the ages. Isaac Newton watched apples falling under their influence and Uri Geller bent spoons with them (or did he?)

This project falls somewhere between these two extremes of the sublime and the ridiculous. It uses ultrasound; a high frequency sound, well above the range of human hearing to control a relay. By selecting a suitable type you can control your TV, Hi-Fi or bedside light at the touch of a button or as you will see later, with a snap of the fingers.

The unit is silent in operation. As the ultrasonic carrier beam consists of very high frequency (40 kHz) waves, special transducers have to be used as ordinary microphones and loudspeakers are very inefficient at this frequency. These transducers are just like crystal microphones and earphones except that they are designed to be resonant, ie very sensitive at a particular frequency. The receiver and transmitter units have different characteristics and best results will be obtained if the correct device is used in each application.

They are usually identified with a suffix 'R' for receiver or 'T' for transmitter marked on the case.

Range obtained will depend to an extent on the sensitivity of the particular transducers used but it is also considerably affected by the conditions under which the unit is operated. Ultrasonic waves are quite directional and can be bounced from hard surfaces like walls and ceilings so that greater range will be achieved in a sparsely furnished room or a corridor and satisfactory operation can often be obtained with the transmitter pointing away from the receiver. Our unit gave a maximum effective range of about twenty feet.

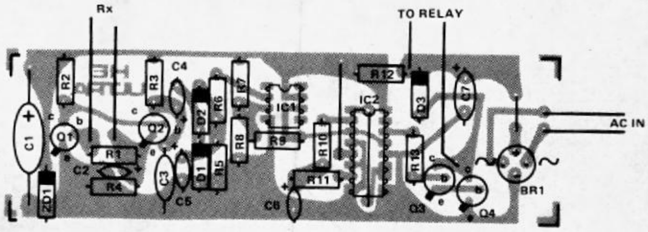
Any method of construction may be used although our PCBs are recommended and no special precautions are necessary. However, if you use your unit to control a mains operated device ensure that the mains is kept safely isolated from the control circuitry and use a relay whose contacts are rated for the job.

We mounted our 'Ultraswitch' in an grounded metal case. No special care was taken to protect the transducer from Mechanical shock and the unit worked quite reliably.

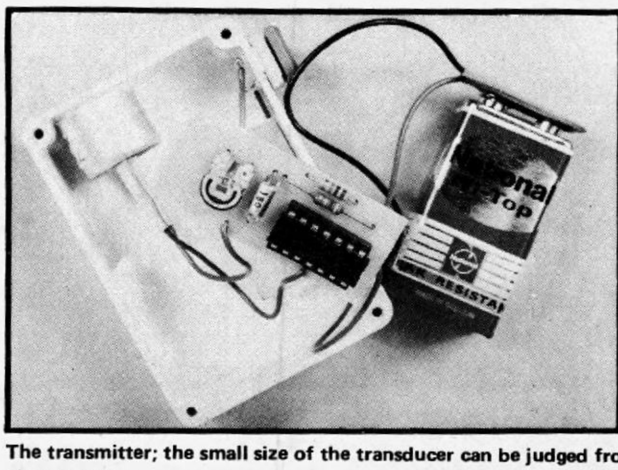
The transmitter was housed in a small Verobox. Ensure that the transmitter tuning control is easily accessible. It should be adjusted for maximum range. There are no other adjustments to make.

Ultrasonic waves are present in many 'natural' sounds and you will find that the switch will operate at varying range in response to jangling keys, crumpling paper and even, at close range, a snap of the fingers. A novel trick is to operate the unit with a handclap.

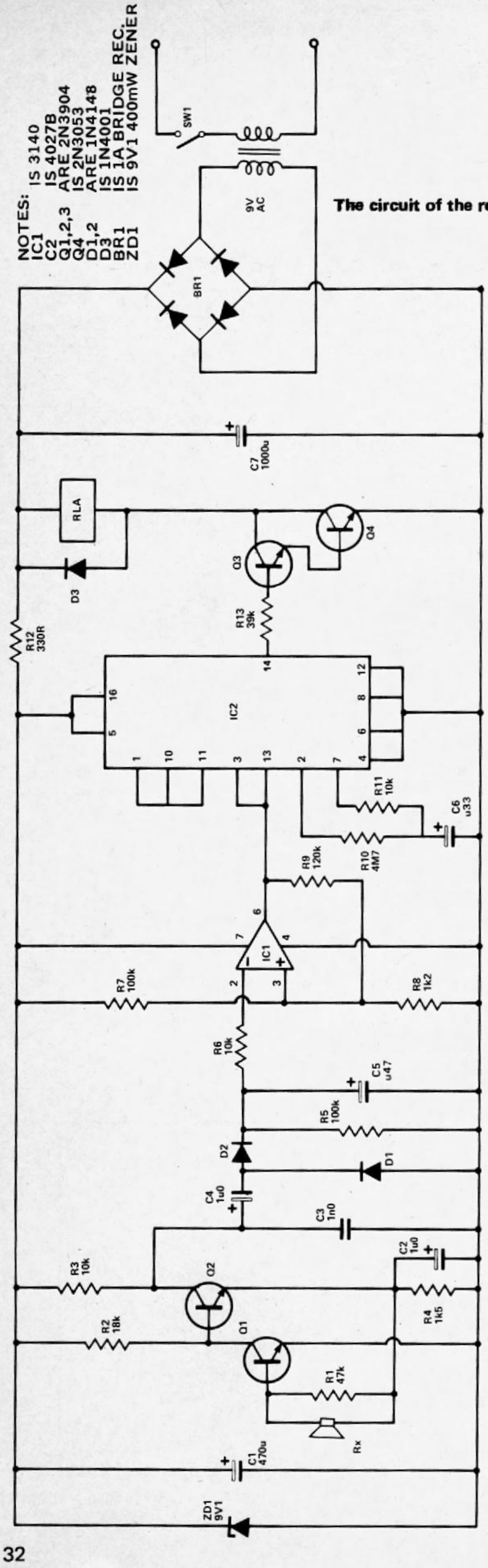
Remember to use a suitable relay for your application and make all connections safe. Then press that button and turn on.



The component overlay of the receiver.



The transmitter; the small size of the transducer can be judged from this photograph.



The circuit of the receiver.

HOW IT WORKS

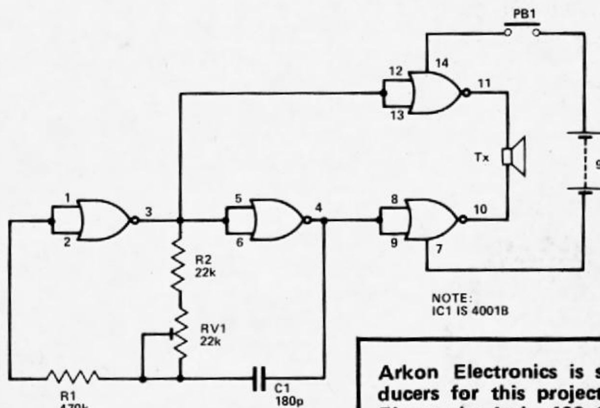
Transmitter

The transmitter consists of a straightforward CMOS oscillator driving the transducer via two complementary buffer stages. R2 and RV1 together comprise the timing resistance and C1 is the timing capacitor.

Receiver

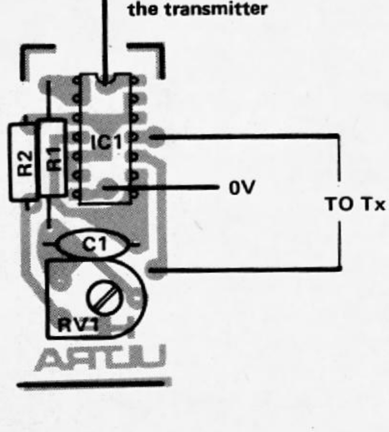
The ultrasonic signal is amplified by Q1, Q2 a direct coupled amplifier and appears at Q2 collector. C3 is a decoupling capacitor to suppress spurious RF oscillation. The amplified signal charges C5 via C4, D1, D2 and the voltage across C5 is compared with a reference provided by R7, R8 and controls the output of 1C1. R9 provides some positive feedback to produce a degree of hysterisis and speed up the transition time.

The output of IC1 clocks IC2. This is a JK flip-flop whose output toggles, ie changes state with each clock pulse. The bistable is disabled for a period determined by R10, C6 to avoid erratic operation. The output of the bistable appears at pin 14 of IC2 and controls super-alpha-pair Q3, Q4 which drive the relay. R12, ZD1 and C1 provide a smooth, stabilised power supply for the amplifier and CMOS circuitry whilst C7 is the main power supply smoothing capacitor.



The transmitter circuit.

Arkon Electronics is stocking the transducers for this project. Write to Arkon Electronics Ltd., 409 Queen Street West, Toronto, Ontario M5V 2A5.



The component overlay of the transmitter

PCB pattern of the transmitter.

Continued page 86

Fast-attack detector optimizes ultrasonic receiver response

by Paul M. Gammell
Jet Propulsion Laboratory, Pasadena, Calif.

A radio-frequency amplifier with low output impedance greatly enhances the performance of an ultrasonic receiver. The low impedance, achieved by an open-collector output configuration, permits design of a detector having a fast rise time and somewhat slower fall time—characteristics important for high-accuracy distance-measuring applications. This inexpensive circuit is a wideband receiver with good overload-signal recovery. It has many pulse-echo uses, including nondestructive evaluation and depth finding, and performs well in biomedical ultrasonic applications.

As shown in the figure, a pulsed signal is simultaneously applied to a transducer and transistor amplifier Q_1. The transducer is one of many commercially available devices that will convert a typical 200-volt, 0.1-to-1-microsecond pulse into an ultrasonic (compressional) wave aimed at a distant target. The echo from the transducer, with an amplitude on the order of 1 to 10 microvolts, may return only microseconds later. Q_1 must therefore recover quickly from the large initial pulse in order to respond to the echo signal.

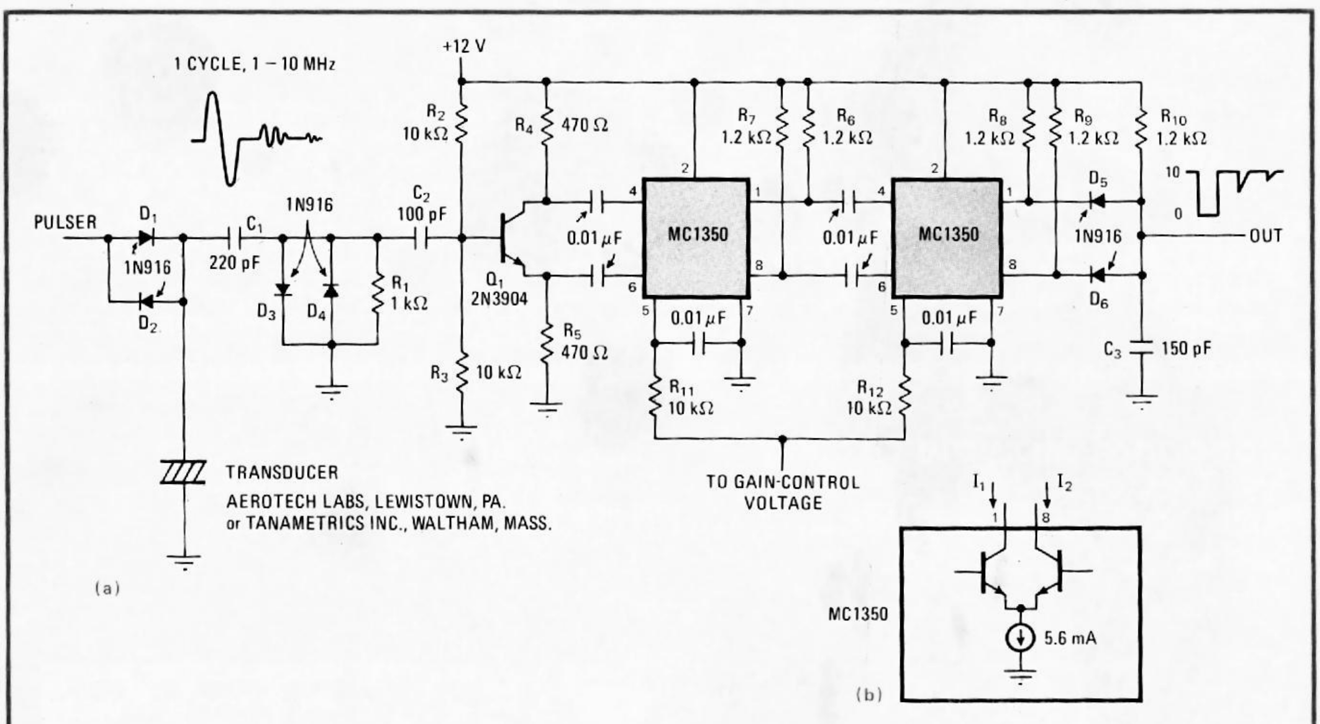
Components C_1, C_2, and D_1 through D_4 aid in isolating the amplifier circuits from the high-voltage pulse. Resistor R_1 improves the transient recovery by draining off any charge present on C_1 and C_2 that remains because D_3 and D_4 have not sufficiently bypassed the pulse to ground.

Q_1 is saturated by the initial pulse. Diodes D_1 and D_2 isolate the pulsed current from Q_1 (and the transducer) after the pulse drops below 0.7 v, thereby keeping the nonthermal noise contributions of the pulser out of the receiver. Q_1 drives the MC1350 radio-frequency/intermediate-frequency amplifier with a phase-split signal to increase the effective gain of the circuit and aids in isolating it from the pulser. To achieve a circuit gain of more than 50 decibels, a second MC1350 amplifier is added.

The output of the second amplifier drives a diode detector composed of D_5 and D_6 and the filter $R_{10}C_3$. Fullwave rectification is essential for optimum resolution, since the echo may be shifted 180° by the reflecting surface producing it.

A simplified equivalent circuit of the output stage of the MC1350 is shown at the bottom of the figure. A fast rise time for incoming signals is achieved by discharging C_3 through the 1-kilohm impedance of one of the output transistors. The longer fall time needed for a smooth

Pulse-echo receiver. Circuit (a) responds to wideband radio-frequency signals with good signal-handling capability. Time-dependent gain control is provided for sophisticated sonar applications. Choice of low-impedance rf amplifier (b) optimizes response.



echo envelope is attained by recharging C_3 through R_{10}. In some applications, it is desirable to provide a control to vary the fall time by adjusting C_3 and to reject echoes of small amplitude by varying R_8, R_9, and R_{10}.

At small signal levels, an approximate square-law response is provided by the logarithmic characteristic of the 1N916 diodes. The sum of currents I_1 and I_2 in the MC1350 is 5.6 milliamperes typical, as specified by the manufacturer. The currents determine the operating point of the diodes. With the circuit values shown, a quiescent current of approximately 0.8 mA flows through each of the diodes D_5 and D_6.

Although integrated circuits are widely available that perform low-level detection, the desired detector characteristics can be more easily achieved with the circuit described. Furthermore, a stable (oscilloscope) baseline and a large dynamic range are easier to attain if the detector is driven by a reasonably high rf voltage source. The amplifiers in this circuit make this possible by providing adequate predetection amplification.

The signal at the output has a well-defined leading edge suitable for determining time differences between the pulse and its echo with an oscilloscope. A 10-v offset occurs at the output. It may be removed with a base-line restorer circuit consisting of a decoupling capacitor, a resistor tied to 12 v, and a germanium diode to clamp the baseline to about 0.3 v. Another approach uses a differential amplifier.

For sophisticated systems, a time-dependent gain control can be added to the rf amplifiers. A 0-to-12-v ramp voltage, the amplitude of which depends on the range and anticipated attenuation of the echo, can be applied to pin 5 of the devices through R_{11} and R_{12}, which control the distribution of stage gain. The ramp voltage should be positive and decrease with time to provide a gain that increases with time. If pin 5 is grounded, the amplifier operates at full gain. Although the ramp is usually synchronized with the transmit pulse, it may be synchronized with other sources, such as the surface echo from an attenuating target. □

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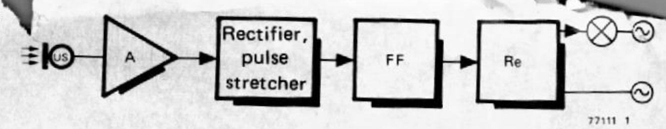
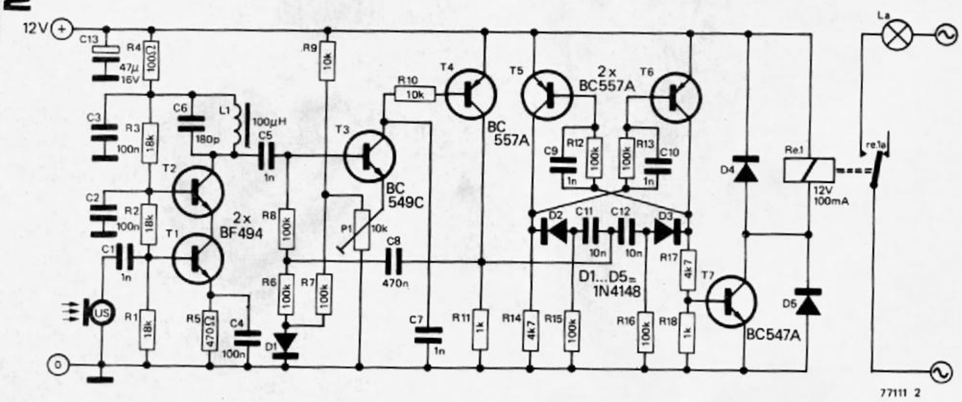
ultrasonic receiver

1



This receiver is intended to be used with the US transmitter described elsewhere in this issue. The input signal is fed to a cascode amplifier comprising T1 and T2, which amplifies it approximately 2000 times. T3 functions as a rectifier, and T4 amplifies the rectified signal, which is used to trigger a flip-flop comprising T5 and T6. This will be set on one US burst and reset on the next, thus turning T7 on and off to successively energise and de-energise the relay.
To reduce the circuit's sensitivity to multiple triggering (caused principally by Doppler-shift) positive feedback is provided via C8 causing T3 and T4 to operate as a monostable. This ensures that only one output pulse is generated for each received pulse and prevents spurious triggering of the flip-flop.
To set up the receiver the following procedure should be observed. Turn the slider of P1 towards the 0 V rail. This should cause the relay to pull in and drop out at random. P1 is then adjusted until this just ceases, when the receiver sensitivity will be at a maximum. Activating the transmitter should now energise the relay. The system will operate at distances of up to eight metres. If this range is too great then it may be reduced by suitable adjustment of P1. The receiver should be set to the minimum range required for a particular application, as too great a sensitivity may cause spurious triggering by normal sounds which have an ultrasonic content, e.g. handclaps, rustling paper etc.

2



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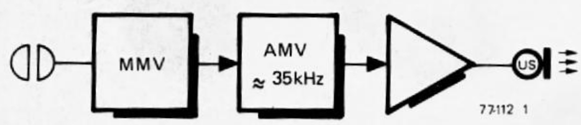
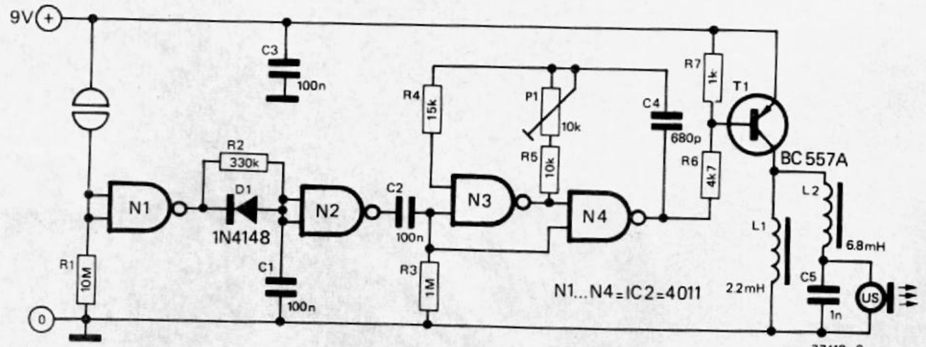
ultrasonic transmitter for remote control

1



This simple ultrasonic (US) transmitter uses only one CMOS IC and a few discrete components, and will generate a short pulse of ultrasound. This can be used to trigger an ultrasonic receiver (such as the one described elsewhere in this issue) to activate a relay or other circuit.
When the touch contacts on the input of N1 are bridged by a finger the output of N1 will go low and the output of N2 will go high, holding the input of N3 high via C2 for about 60 milliseconds.
During this time the astable multivibrator comprising N3 and N4 will oscillate at about 40 kHz (adjustable by P1). Since the output of N4 can supply little current, drive to the US transducer is provided by T1, which feeds the resonant circuit L2/C5. This is tuned to around 40 kHz, which is the resonant frequency of most US transducers. Although only a 9 V supply is used, the 'Q' of the resonant circuit ensures that a high drive voltage appears across the transducer (up to 100 V), and a range of up to eight metres can be achieved in conjunction with the aforementioned receiver.
As the circuit consumes virtually no power except when actually transmitting, no on-off switch is required. Almost any 40 kHz US transducer can be used.

2



ROBOTICS

MARK J. ROBILLARD
ROBOTICS EDITOR

Ultrasonic rangers and stepper motors

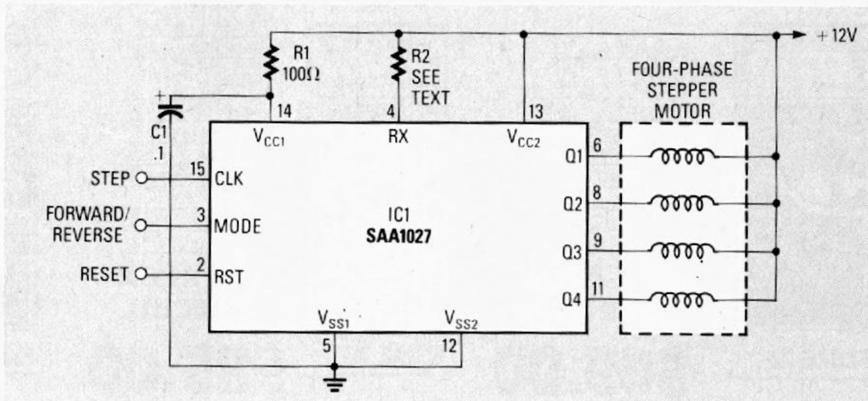


FIG. 1

WE'VE DISCUSSED ULTRASONIC-RANGING and stepper-motor circuits the past several months; this month we'll mention several other ways to implement such circuits, and then go on to discuss how they may be used to map and navigate an arbitrary area.

We discussed the operation of a typical ultrasonic ranger in detail last month, but, to summarize briefly, a timing pulse is applied to a circuit that generates a burst of ultrasonic waves. A timing circuit begins counting at the same time, and, after an echo has been received, the time is divided by two, and the distance is calculated, based on the speed of sound in air. Normally you connect an ultrasonic ranging system to a microcomputer that is used to initiate ranging, do the calculations, and control the robot's stepper motor (or motors).

Last month we discussed Polaroid's ultrasonic ranging kit; another such kit is made by Texas Instruments. The SN28827 is available from the Micromint (25 Terrace Drive, Vernon, CT 06066) with a transducer for about $60. I recommend using a kit rather than a home-made system. That way you can get to the really difficult problems—like mapping and navigating—without spending time debugging standard circuits.

A stepper motor allows you to rotate the ranging circuitry (or the whole robot, if necessary) a precise amount, and then make, and record, a distance measurement. Steppers require a little more power than regular DC motors, but their position is much easier to control. The circuit in Fig. 1 shows how an LSI IC can be used to drive a four-phase stepper motor. A direction signal is applied to the MODE input, and then the CLOCK input is pulsed. The RESET input should normally be held high. Resistor R2 determines the base current of the IC's driver transistors, and it must be selected in accordance with the current requirements of the motor that will be used.

The SAA1027 used in that circuit is made by Signetics; Sprague also manufactures stepper-motor drivers, the UCN-4202A and UCN-4203A, among others. Moreover, there are ways of controlling steppers without custom IC's. Let us know if you're interested; we could devote a column to that subject.

Robot mapping

With a stepper motor and an ultrasonic ranger we can make a rough map of an area by rotating the ultrasonic transducer while taking distance readings at periodic intervals. Using a computer to record those readings will allow a map of distances to be compiled. With a simple system such as that we're discussing, the resulting map barely resembles the space mapped; in early experiments, I could hardly recognize the area I had just mapped. The reasons for the discrepancies are many.

For example, assume we want our robot to navigate a room with a table and an open doorway. When we see a table, we have no trouble distinguishing it from a doorway. But the robot would see the legs as spikes and the in-between areas as caverns. The robot might try—mistakenly—to pass under those legs. As robot programmers, it is our job to interpret what the map actually represents, so that we could, for example, find the doorway without running into the table.

But let's assume that a trial-and-error method is necessary to move the robot out the doorway. At any arbitrary location, three readings might be taken: straight ahead, 90° right, and 90° left. Those readings will tell you whether it is safe to move in one of those directions. If the straight-ahead reading reveals that there is an obstacle within a

continued on page 113

BY BRIAN DANCE

Listen to a NEW WORLD OF SOUNDS WITH ULTRASONIC DETECTOR

Inexpensive detector converts ultrasonic sounds from insects, compressed gas leaks, etc., to an audio output.

EXPLORING the world of ultrasonic sound—which lies above approximately 20 kHz—can be exciting and educational. Here is a frequency spectrum beyond human hearing where many insects and rodents communicate with each other, where sounds from leaks in pressurized gas lines occur, etc.

The inexpensive circuits presented here convert these ultrasonic sounds to audio frequencies, enabling anyone to hear them. Also included is a simple ultrasonic transmitter circuit that will enhance your ability to probe this interesting electronics area.

An Ultrasonic Receiver. The schematic diagram of a heterodyne-type ultrasonic receiver is shown in Fig. 1. This receiver hyterodynes ultrasonic signals with those from an internal oscillator, converting them to audible frequencies for reproduction by a dynamic speaker. Thus, it allows you to "hear" any signals it detects.

Piezoelectric transducer *TR1* converts ultrasonic waves impinging upon it into ac waveforms which are applied to the noninverting input of operational amplifier *IC1A*. Because a single-ended power supply is used, resistors *R1* and *R2* bias the noninverting input to one-half the supply voltage. Resistor *R3*, effectively connected across *TR1* by electrolytic capacitor *C1*, damps the transducer's resonant response and broadens its bandwidth. At dc, *R5* provides 100% negative feedback to stabilize the operating point. At signal frequencies of interest, the gain of *IC1A* is 60 dB for the values given in Fig. 1.

The output of *IC1A* is directly coupled to op amp *IC1B*, a similar amplifier stage. The voltage gain of *IC1B*, about 43.5 dB with the component values specified, is somewhat lower than that of the preceding stage. Signals at the output of *IC1B* are capacitively coupled by *C5* to diodes *D1* and *D2*.

Also applied to the diodes is the output of an ultrasonic oscillator comprising *IC3* and its related components. The frequency of this oscillator is determined by the setting of potentiometer *R12* and the capacitance of *C9*, which is chosen so that the oscillator output corresponds to the resonant frequency of the transducer. (Transducers are readily available from surplus dealers with resonant frequencies ranging from 22 to 44 kHz.)

The two diodes form a nonlinear net-

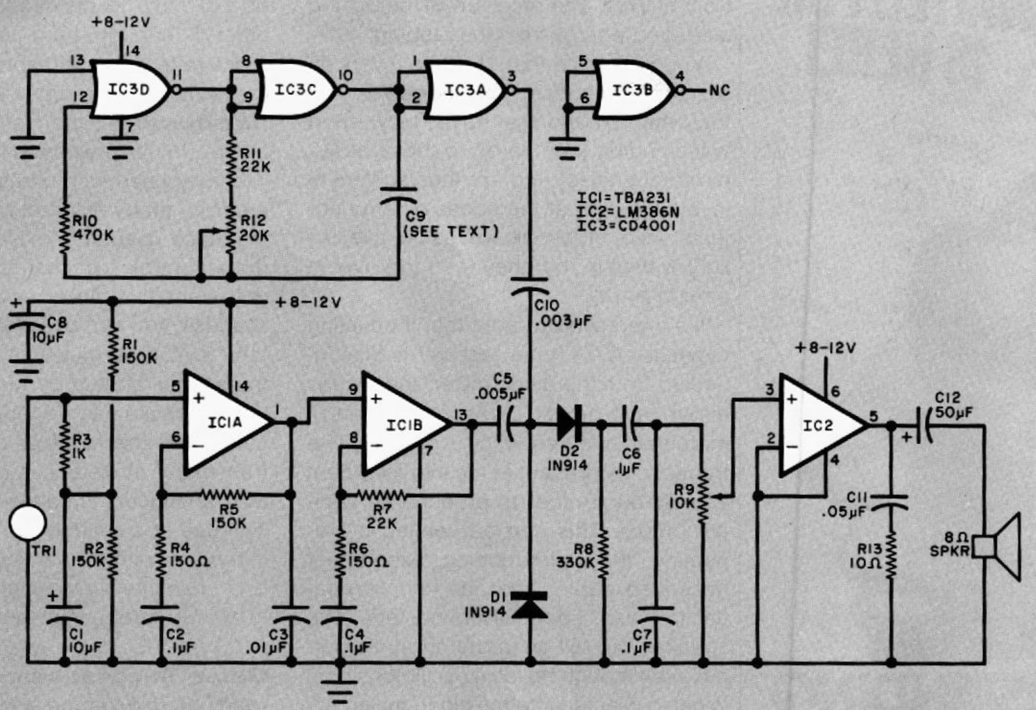


Fig. 1. An ultrasonic receiver, where incoming signals heterodyne with those from the local oscillator to produce an audible output.

PARTS LIST FOR FIG. 1

C1,C8—10-µF, 25-V tantalum
C2,C4,C6,C7—0.1-µF disc ceramic
C3—0.01-µF disc ceramic
C5—0.005-µF disc ceramic
C9—180-pF (or 330-pF) disc ceramic, polystyrene, glass or silver-mica (see text)
C10—0.003-µF disc ceramic
C11—0.05-µF disc ceramic
C12—50-µF, 25-V electrolytic
D1,D2—1N914 signal diode
IC1—TBA231 dual op amp (see note)
IC2—LM386 audio amplifier
IC3—CD4001 quad 2-input NOR gate
The following fixed resistors are ¼-W, 10% carbon composition:
R1,R2,R5—150,000 ohms
R3—1000 ohms
R4,R6—150 ohms
R7,R11—22,000 ohms
R8—330,000 ohms
R10—470,000 ohms
R13—10 ohms
R9—10,000-ohm linear-taper potentiometer
R12—20,000-ohm linear-taper potentiometer
SPKR—8-ohm dynamic speaker
TR1—Piezoelectric ultrasonic transducer
Misc.—Printed circuit or perforated board: suitable enclosure: hook-up wire; dc power source; machine hardware; etc.
Note—The TBA231 dual op amp is imported from the U.K. by SG-ATES Semiconductor Corp., 435 Newtonville, MA 02160 (Tel: 617-969-1610).

work. Hence, when signals from the oscillator and the op amp are applied, they heterodyne with each other. If *IC3* oscillates at a frequency fairly close to that of an ultrasonic wave detected by *TR1*, an audible beat signal will appear at the cathode of *D2* at a frequency equal to the difference between the two ultrasonic frequencies. The process is similar to that performed in a conventional superheterodyne r-f receiver. The beat note, which can be tuned by adjusting *R12*, is amplified by *IC2*, an audio IC, to a level sufficient to drive the dynamic speaker. Potentiometer *R9* serves as an audio gain control.

An Ultrasonic Transmitter will help you explore the ultrasonic region more fully. A suitable design is shown schematically in Fig. 2. The circuit is similar to the local oscillator stage in the receiver, but the previously unused fourth gate in the 4001 is employed to provide push-pull drive for transducer *TR2*. The output frequency is variable by means of *R3*. The capacitance of *C1* should be chosen so that the nominal oscillating frequency corresponds to the resonance of the transducer. As was the case with *C9* in the receiver, *C1* should be 180 pF if 44-kHz transducers are used, or it should be 330 pF for use with 22-kHz transducers.

Construction. Either printed circuit or perforated board can be used to duplicate the transmitter and receiver circuits. Parts placement is not espe[illegible]lly critical. The use of sockets or Molex [illegible]dercons is recommended when [illegible]ing the IC's on the boards. B[illegible] observe normal precautions when handling the CMOS devices. Install polarized capacitors and semiconductors with due regard for polarity and pin basing. Batteries are well suited to power the transmitter and receiver circuits. Note that, when transmitter switch *S1* is in the OFF position, the output states of *IC1*'s gates are frozen. The quiescent current drain of the circuit is so small that no power switch is necessary. If a battery supply is used with the receiver, however, an spst power switch should be used to disconnect the circuit from the supply when it is not being operated.

Use. Receiver potentiometer *R12* tunes the circuit across a limited portion of the u[illegible]onic frequency range. Apply power [illegible]dio gain control *R9* until [illegible]eard through the speak[illegible] er. Then rub the palms of your hands in front of *TR1*. The receiver will detect the ultrasonic energy from the rubbing.

You will notice that *TR1* has a very directional response. This is due to the fact that ultrasonics have very short wavelengths (compared to those at audio frequencies) and are thus subject to less diffraction at the edges of large objects. Also, ultrasonic waves behave like light waves in that they tend to travel in straight lines.

It's interesting to note that if coupling capacitor *C10* in the receiver is disconnected from the diode mixer, the receiver will still detect ultrasonic signals if more than one frequency is present. The frequencies present at the input will beat against each other to produce an audible output. This can be verified by repeating the palm-rubbing experiment described earlier after the coupling capacitor has been disconnected. The speaker will still generate an audio output even though no local oscillator signal is being injected into the diode mixer.

If an ultrasonic wave generated by transmitter transducer *TR2* now impinges upon *TR1*, the random noise reproduced by the speaker will drop to a low level. No tone will be heard because only one frequency is applied to the mixer. Stray coupling that allows a portion of the local oscillator output to reach the mixer will create an audible beat.

When the receiver and transmitter are operating in the same room, a signal will be heard as *R12* tunes the receiver across its range. The two transducers do not *have* to be directly facing each other if enough hard surfaces in the room reflect the ultrasonic waves, and the room is not so large that it introduces excessive signal attenuation.

The circuits presented have been successfully used with ultrasonic transducers from many different sources, including those used in television receiver remote control accessories. Of course, if you want to tune in several ultrasonic "bands," you can use a multiple-pole rotary switch to select the appropriate transducer and its corresponding oscillator capacitance. Experimentation indicates that the receiver can "hear" the transmitter at distances up to 125 feet if the transducers are aimed at each other. The use of a suitable parabolic reflector in tandem with *TR1* and/or multiple driven transmitter transducers should result in even greater useful range.

Other Suggestions. We have already mentioned the possibility of using these circuits for signalling purposes. Many other practical applications exist. For example, leaks in the rubber sealing of car doors and windows or in the sealing of a freezer door. The transmitter is placed in the car or freezer and fills the interior with ultrasonic waves. The walls of the interior reflect the waves to create a wide dispersion of ultrasonic energy. If the receiver's transducer is moved over the exterior, a tone will be heard whenever it passes any leaks. ◇

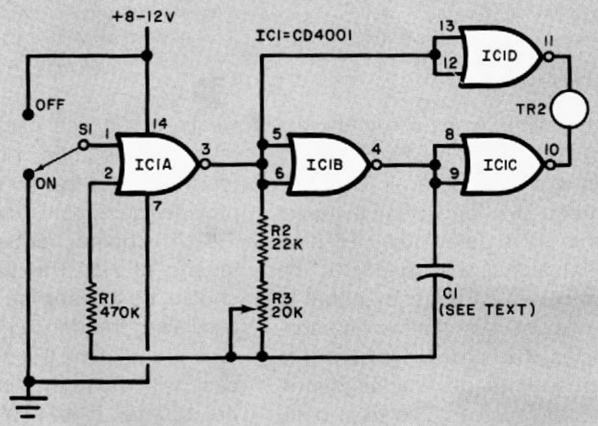


Fig. 2. This ultrasonic transmitter employs four NOR gates.

PARTS LIST FOR FIG. 2

C1—180-pF (or 330-pF) disc ceramic, polystyrene, glass or silver mica capacitor
IC1—CD4001 quad dual-input NOR gate
R1—470,000-ohm 10%, ¼-W resistor
R2—22,000-ohm 10%, ¼-W resistor
R3—20,000-ohm linear-taper potentiometer
S1—Spdt switch
TR2—Piezoelectric ultrasonic transducer
Misc.—Printed circuit or perforated board; suitable enclosure; hook-up wire; dc power source; machine hardware, etc.

INSIDE ULTRASONICS

Ultrasonic sound at very high frequencies is being used increasingly for medical diagnosis. Dr P. N. T. Wells of Bristol General Hospital reports.

THE IMPORTANCE OF ultrasonic diagnostic methods lies in the fundamental differences between them and other techniques such as radiology and radioisotope scanning. The symptoms of some diseases, and of natural conditions such as pregnancy, are best investigated by ultrasound. It maps out anatomical cross-sections, measures the performance of the heart and the flow of blood, and identifies many kinds of abnormality, including several types of cancer, all without encroaching into the body in any way.

Twenty-five years ago, doctors seeking to investigate the structures of the body had no alternative to X-rays and this often involved injections of substances to give better contrast to obtain information about soft tissues. Nowadays, ultrasonic methods have replaced radiology in helping to solve a number of clinical problems doctors depend on ultrasonic diagnosis, and patients demand this kind of investigation. The procedures are rapid and painless and nothing enters the body other than ultrasound waves. Unlike ionizing radiations, ultrasound at diagnostic exposure levels seems to be harmless.

Basic Principles

Most diagnostic applications of ultrasound depend on the reflection of ultrasonic waves at surfaces between tissue structures which differ in their so-called characteristic impedance. The characteristic impedance of a material is equal to the product of its density and the velocity of ultrasound within it. The densities of soft tissues, about 10^3 kg m^{-3} (kilograms per cubic metre), and the velocities of ultrasound within them, about 1500 m s^{-1} (metres per second), are similar to those for water. When an ultrasonic wave strikes the boundary between tissues that differ in characteristic impedance, a proportion of the energy in the wave is reflected in much the same way that light is reflected when it meets a change in reflectivity at a surface.

The characteristic impedances of soft tissues are similar, so the echoes from their boundaries are very small. For example, only about 0.5 per cent of the▶

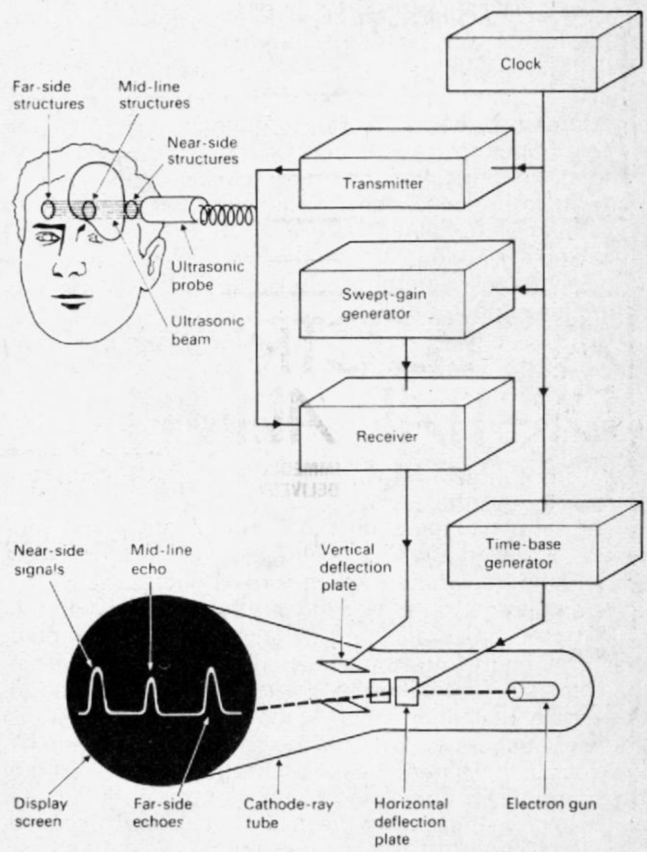


Fig. 1. Basic arrangement of the A-scope system, in use in this instance to show the mid-line structures of the brain in their relative position halfway between the sides of the skull, as indicated by symmetry of the deflections of the cathode-ray tube trace. Asymmetrical spacing of the deflections may mean that disease has brought about a physical change such as a tumour on one side of the brain. The swept-gain generator gradually increases the receiver amplification over each sweep of the time base to compensate for the attentuation of the deeper echoes by intervening tissues.

energy striking the boundary between kidney and fat is reflected. However, such echoes are large enough to be detected by a sensitive receiver, but almost all the energy crosses the boundary and is available for reflection by deeper structures.

Much larger reflections occur at boundaries between soft tissues and either bone or gas, because of large differences in characteristic impedance. These large reflections restrict the use of ultrasound in medical diagnosis. Moreover, it is necessary to exclude air from between the probe and the patient. This may be done either by examining through a water bath or through a film of oil smeared on the patient's skin.

Resolution

Ultrasonic echo-ranging techniques depend on the measurement of the time interval between the transmission of a brief pulse of energy and the reception of its echo, just as in radar. In any imaging system, whether using light, ultrasound or any other kind of radiation, the resolution is limited by the wavelength of the radiation. It is for this reason that ultrasound, as opposed to sound, is used in medical diagnosis. We need to visualise structures of only a few millimetres in size, so that wavelength has to be around a millimetre or less. In soft tissues, it is about 1.5 mm at a frequency of 1 MHz and proportionately less at higher frequencies. The highest audible frequency, about 20 kHz, has a wavelength of 75 mm. In principle, the performance might appear likely to improve as the frequency is increased, but ultrasound is attenuated as it travels through tissues and the rate of attenuation also increases with the frequency, so we have to compromise between better resolution and reduced penetration.

Pulse-Echo Techniques

In an ultrasonic instrument for diagnosis, a probe containing a piezoelectric transducer converts electrical signal into ultrasound waves for transmission into the patient. It does the opposite for the echoes.

The simplest type of ultrasonic pulse-echo diagnostic system is called the A-scope. (See Fig. 1). The clock triggers the transmitter, which feeds a brief pulse with a large amplitude to the transducer. Echoes return to the probe from those reflecting surfaces inside the patient that lie along the ultrasonic beam. Electrical signals from the echoes are amplified by the receiver and applied to the vertical deflection plates of the cathode-ray tube; the time-base generator, which is triggered into operation by the clock at the instant the ultrasonic pulse is transmitted by the probe, is connected to the horizontal deflection plates to drive the spot on the display at a constant speed from left to right. In this way the beam sweeping across the display is deflected vertically at intervals along the horizontal axis, corresponding in distance from the start of the sweep, to echo-producing surfaces at various distances along the ultrasonic beam. A special circuit in the receiver increases the amplification of the deeper echoes to compensate for theit attentuation by intervening tissues. The clock operates at a repetitin rate fast enough to give a flicker-free trace on the display.

The A-scope has clinical applications in neurology, ophthalmology and internal medicine. It allows the depths of echo-producing surfaces to be measured, and the characteristics of echoes from within structures to be studied.

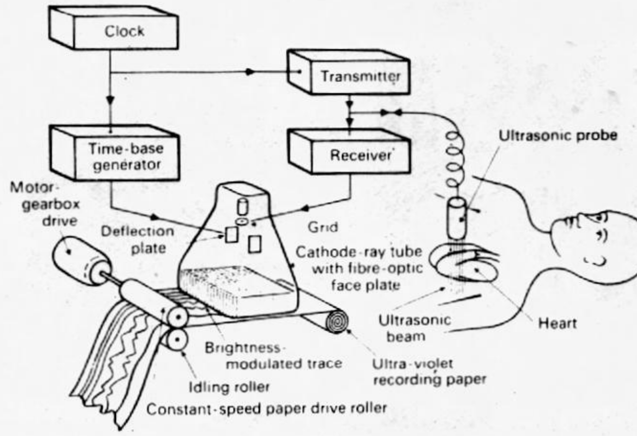


Fig. 2. Time-position recording system based on the B-scope display, shown in use for echocardiography. The fibre-optic face plate of the cathode-ray tube collects enough light to produce a self-developing trace on ultra-violet recording paper.

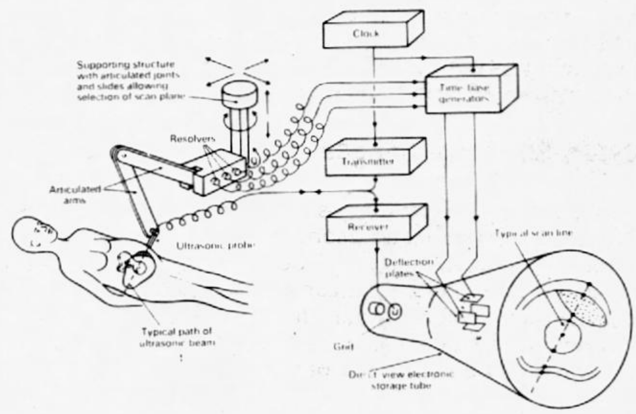


Fig. 3. Two-dimensional scanner and B-scope display system studying a foetus. The time-base generators are driven by electrical outputs from a series of resolvers that measure the position of the ultrasonic beam as it moves across the patient. Horizontal and vertical time-bases combine to deflect the spot in such a way that its movement across the display corresponds to the movement of the beam. Echoes received as the probe moves over the patient produce a cross-sectional image in a plane corresponding to that of the scan. In this example, the image is built-up on the screen of an electronic storage tube for direct viewing.

Echoes from moving structures, such as the valves of the heart, oscillate in position along the horizontal axis, or time base, of the display. In cardiology particularly, patterns of movement can give diagnostic information. They can be studied by making recordings with the aid of a B-scope display (see Fig. 2).

In the B-scope, the time-base sweep is normally visible, but it is brightened by returning echoes to

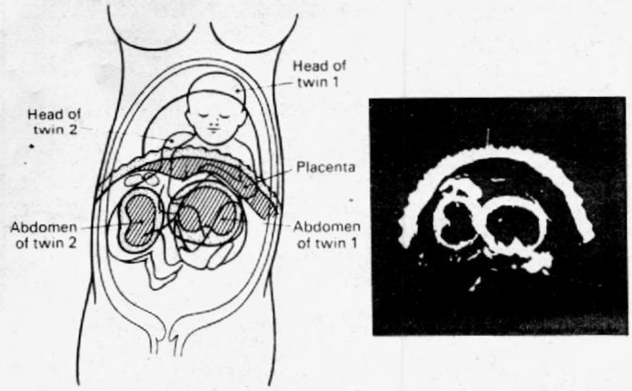


Fig. 4. A two-dimensional scan reveals twins at about 25 weeks of pregnancy. The placenta on the anterior wall of the uterus is clearly defined while the abdomens of the twins, identified in the explanatory diagram, appear in section.

produce spots of light on the display in places where, on an A-scope, there would be deflections of the beam. The positions of the spots of light correspond to echo-producing structures in the patient, and the pattern of their movement can be permanently recorded.

Cross-Sectional Images

The B-scope forms the basis of another display method, the two-dimensional ultrasonic scanner (see Fig. 3). The ultrasonic probe, instead of being held in the hand, is mounted on a scanner. It can be moved to any position in a two-dimensional plane. In this way it is possible to arrange for the beam to pass through structures lying in a chosen plane within the patient, while the position of the probe and the direction of the beam are measured continuously by 'resolvers' mounted in the scanner. The electrical signals from the resolvers control two time-base generators, driving the vertical and horizontal beam deflection plates of a cathode-ray tube. The direction and position of the ultrasonic beam across the patient controls the position of the cathode-ray beam showing up on the display, related to the positions of the echo-producing surface.

A cross-sectional image of the surfaces can be built up photographically by a camera with an open shutter that records the bright spots on the display while the patient is being scanned. The echo information can also be stored electronically.

Two-dimensional scanners in which the probe is moved in contact with the patient produce individual images in scanning times of about 10 seconds, images can be produced at a much faster rate by moving the probe mechanically. Images in rapid succession allow physiological movements to be studied; their main importance is in cardiological diagnosis. But although these rapid mechanical scanners produce so-called real-time images, they lack flexibility. This difficulty can be overcome by using ultrasonic probes containing many separate transducer elements, operated separately or in groups, which can produce ultrasonic scans made up of parallel lines or or lines arranged in a fan shape, at frame rates of tens per second.

As well as making it possible to study rapidly moving structures, real-time scanners can also be used to explore large volumes of anatomy in a short time. A doctor using one can examine a patient in about a quarter of the time it takes with a 'conventional' two-dimensional scanner.

Doppler Effect

The frequency of an ultrasonic wave reflected from a stationary structure is equal to that of the incident wave. If the beam is reflected by a surface which is moving ▶

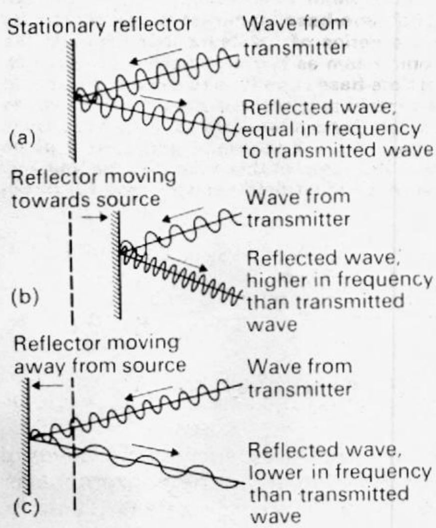


Fig. 5. The Doppler effect occurs when a wave is reflected from a moving surface, giving an upward or downward 'shift' in frequency as in (b) and (c).

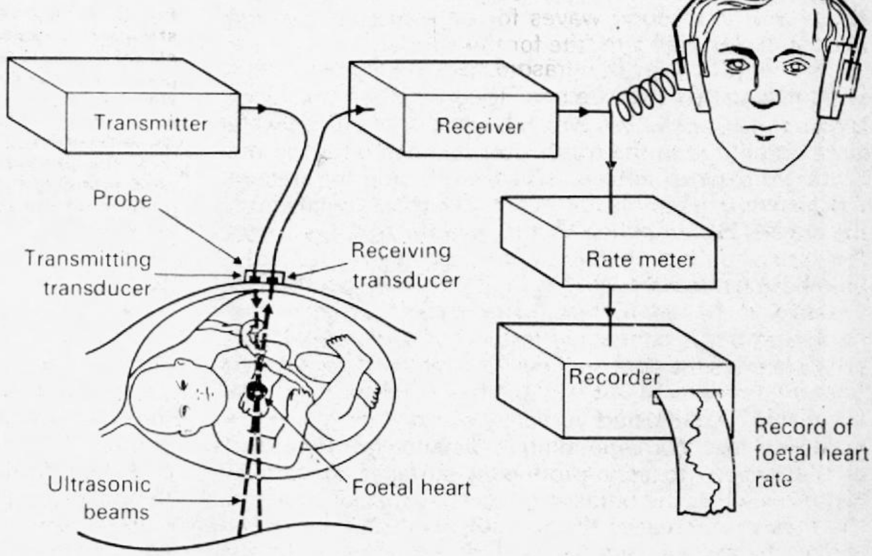


Fig. 6. One use of the Doppler 'shift' is to monitor the foetal heart. The echoes usually fall in the range of audible frequencies.

towards the ultrasonic source, the reflected wave is compressed into a shorter space. This means that the wavelength is reduced. It shows as an upward 'shift' in its frequency. Reflection by a surface moving away from the source gives a downward shift. This phenomenon, the well-known Doppler effect, conveniently gives shift frequencies that fall in the audible range when ultrasound is reflected by moving structures in the body such as heart valves or flowing blood. A simple instrument based on this makes it possible to detect the movement of the foetal heart. Similar instruments to measure blood flow allow peripheral arterial disease to be assessed.

Because Doppler shifted signals are received only from structures that move, two-dimensional maps of them can be built up by using a Doppler probe to scan the patient. In this way the distribution vessels close to the surface can be studied. Such information may obviate the need for X-ray angiography, which is a dangerous and expensive procedure.

It can also be combined with other information about structure position obtained by the pulse-echo method, making it possible to map out blood vessels within the body and measure the rate of blood flow at the same time.

The clinical value of ultrasonic techniques has already been proved, but their spread into general, everyday service will depend on the development of instruments that are simple to use. These, paradoxically, may be more complicated than the ones we already have. It will also mean training doctors and technicians to obtain and interpret results. But it is clear that ultrasonic diagnosis is, in many instances, the best and most economical way of getting the information essential to proper care of the patient. ETI

Ultrasonic pulser needs no step-up transformer

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When a transducer is used in a pulse-echo ultrasonic system of the kind that is excited by high-voltage impulses at a low duty cycle, the device often requires the services of a bulky, step-up line transformer and switching circuits that must withstand the full supply voltage. The ultrasonic pulser shown in the figure, however, generates a 300-volt pulse train at a low-duty cycle (about 1/20,000 of a cycle rise time at 2 kilohertz) without the need for a transformer and without placing an excessive voltage on the switching devices.

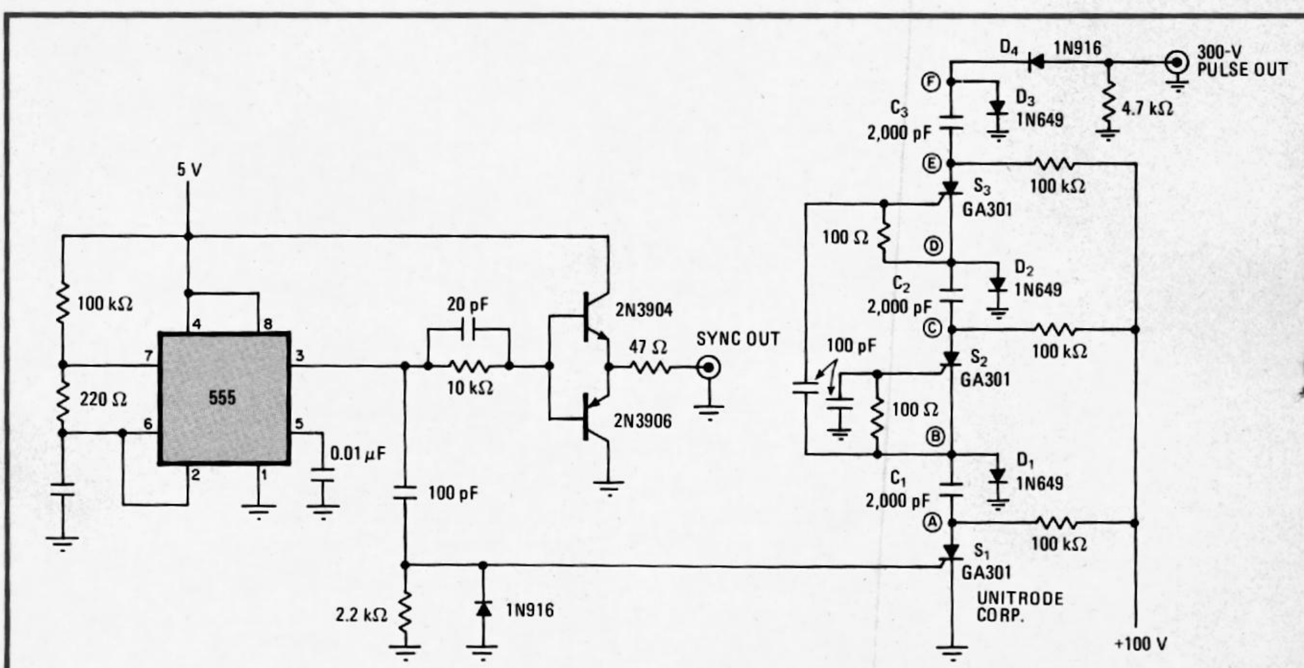
Used in place of the transformer supply is a voltage tripler circuit that arranges for each of three capacitors, in effect arranged in parallel, to be charged by a 100-v dc input voltage. The circuit then places the capacitors in series during discharge so that the output voltage is three times the input voltage. Moderately priced ($6) silicon controlled rectifiers with a fast, 10-nanosecond rise time serve as the switching elements and need withstand only 100 v each. Furthermore, since the power drain is modest, merely a few tens of milliamperes, a small power supply of the kind intended for glow-discharge displays is suitable.

As for the operation of the circuit, at times when no signal is applied to the gate of S_1, as during a power-up, S_1–S_3 are off and C_1–C_3 charge up through their respective 100-kilohm resistors and diodes, D_1–D_3.

A positive-going signal applied to the gate of S_1 by the 555 timer, which operates as an astable multivibrator at 2 kHz, turns S_1 on, pulling point A from +100 v to ground. The 555, with the aid of the Q_4–Q_5 line driver/buffer, generates a waveform at the sync output that precedes the pulse to S_1 by 2 microseconds or so and thus is suitable for triggering a scope.

Because the voltage across C_1 cannot change the instant S_1 switches, point B also changes by 100 v, moving from ground to −100 v. Point B was clamped close to ground potential by D_1 during the charge period but is free to make negative excursions after the period ends. S_2 then turns on. The RC network connected to the gate of S_2 limits gate current to a safe value and allows the SCR to return to the off condition when required. With S_2 on, points B and C assume the same potential of −100 v. Because C_2 is charged to 100 v, point D is pulled to −200 v.

The cathode of S_3, which is connected to point D, also assumes a value of −200 v, while the gate is at −100 v for a brief instant. S_3 thus turns on. In a like manner described above, point F is pulled to −300 v. The fall in voltage from 0 to −300 v happens in 20 to 30 μs, then decays back to zero at a rate determined by the output load resistance and capacitance. D_4 has been incorporated to isolate the particular receiver used in the system from any noise generated in the pulser's high-voltage



Pulsed tripler. Circuit generates 300-V pulse without the benefit of step-up transformer by charging capacitors $C_1 - C_3$ in parallel from 100-V source and then discharging them in series. Output has repetition rate of about 2 kHz and a rise time of only 20 to 30 ns.

supply and also to minimize the loading of the receiver by the pulser during receive (echo) time slots. The high-speed, low-voltage diode used for D_4 is adequate in most cases, since it never needs to stand off more than a few volts unless a highly reactive echo signal is reflected back into the pulser. The resistor at the output of the circuit provides a dc return path for the output pulse.

The use of slow diodes for D_1–D_3 does not preclude obtaining pulses of fast rise times at the output. Because C_1–C_3 are fully charged when a pulse is commanded, there is practically no current flowing through D_1–D_3; hence, there are no stored carriers.

Additional voltage-multiplying stages may be added as required, using the technique described here. The rise time at the output will increase slightly for each new stage added. □