LED Top with Special

Spin the top to display programmed text

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If you fit a line of LEDs on a circular PCB and power them on continuously, they generate rings of light when the board is spun. If you add a microcontroller, you can use the same set of LEDs to obtain a more interesting effect by generating a 'virtual' text display. This article also describes a simple technique for using the Earth's magnetic field to generate a synchronisation pulse. The potential applications extend from rotation counters to an electronic compass.

Do you still remember your secondary-school physics classes? Some students found them very relaxing, while others (which presumably includes many of our readers) probably recall the following situation: a free-hanging loop of wire is suspended in the magnetic field of a horseshoe magnet. The teacher causes a DC current to flow briefly through the loop of wire, and it moves to one side and then back as though pushed by an invisible hand. The teacher then tells you that the operating principle of the electric motor is based on this phenomenon.

After you had more or less accepted this remarkable fact, the next physics class brought yet another surprise: the teacher said that the effect also worked in the opposite direction. This time, he connected a sensitive moving-coil meter to the loop of wire instead of a current source as before, and then he moved the loop back and forth in the magnetic field. Each movement of the loop caused a deflection of the meter pointer. He concluded this lesson with the words, 'This is the operating principle of an electrical generator'.

Now you may be wondering what this would-be generator has to do with our LED top. Let's briefly recall another version of the above scene: a coil is rotated between the arms of a horseshoe magnet, and at the same time a sinusoidal trace appears on the screen of an oscilloscope connected to the coil.

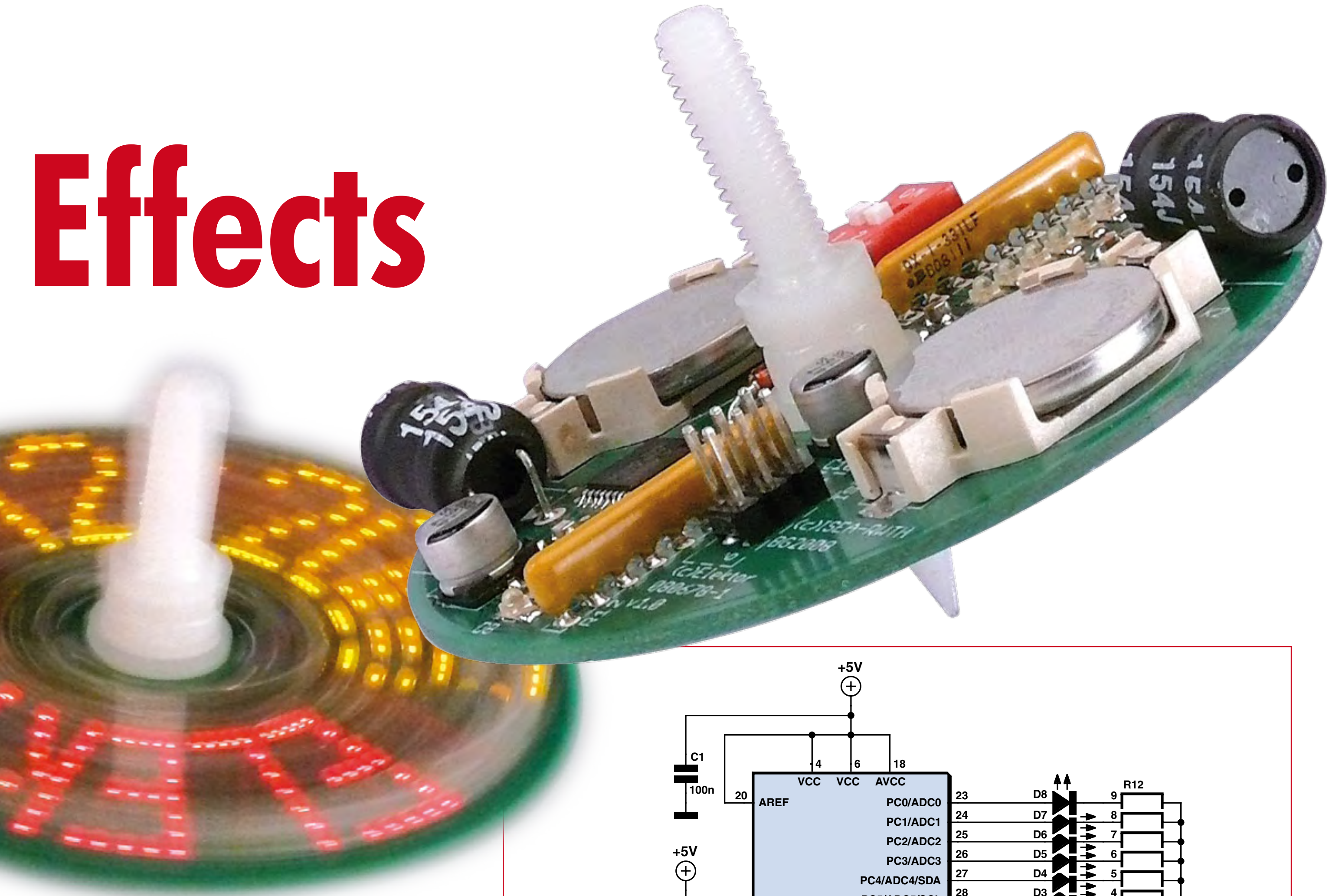
The top described here includes a small coil, which is located in the Earth's magnetic field instead of the field of a horseshoe magnet. To put it more precisely: when the top spins, the coil rotates in the horizontal component of the Earth's magnetic field. If the speed of rotation is constant, the voltage induced in the coil is sinusoidal – in other words, the coil acts as an electrical generator. Of course, the Earth's magnetic field is very weak; the horizontal component used here has a strength of less than 20 μT in Central Europe. The generated voltage is proportional to the enclosed area of the coil and the number of turns. There are upper limits to both of these quantities, since the coil must fit in a top that can be spun by hand. To avoid the effort of making a hand-wound coil, here we use a commercial fixed inductor. Naturally, the amplitude of the voltage is also proportional to the speed of rotation, and thus to the skill of the user. The coil voltage that is needed for this application is on the order of 50 μV.

Concept

Moving LEDs driven by rapidly changing signals have become relatively popular in recent years. *Elektor* has also published construction articles for devices with rotating LEDs that can display a virtual text or pattern in space [1]. They operate on the same principle as a raster-scan monitor. The LEDs move over a surface in space in the same way that an electron beam moves over the phosphorescent screen of a CRT. Both systems owe their operation to the latency of human visual perception. The persistence of the individual picture elements and their constant fast repetition produce the illusion of a coherent, stable image.

Most systems with rotating LEDs are standard products. They must overcome two problems that are inherently associated with the principle. The first problem is transferring electrical power to the rotating part, while the second problem is generating a suitable synchronisation signal.

Effects



The power transfer problem is often solved by using a special transformer consisting of a winding in the stationary part and another winding in the rotating part. The top described here does not have this problem, because it does not have a stationary part. Electrical power is supplied by batteries on the round circuit board, which are arranged symmetrically relative to the axis of rotation and rotate with the board.

For synchronisation, it is necessary to recognise when the board has completed a full rotation (one spin of the top). This is essential if the objective is to display a stationary image. In the commonly used designs with a stationary part, an IR light beam or a Hall sensor is used to generate a pulse once per rotation. This solution is very exact and easy to construct, but generating a synchronisation pulse is much more difficult with a top that does not have a stationary external reference point. Costly acceleration sensors or angular

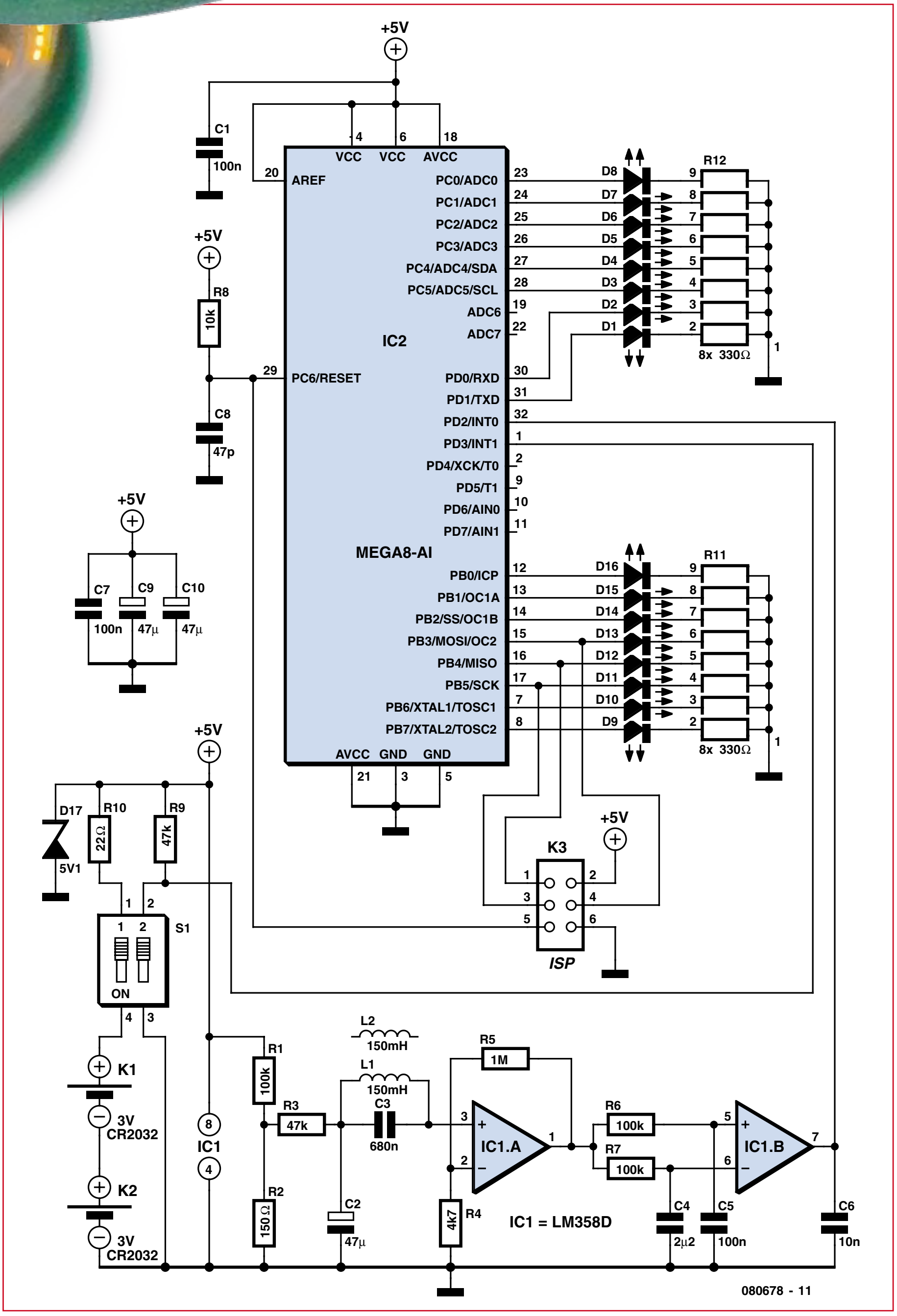


Figure 1.
The circuit of the LED top essentially consists of an Atmel ATmega8 microcontroller linked to an opamp circuit that generates the synchronisation signal.

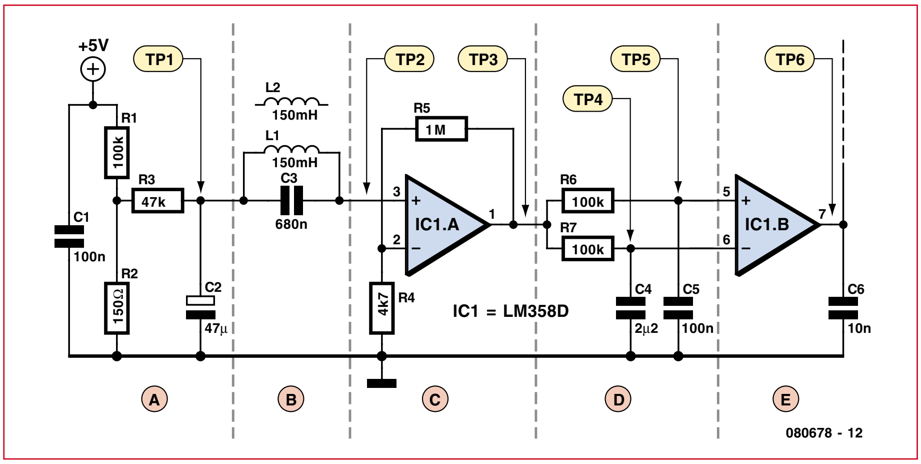


Figure 2. For the sake of clarity, the analogue portion of the circuit is shown separately here, divided into five functional parts (A to E). The signals shown in Figures 3 to 5 were measured at the test points marked in this diagram (TP1 to TP6).

velocity sensors are also of no use here. As previously mentioned, the sensor used with this top is a small, inexpensive inductor spinning in a local, homogeneous magnetic field. For example, the magnetic field could be the Earth's magnetic field.

The top will also work just as well if you hold a permanent magnet next to it. With appropriate amplification and phase comparison of phase-offset signals, a square-wave signal suitable for triggering a microcontroller interrupt can be generated from the small, induced sinusoidal voltage.

Circuit

The schematic diagram of the LED top (**Figure 1**) essentially consists of an Atmel ATmega8 microcontroller linked to an analogue circuit that generates the synchronisation signal. The microcontroller (IC2) drives two LED strips, each with eight SMD LEDs. The LED currents are limited by resistance networks. The rest of the digital portion of the circuit corresponds to the usual minimum configuration of an Atmel AVR microcontroller, with a power-on reset network (R8/C8) and an ISP connector (K3), which can be used to load the software into the microcontroller. Capacitor C1 is intended to decouple HF interference from the analogue portion.

The power supply of the circuit has been kept very simple. The two CR2032 cells wired in series provide a nominal voltage of 6 V. The combination of R10 and D17 (a 5.1-V Zener diode) limits this to a value that the microcontroller can handle. Battery utilisation is fairly good, since the circuit will continues to operate until the microcontroller stops running at around 3 V. The supply voltage is buffered by the parallel combination of C9 and C10, which provide a capacitance of around 100 µF. This is divided between two capacitors to maintain a balanced weight distribution on the rotating PCB.

For the sake of clarity, the analogue portion of the circuit is shown separately in **Figure 2**, divided into five functional parts (A to E). Part A supplies the left lead of inductor L1 (at TP1) with a constant voltage of 7.5 mV via R3 and buffer capacitor C3. This voltage is produced by a voltage divider with

Listing

Main algorithm for rotation detection in the LED top

```
ISR (INT0_vect)
{
   // rising edge of the sensor pulse
   current_round_time = current_round_time_zaehl;

   // counts the duration of the last round in ms
   // is starting a new round realistic?
   (80% of the time of the last round)
   if (current_column > (column_number*8)/10) {
        // here: adopt lap time for new co-
   lumn timing, Timer1 runs with 1MHz
        timer1_startvalue =
   1000/column_number*current_round_time;
        current_column = 0;
#ifdef ROTATION_COUNTER
        if (game_status == GAME_ONGOING)
                number_of_turns++;
#endif // ROTATION_COUNTER
   }

   // clear elapsed time meter for the
   time in ms between two rising edges
   current_round_time_zaehl = 0;
}

ISR (TIMER0_OVF_vect)
{
   // this routine should be cal-
   led every millisecond
   TCNT0 = 255 - 125;

   // increment the cyclic coun-
   ter (without overflow)
   if (current_round_time_zaehl < 255) {
        current_round_time_zaehl++;
   } else {
        current_round_time_zaehl = 255;
   }
}

ISR (TIMER1_OVF_vect)
{
   // calling time is based upon the actual speed
   TCNT1H = 255 - (timer1_startvalue >> 8);

   TCNT1L = 255 - (timer1_startvalue & 255);

   // next column, or missed syn-
   chronization condition,
   // then new start: time-controlled
   if (current_column < column_number) {
        current_column++;
   } else {
        current_column--;
   }
}
```

its associated decoupling capacitor. Part B has another decoupling capacitor and the sensor coil L1, in which the voltage is induced. With typical coil characteristics, rotation in the Earth's magnetic field generates an induced sinusoidal voltage with an amplitude of around 50 μV. The induced 50-μV AC voltage is present at TP2, superimposed on the 7.5-mV DC voltage (see **Figure 3**). Inductor L2 is not connected to the circuit; it is only present on the board for balancing.

The third part (C) of the analogue portion contains opamp IC1a, which is configured with R4 and R5 as a non-inverting amplifier with a voltage gain of 200. This yields a sinusoidal voltage with an amplitude of 10 mV at the output of the opamp (LM358 pin 1, or TP3), superimposed on a DC voltage of 1.5 V (**Figure 4**). This voltage forms the input signal of part D of the circuit, which consists of two passive low-pass filters (R6/C5 and R7/C4). In addition to attenuating HF interference, which is unavoidably present when the top is used close to a source of electromagnetic interference such as a PC, the differing time constants of these filters (C4 is much larger than C5) produce a phase offset between the filter outputs at TP4 and TP5. This can be seen graphically in **Figure 5**.

These two sinusoidal signals are fed to the inputs of IC1b (pins 5 and 6) in part E. This opamp does not have any feedback, so it operates as a comparator with its full open-loop gain and compares the two phase-offset sinusoidal signals on its inputs (which have nearly the same amplitude). This comparison causes the opamp's output to be High when the voltage on the non-inverting input of the opamp (TP5) is higher than

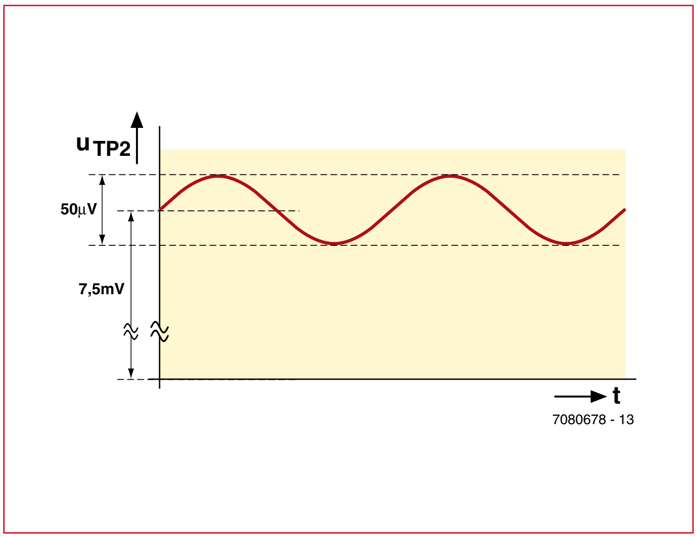


Figure 3. The signal voltage induced in inductor L1 by the Earth's magnetic field is only around 50 μV.

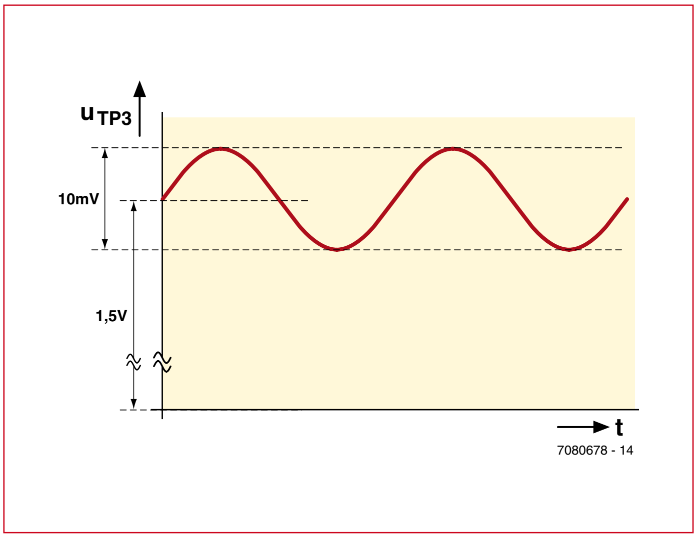


Figure 4. The signal after amplification by opamp IC1a.

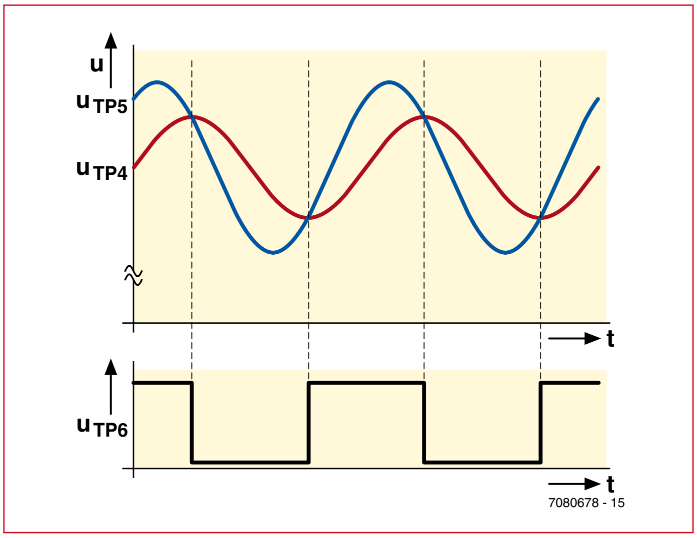


Figure 5. Comparator IC1b generates a pulse signal from the phase-shifted outputs of the RC networks. The pulse signal drives the interrupt input of the microcontroller

the voltage on the inverting input (TP4). This is the case for half of the sine-wave period, and thus for half of the top rotation. The output of this opamp is fed directly to the interrupt input of the ATmega8 (IC2), where each rising edge indicates the start of a new rotation.

Assembly

Fitting the components on the circular PCB (**Figure 6** and **Figure 7**) is very easy if you use the parts kit available from the Elektor Shop. This is because all the SMD components are pre-assembled, so you only have to solder the leaded components to the board. You can adjust the weight balance of the components on the board by slightly shifting the positions of the leaded components, in order to obtain the least amount of wobble when the top spins.

If you want to assemble your own board from scratch, pay careful attention to the polarity of the SMD LEDs. Study the data sheet closely, and if necessary test the LEDs with a 9-V battery and a 1 kΩ series resistor. Of course, proper orientation is important for all components that have a specific orientation.

For the axle of the top, we used two plastic (polyamide) M6 screws with good results. We glued the heads of the screws together to form an axle, and then fitted the PCB of the top to the lower screw between two washers and secured with a nut. It's a good idea to use a normal pencil sharpener to put a point on the lower plastic screw in order to reduce friction so the top will spin longer.

Software

The software for the LED top was written in AVR Studio [2], which is available from Atmel for free download via

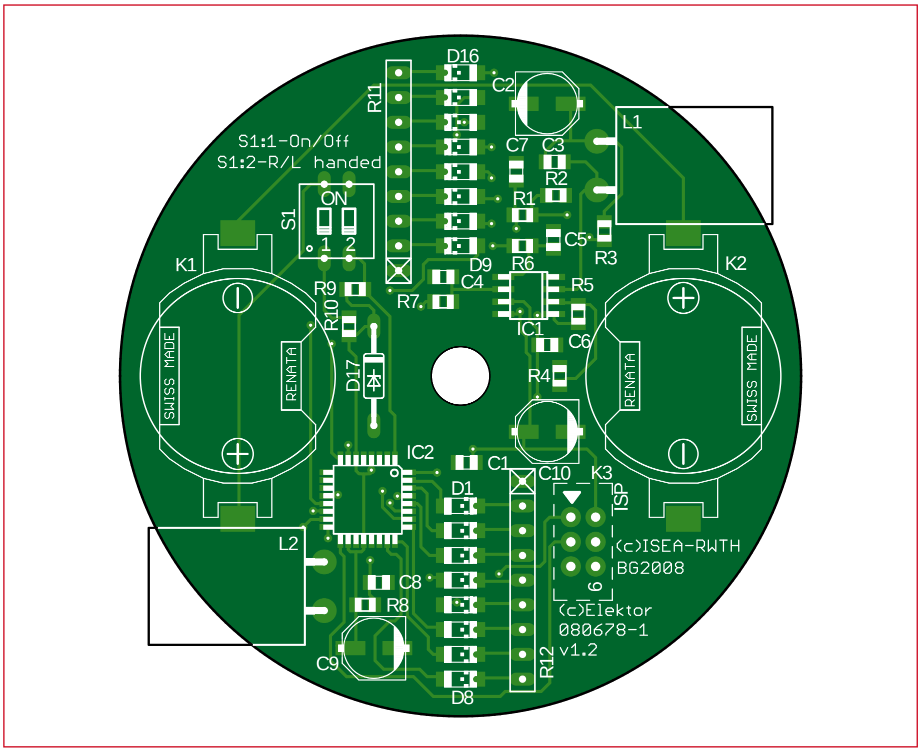


Figure 6. The circular PCB for the top is available with the SMDs pre-assembled.

the Internet. The C code was compiled using the GCC cross-compiler. The code can be loaded into the ATmega8 via the ISP connector on the PCB. Operation of the code is essentially interrupt-driven. After the initialisation and generation of the display matrix, the main routine constantly tests whether the running condition is still satisfied. It is satisfied if the duration of one rotation falls within certain range, which can be configured using constants. The core algorithm for the detection of a complete rotation is described briefly below. It is also shown in the listing, and it comprises three interrupt handlers that service the external interrupt and two timer interrupts. The rest of the program should be self-explanatory and adequately commented.

The hardware interrupt routine becomes active when a rising edge is detected on the INT0 pin. After this interrupt is triggered, the ISR(INT0_vect) routine first checks whether the time of the last rotation is plausible. The start of a new rotation is only plausible if the duration of the previous rotation is at least 80% of the time of the new rotation. Next, the exact time for a new column is determined from Timer1, which runs at 1 MHz.

This time must be adjusted constantly because the top spins slower and slower while the program is running, so the columns must be displayed for a slightly longer time on each rotation. The variable current_column is set to zero, which causes the image to be built up again from the first column of the display matrix. The variable current_round_time_zaehl uses Timer0 to count the time between two rising edges for the purpose of plausibility checking, and it is also reset to zero here. The timer interrupt routine ISR(Timer0_OVF_vect) is called every millisecond under time control, and it increments (without overflow) the counter for the duration of the current rotation (current_round_time_zaehl).

Timer1 and its routine ISR(Timer1_OVR_vect) are used to increment the columns in the display matrix. This timer is first updated with the time to the next call (which means the distance between the two columns) by adjusting it according to the current rotation speed of the top as determined for the last rotation. If the synchronisation pulse is missing, which means that the external interrupt does not occur at approximately the expected time, a new rotation can be started here under purely time-based control. However, practical experiments have shown that this is not necessary, so all this does is to prevent an overflow of the variable current_column.

The full source code is available on the project page for this article at www.elektor.com for free download. After downloading the source code, you can easily modify the text to be displayed, which is contained in a string in the

COMPONENTS LIST

Resistors
All SMD 0805, 1 %, unless otherwise indicated
R1,R6,R7 = 100kΩ
R2 = 150Ω
R3,R9 = 47kΩ
R4 = 4kΩ7
R5 = 1MΩ
R8 = 10kΩ
R10 = 22kΩ
R11,R12 = 330Ω 9-pin SIL resistor array

Capacitors
C1,C5,C7 = 100nF (SMD 0805)
C2,C9,C10 = 47µF 16V (SMD electrolytic)
C3 = 680nF (SMD 0805)
C4 = 2µF2 16V (SMD 0805)
C6 = 10nF (SMD 0805)
C8 = 47pF (SMD 0805, NP0)

Inductors
L1,L2 = 150mH fixed inductor, Q_{min} = 50, RM5 (12x16 mm), e.g. Fastron 11P-154J-50 (Reichelt.de # L-11P 150M)

Semiconductors
D1-D8 = LED, red, 628nm, SMD 1206 with lens, e.g. Kingbright KPTD-3216SURC (Reichelt.de # 1206K RT)
D9-D16 = LED, yellow, 588 nm, SMD 1206 with lens, e.g.. Kingbright KPTD-3216SYC (Reichelt.de # 1206K GE)
D17 = zener diode 5.1V 1.3 W (BZV85-C5V1)
IC1 = LM358 (SMD SO8)
IC2 = ATmega8-16AU (Atmel), SMD TQFP-32

Miscellaneous
S1 = DIP switch 2-way (MULTICOMP MCDS02, DIL04)
K1, K2 = CR2032 SMD battery holder (Renata SMTU-2032-1-LF, SMTU-2032-1, Reichelt.de # KZH 20PCB-1)
K3 = 6-way DIL pinheader, lead pitch 2.54mm (Tyco-AMP # 1241050-3 AMP)
Polyamide screw, M6x20 with nut and 2 washers
BAT1, BAT2 = Lithium button cell type CR2032
Kit of parts incl. SMD-populated board, Elektor SHOP # **071120-71**

header. After this, compile the entire source code with the widely used GCC compiler and load it in the top via the ISP port. Leave the fuse bits in the ATmega8 set to their factory default values (1 MHz internal clock). The microcontroller in the parts kit available from the Elektor Shop is pre-programmed, so the top is ready to use immediately after assembly and will display a demo text. However, you can replace the program code at any time with newly compiled code containing your own text.

Applications

Of course, you are free to choose the text to be displayed by the top – anything from 'Hello World' to a company name or a short slogan is possible. With 'Happy Birthday' plus the name of the recipient, the top makes an ideal personalised birthday gift. You can also extend this idea to the pre-Christmas season.

By programming an additional timer in the ATmega code, you could implement a sort of miniature Advent calendar. For example, the top could display a nice phrase or the keyword for a little surprise on each day of Advent. A software version with a rotation counter has also been developed to cause the top to generate a 'live' display of the number of rotations it has completed. You could then organise a competition to see who is the best top spinner (such a competition was staged live at the Elektronika show in Munich last November). At the time of publication of this article, several tops with this software will in action in the Elektor booth at the electronics trade show in Munich, where they form the basis for a sporting competition. Several hundred rotations can certainly be achieved, and the daily champion among the top spinners will receive a prize – a LED top, of course!

Storing the results in an internal EEPROM is another conceivable extension. In addition to the number of rotations, it would also be possible to display the angular velocity or other derived quantities. Another effect that illustrates the basic principle of the circuit can be achieved by displaying the letters 'WSEN' with a space between each pair of letters.

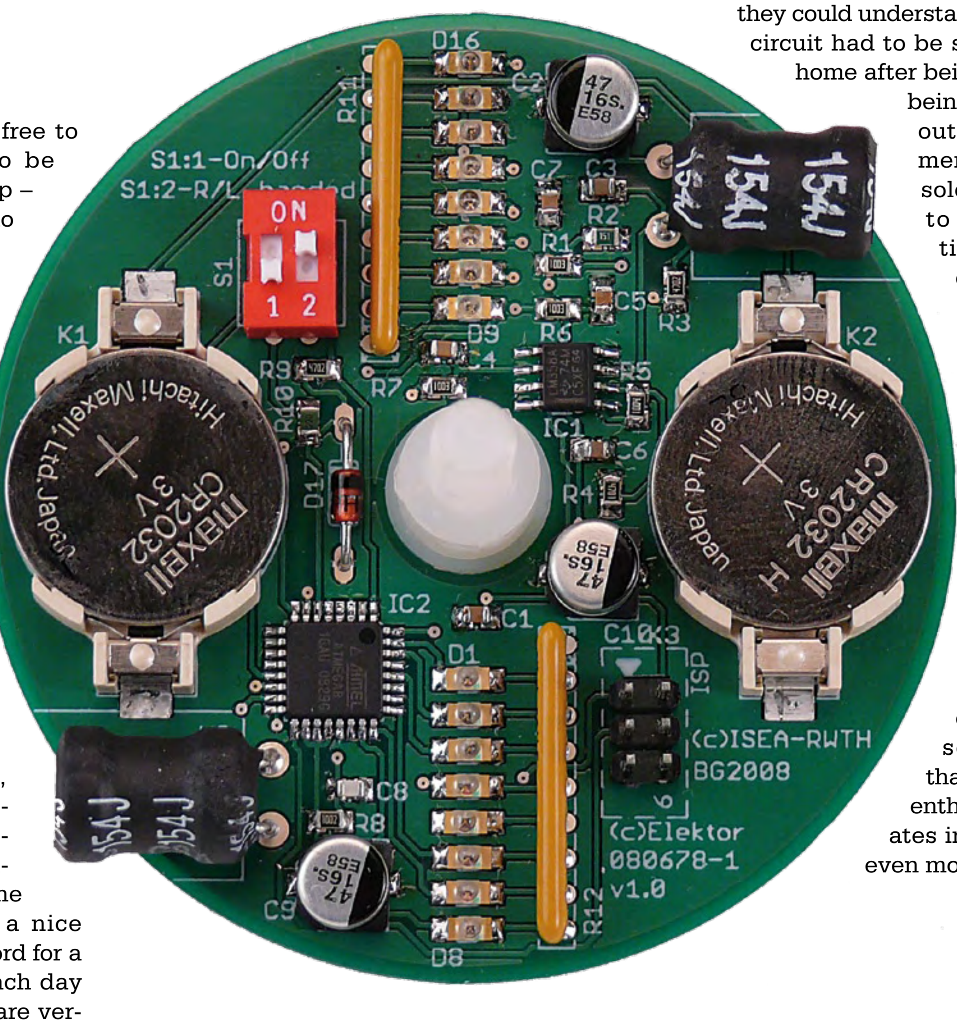


Figure 7. Top view of the spinning-top PCB. Only one of the two inductors is used in the circuit. The second one is only present for mass balance.

This gives you a sort of compass that shows the observer the orientation of the currently dominant magnetic field. Although there may be devices that are simpler and more suitable for showing compass directions on a desert expedition, they certainly do not create the same sense of marvel as our spinning top compass.

Conclusion

When Michael Faraday investigated the basic principles of induction in 1831, he presumably did not envisage that one day they would be applied to an LED top. Your secondary-school physics teacher was probably equally unsuspecting. The top was developed for students in a hands-on group at the Institute for Power Electronics and Electrical Drives of RTWH Aachen, Germany [3], with the aim of offering first-semester students a circuit that even electronics neophytes could assemble and whose operation they could understand. In addition, the circuit had to be suitable for taking home after being assembled and being used there without elaborate equipment (power supply, soldering iron or PC) to display a function that everyone could understand. If in addition the theoretical contents of the lectures (including the principle of induction, non-inverting operational amplifiers, and C programming) can be incorporated in a pocket-sized project, experience from past semesters shows that this often creates enthusiasm and generates interest in learning even more.

(080678-1)

Links and references

[1] 'Rotating Message Display with LEDs and an AVR Micro', Steffen Sorge, Elektor January 2007.

[2] AVR Studio: www.atmel.com/avrstudio

[3] ISEA: www.isea.rwth-aachen.de/en