AN EASY-TO-BUILD ELECTRONIC SPINTOP FOR YOUNG ENGINEERS

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ABSTRACT
A spintop with a LED text displayed during the spinning process is an attractive toy that can be built in an afternoon by youngsters in order to attract offspring for engineering. Except for the LEDs the only other semiconductor part needed is a TI MSP430 on the spinning PCB. The rotation is detected or rather estimated using a discrete inductance coil measuring the magnetic field of the Earth. The software on the microcontroller contains a PLL to stabilize the multiplexing of the LED line text. Different modes such as plain text, compass indicating W-N-E-S, and competition mode with a score of the achieved revolutions kept in memory make the gadget a device in high demand.

1. INTRODUCTION
In an effort to engage more young people into the field of engineering, many institutions on all continents have started programs to foster STEM (science, technology, engineering, and mathematics) or MINT (mathematics, information sciences, natural sciences, and technology) interest. One such program is an electronics course aimed at grade-7 and grade-8 pupils where the attendants build hardware projects such as a sound box for their smartphone, a PNA (personal navigation assistant), a game console, or a microcontroller board in order to gain experience in embedded computing. Whereas the latter is a generic platform that allows the implementation of many applications, the spintop has been designed as an electro-mechanic µController application with an immediate amazement of the observer in mind. Depending on the soldering skills of the pupil, an SMD or a THT version can be assembled, soldered and programmed in a single session lasting two to three hours.

2. USING AN EXTERNAL REFERENCE: EARTH’S MAGNETIC FIELD
The function of the spintop is fairly easy to understand. During each rotation, the LEDs always light up at the same position. In that manner, if the rotational frequency is faster than what the eye can realize, the LEDs create the illusion of a stationary text.

In order to know its exact position (or angle), the spintop needs an external reference that is stationary. In this case, the Earth’s magnetic field has been chosen as the reference since it has the main advantage of being globally present. As it can be seen in the picture visualized in Fig. 1 and the schematic overview in Fig. 2, the number of components on the spintop’s PCB has been reduced to a bare minimum. This not only simplifies the assembly of the PCB but also demonstrates that it is possible to develop an addictive toy even with a small µController and some few parts.

Figure 1: The spintop in action (SMD version)

Figure 2: The circuit contains only a few components: a coil, an MSP430(F2013), 7 LEDs, a push button and a 3V lithium coin cell.

As visualized in Fig. 3, the Earth’s magnetic field is approximately the field of a magnetic dipole placed at the center of the Earth. Unlike a bar magnet, the Earth’s magnetic field is generated by a geodynamo [1]. In navigation, the magnetic compass is used as a direction-finding instrument, which determines the direction of magnetic North. Actually, there is an angle variation relative to true North, which is called declination. This error is dependent on the actual geographical position and the location of the magnetic poles as they move over time. The current declination error can be read in [2].

Further, the inclination angle between the magnetic field and the Earth’s surface is between 0 and 90 degrees, at the equator and at the magnetic poles, respectively. The reading of a compass would be falsified by the inclination if its needle would not be level. In this case, this is not critical as the spintop levels itself out.
3. SIGNAL ACQUISITION

While rotating in the Earth’s magnetic field, the coil produces a sinusoidal voltage as visualized in Fig. 4(a). This effect is called electromagnetic induction [3] and is the same as in every electromagnetic generator. Due to the low field strength, the induced voltage of the coil has an amplitude of less than 1 mV at a nominal revolution speed of 30 rev/s.

In order to resolve such a small signal, the internal 16-bit sigma-delta analog digital converter (ADC) of the MSP430F2013 [4] has been used. If configured appropriately [5], the ADC exhibits a resolution of 0.57 µV/LSB (!) at a sampling rate of 1 kHz and over an input voltage range of 37.5 mV. This provides a sufficient dynamic range that covers both very low and very high revolution speed scenarios.

The coil eventually also picks up some external interferences produced by electronic devices nearby such as noisy switching power supplies. Those disturbances can be effectively mitigated by low-pass filtering the signal prior to analog-digital conversion. In order to simplify things, a simple capacitor has been connected in parallel to the coil to form a second-order LC low-pass filter as visualized in Fig. 5.

The (complex-valued) frequency response of the low-pass filter is defined by

$$H(j\omega) = \frac{V_c}{V_t} = \frac{1}{j\omega C_p} + \frac{1}{j\omega L_s + R_s}$$

(1)

where \( L_s = 100 \text{mH} \) is the inductance of the coil, \( R_s = 420 \Omega \) is the ohmic resistance of the coil and \( C_p \) is the capacitance of the external capacitor. The angle of \( H(j\omega) \) is called the phase response

$$\phi(\omega) = \arg(H(j\omega)) = -\frac{\pi}{2} - \arctan\left(\frac{\omega L_s - \frac{1}{\omega C_p}}{R_s}\right)$$

(2)

and expresses the phase shift applied by the filter on a sinusoid with a certain angular frequency \( \omega \). In this case, a frequency-dependent phase shift is unwanted since it creates an angle misalignment between the reference signal and the magnetic field. This would be especially annoying within the compass mode, where the cardinal points shown should always indicate into the right directions. A tradeoff between low cut-off frequency and low phase shift had to be made. With \( C_p = 100 \text{nF} \), the resulting phase shift at a nominal rotational speed of 30 rev/s is \( \phi(2\pi \cdot 30 \text{Hz}) = -0.45 \text{deg} \) and the cut-off frequency is below 2 kHz.
4. ESTIMATION OF THE ANGULAR POSITION

The amplitude of the induced voltage is proportional to the rotational frequency. In order to get an amplitude-independent reference point estimation, the zero-crossing on the positive slope of the signal has been chosen, as shown in Fig. 4. This corresponds to the instant when the inductance coil aligns itself to the magnetic field lines during the rotation. Depending on the actual sense of winding of the coil used, the spintop points to either magnetic north or south. Due to the relatively low sampling rate of the ADC, the zero-crossing instant \( t_c \) has to be interpolated from the nearest two samples as visualized in Fig. 4(b). The interpolation is done by applying the intercept theorem:

\[
t_c = t_1 - a_1 \frac{t_2 - t_1}{a_2 - a_1},
\]

where \( t_1 \) and \( t_2 \) are the sampling instances and \( a_1 \) and \( a_2 \) are the amplitudes of the measured samples. The actual rotational frequency may be derived from the interval time between two subsequent reference points (zero-crossings).

In order to get a more accurate and stabilized estimate of both the actual rotational phase and frequency, a software phase-locked loop (PLL) has been implemented on the µController. The block diagram of the adopted PLL can be seen in Fig. 6.

![Block diagram of the phase-locked loop (PLL)](image)

Figure 6: Block diagram of the phase-locked loop (PLL)

The main function of the PLL is to produce a clean (preferably noise-free) replica of the development of the rotational phase, frequency and the derivative of the frequency. The phase detector compares the measured phase at each reference point (pos. zero-crossing) with the current phase of the internal numerically-controlled oscillator (NCO). The difference (phase error) is fed through a second-order low-pass filter, whose main task is to reduce the noise of the error signal. The output of the filter is then fed into the NCO as an estimate of the rotational frequency. The feedback from the NCO to the phase detector closes the loop.

The performance of the PLL has been verified by simulation. The simulation results of a typical scenario is visualized in Fig. 7. The behavior of the simulated PLL also seems to match well with real measurements.

5. MULTIPLEXING OF THE LED LINE TEXT

As soon as the spintop has an accurate estimate of its rotational phase, it begins to output the text on the LEDs. The seven LEDs are arranged in a closely spaced column near the outer edge of the PCB. The text (or display area) can be either composed by predefined 7×5-pixel characters as shown in Fig. 8 or can be freely defined on a pixel-by-pixel basis.

The total available display area consists of 7×256 monochrome pixels. Depending on the character spacing, a total of 32, 36 or 42 characters can be displayed. The seven LEDs, which are placed along a straight line, write a column at a time. The 256 columns are evenly distributed along the circumference of the PCB and are output consecutively by the LED line as it rotates. The dwell time of each pixel column is derived from the rotational frequency, which is estimated by the PLL. Since the spintop slows down as time goes on, the multiplexing has to slow down too in order to make the illusion of a constant text width.

6. BALANCING THE COMPONENTS

An important aspect that had to be considered during the design of the layout is the balancing of the PCB and its components. For the PCB to be in complete balance, both static and dynamic balancing has to be performed. In order to get a static balance, the centre of gravity of the whole spintop must be on the axis of rotation. Following the example in Fig. 9, that means that the torque at the axis caused by the masses \( m_t \) needs to counterbalance:
where \( g \) is the Earth’s standard acceleration, \( m_i \) is the mass of the \( i \)-th object and \( \vec{r}_i \) is a vector orthogonal to the rotation axis of the PCB and points to the centre of mass \( i \).

Further, the PCB is in dynamic balance if there is no resulting turning moment along the axis. By fixing the axis at point \( A \), the condition that has to be met is:

\[
\sum F_{Gi} \cdot \vec{r}_i = g \sum m_i \cdot \vec{r}_i = 0 \,.
\]

(4)

where \( \omega \) is the angular velocity of the rotating PCB and \( d_i \) is the distance between the centre of mass \( m_i \) and \( A \). And analogously for point \( B \):

\[
\sum F_{Bi} \cdot (l - d_i) = l \sum \vec{F}_{Bi} \cdot \vec{d}_i = 0 \,.
\]

(5)

As it can be seen in (4) and (5), \( g \) and \( \omega \) are not relevant as they can be canceled. By combining Eqs. (4) to (6), they can be reduced to the following two constraints:

\[
\sum m_i \cdot \vec{r}_i = 0 \,.
\]

(6)

7. PROGRAMMING

Actually, the course participants begin to learn the C language and to program a MSP430 with a dedicated µController board. They write the source code with SciTE [9], an easy-to-use and configurable text editor. The preconfigured text editor enables the use of simple shortcut commands that invoke makefile targets containing all the needed procedures to compile, link and download the code.

In the case of the spintop, the device serves primarily as a demonstration tool during the course to explain the various electrical and mechanical challenges. But interested pupils have the possibility to write part of the firmware by themselves, e.g. the multiplexing of the LED text. However, most people just want to solder their spintop and download an existing firmware with a customized text. Thus, an additional GUI software has been written in Python language and bundled with mspdebug, which is used to download the firmware with the TI ez430-F2013. This PC program can even be used by people without any programming skills as there is no need of installing the programming tool chain or writing any lines of C code. The software includes a precompiled firmware for the MSP430 in Intel HEX format, which conveys machine code in ASCII text form. The part of the .hex file containing the display data will be overwritten by the software prior the download to the µController. The actual location of the data array in the .hex file can be found out by looking at the .map file generated by the linker, which includes all starting addresses of functions and static variables.

As it can be seen in Fig. 10, the software allows the export and import of that display data to/from a bitmap image, which can be edited with any image painting software. This allows the easy inclusion of custom drawings or symbols to the visualized text. The source code of both the firmware and the GUI software are available for download from our dedicated website.

![Figure 10: A GUI program to conveniently edit the text and program the spintop](image-url)
The firmware of the spintop includes three different modes, which are visualized in Fig. 11. The modes can be selected by repeatedly pushing the button. The *plain text* mode displays the static text, which can contain up to 42 characters. The *counter* mode displays on the one side the current number of revolutions done since the rotation started and on the other side the best score achieved so far. The *compass* mode displays the cardinal points.

![Modes](a) Plain text  (b) Counter  (c) Compass

Figure 11: The three available display modes

After an idle time of 20 seconds, the spintop automatically switches off the LEDs and enters LPM4, which is the deepest low-power mode of the MSP430. Once in the sleep mode, it can only be awakened by an external interrupt like pushing the button again. Thus, there is no extra power switch needed on the PCB.

8. OUTLOOK

The TI MSP430F2013 µController currently used for the spintop could be exploited very efficiently. Not only the I/O ports are all occupied by external components but all internal hardware components except the universal serial interface (USI) have been used. The sigma-delta ADC is used for acquiring the small induction voltage, the timer and its two capture/compare registers are used for round and pixel timing, the watchdog timer is used to measure the 20-second idle time and the flash memory is 99% full, i.e., 20 Bytes of 2048 remaining. In order to pursue some further ideas, the next larger type of TI MSP430 will have to be involved, e.g. the TI MSP430AFE253. One idea to follow is an optical interface for programming the LED message. Simple flashing of the PC screen will transfer the message from the PC to the spintop, which sits close to the PC. To keep the bill-of-material short, the existing LEDs may be used as light sensors to detect the flashing. A custom flashing image may be edited and created online in a browser. That way, no additional programming hardware would be needed.

9. CONCLUDING REMARKS

An easy-to-build spintop displaying a LED message, serving as a compass or as a competitive gadget using an MSP430 has been presented. The achievable number of revolutions depends on the skill, a typical number is >1500, starting at roughly 45 rev/s. The PLL, the multiplexing text and the administration of the three modes fit all in a 2048 Bytes flash memory. The design is released under the GNU General Public License, which encourages the studying and enhancement of the device. From our website dedicated to the electronics course, not only the full layout and source code can be downloaded but also assembly sets of the spintop as visualized in Fig. 12 and other projects can be obtained: [http://www.electronics4you.cc](http://www.electronics4you.cc)

![PCBs](a) SMD version of the spintop  (b) THT version of the spintop

Figure 12: The two available PCB layouts

REFERENCES


