Multidisciplinary Senior Design
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York 14623

lProject Number: P13321

LEVITATION CLOCK

Trong Duong
Electrical Engineering

Kevin Fronczak
Electrical Engineering

Holden Sandlar
Electrical Engineering

Abstract

This paper outlines the design and creation of a clock that utilizes magnetic levitation as a time display mechanism. The clock operates by using an array of four solenoids that are used to propel small, lightweight, magnetic objects vertically. Each object can be in one of two states: on or off. This allows the user to be able to read time in a binary fashion such that if an object is floating, it is a bit value of '1', and if it is not floating, it is a bit value of '0'. By using four solenoids and four objects, the numbers 0 through 15 can be represented which enables the clock to display a 12-hour format. The minutes are displayed abstractly using an RGB LED to show time in 10-minute increments with six distinct colors representing the 10-minute increments.

Introduction

The levitation clock is a clock that uses magnetic properties to levitate objects and display time. The clock's main purpose is to appear aesthetically pleasing and appear to be "magical", which means that levitation mechanism is ambiguous to the viewer. The dedicated clock IC used to keep track of the time is very accurate and can be set using the three buttons on the rear of the clock. The minutes within the hour are shown by the use of color lights on the bottom of the frame. These colors are generated from an RGB LED, which displays certain colors for different minutes within the hour.

Design Process

Due to the artistic nature of the device, it was crucial to design a frame that would adequately mask the underlying levitation mechanism in order to maintain a certain degree of 'mysticism' while, at the same time, be aesthetically pleasing. However, there was also the concern of technical limitations involved in magnetic levitation since, as (1) describes, levitation height is inversely proportional to distance squared which results in a very limited operating range for a given mass.

$$F = \frac{(N \cdot I)^2 \cdot \mu_r \mu_0 A}{2d^2} \tag{1}$$

In order to circumvent this problem and still maintain a visually pleasing product, a choice was made to display the hours in a binary format using four individual solenoids to lift small, lightweight, and magnetic objects vertically within a transparent cylindrical container. The container permitted the design to neglect the horizontal component of the magnetic field lines intrinsic to a solenoid, as shown in Figure 1, which vastly simplified the required circuitry. Figure 2 shows an early sketch of this device displaying the time of five hours.

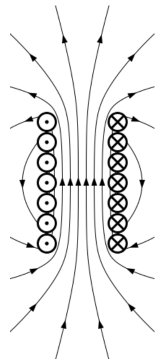

Figure 1: Magnetic Field Lines in a Solenoid

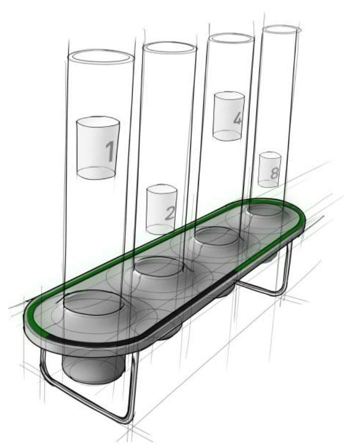

Figure 2: Early Levitation Clock Concept Sketch

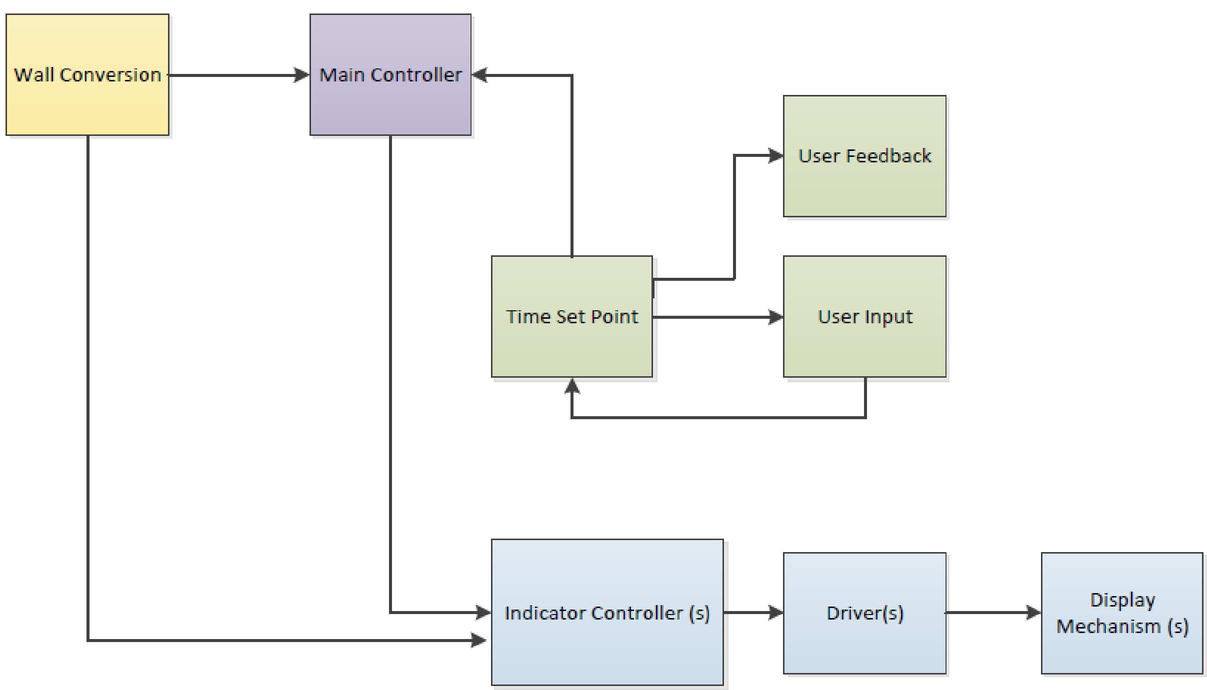

Figure 3: System Block Diagram

Once the concept was selected, system architecture was established. The system block diagram is shown in Figure 3. The design process for each sub-system block has been outlined in subsequent sections of this paper. The first main consideration was power distribution. In order to be a low-maintenance project, a decision was made to use an AC-DC supply so that the process of powering the device would simply involve plugging it into a wall outlet. However, in order to save time and comply with safety standards, an off-the-shelf converter would need to be purchased. Due to the product containing four solenoids, each capable of drawing 1 A continuous, the power supply would have to be able to supply a large amount of current which limited the choice of supplies to ones in the 12 V – 20 V range. This required further on-board DC-DC regulation in order to increase the efficiency of the regulators supplying the power to the solenoids. This had a secondary benefit in that the size and, likewise, the cost of the required regulator heatsinks could be shrunk significantly.

A concern introduced after design had already been underway was that, at this point, the clock could only be accurate to within an hour which, ultimately, makes it useless as device which displays time. As such, an elegant solution was proposed wherein a single RGB LED would be used so that the color being displayed would correspond to a certain time division. This choice was interesting, because rather than telling time via the position of an object, the user tells time based on the *color* of the display. This solution served two purposes: provide a method of increasing clock accuracy, and introduce a further artistic element which could increase the aesthetics of the piece. Table 1, below, shows the division of time based on LED color.

Color	**Time Division (Minutes)**
RED	0-9
ORANGE	10-19
YELLOW	20-29
GREEN	30-39
BLUE	40-49
PURPLE	50-59

Table 1: Color to Minute Division Table

PCB Layout

Two PCB layouts were required for this project: one for the main control board (Figure 5) and another for the user interface board (Figure 4). Both boards utilized two layers and were designed using EagleCAD Professional v5.11.0.

The Main Control Board featured the DC-DC Converter used to step down an external regulated 19 V Power Supply and distributed this new voltage to each individual solenoid regulator. The main control board also includes the RGB LED used for the minute display, as well as the RTC and microcontroller used to communicate with each part of the system.

The User Interface Board featured two dual-seven-segment displays and three tactile buttons with which the user can easily set the time. This board required its own 3.3V regulator in order to supply power to all of the ICs used to drive the seven segment displays, as well as the supply power to the seven segment displays themselves. Care was taken during layout to ensure that the position of the buttons and the displays made sense from an aesthetic and usability standpoint as this is the only interface the user has to communicate with the clock. Making the interface as seamless and intuitive as possible was of a very high priority. As such, the buttons were positioned directly to the right of the display with the first acting as a toggle to set the time, and the remaining two functioning as “Hour-Up” and "Minute-Up", respectively. Every component aside from the displays and the buttons, were placed on the back of the PCB so that side-wall mounting within the frame would be possible. This allows for all of the sensitive circuitry to be hidden from the end-user which was very important in order to ensure an aesthetically pleasing product.

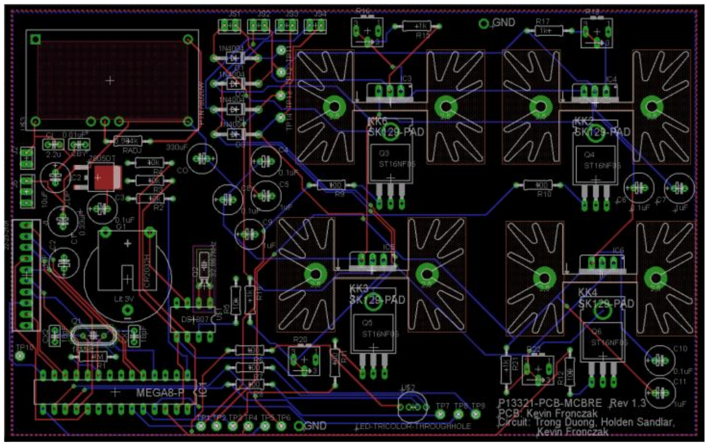

Figure 4: PCB Layout for Main Control Board

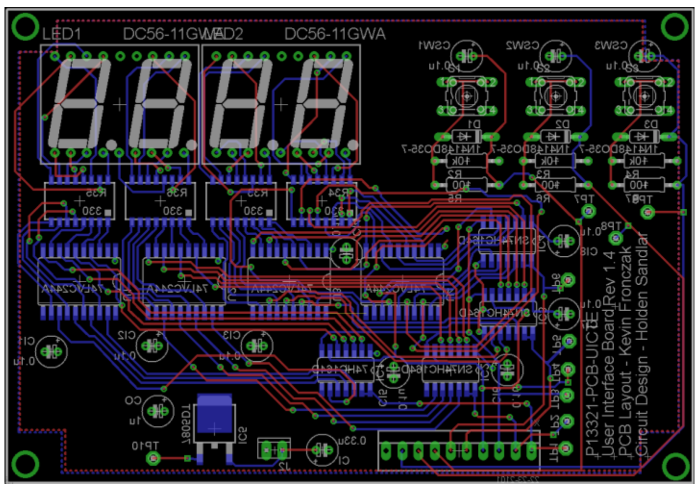

Figure 5: PCB Layout for User Interface Board

Power Distribution

Since the product is being powered from a 19V 4.7A wall supply, it was necessary to step the voltage down further so that power consumption (at, thus, heat generation) could be kept at a minimum. As such, a 7V Buck Converter was implemented. The resulting 7 volts power rail was distributed to the microcontroller through a 5V Linear Regulator, the User Interface Board through a 3.3V Linear Regulator, and each solenoid via an adjustable Linear Regulator. Stepping the voltage down from 19V to 7V enabled a power consumption savings in the adjustable regulators of roughly 9W on average for EACH regulator (so 36W total savings).

Main Controller

The Main Controller chosen was an Atmel ATMega328P. This choice allowed the use of the popular rapid prototyping development board Arduino UNO which allowed quick design changes to be made. The controller was then implemented on the PCB in order to minimize area consumption (by omitting unnecessary parts that are located on the development board). The only downside is the need for an Arduino boot-loader to be uploaded to the chip in order to properly utilize the PC-side software.

RTC Interface/Software Design

The Maxim Integrated DS1307 I^2C real-time clock module was selected for tracking the passage of time. The interface to the DS1307 is a standard I^2C two-wire communication protocol allowing for reads and writes of the internal registers. The device can be configured to compute time in either 12-hour or 24-hour format and can also track the date and year. All software interfacing was performed using the built-in Arduino I^2C library. The DS1307 also provides a secondary set of power pins designed to take input from a battery. A coin cell battery was included on the main board to ensure the user-entered time is not lost.

User Interface

The user interface for the clock was designed to provide an input mechanism for the user to set the time and an output mechanism for user feedback. This was accomplished using 7-segment LED displays to indicate the currently programmed time and three buttons for the user to provide input. It is necessary to drive this hardware from the main control board (where the RTC is located). To drive the hardware on the user interface PCB, four shift registers were used in a parallel configuration with their output tied to line drivers which drive the displays. This allows the main control board to shift in the appropriate data over the data cable to display any desired pattern (the current time) on the displays. A simple debounce circuit has been included on the UI PCB for all three buttons. The output of the debounce circuit is connected to the data cable and is received by the main control board.

Hour/Minute Display Software Implementation

All software implementation was done using the Arduino development environment and microcontroller programming was made possible through the use of an Arduino UNO development board. The hour and minutes display software implementation was designed to read the current time from the RTC, check if it is different than the previously displayed time, and update the displays if necessary. The displays under control of this section of code are the solenoids and the RGB LED. Two functions were designed to drive the displays – displayMinutes and displayHours. The code segments in each of these functions simply use a lookup tables to drive the electromagnets and the RGB LED. The RGB LED is driven using the digital-to-analog converter (DAC) included in the ATMEGA328P, allowing for blending of colors throughout the hour. The solenoids are driven via Power MOSFETS (more details follow).

User Interface Software Implementation

The software design for the user interface board was relatively straight-forward. The main control board is configured to constantly read the current time from the RTC, check if it is different than the last time read and drive the displays if necessary. Aside from the primary main controller tasks (displaying the time), the main controller is constantly polling for button presses on the user interface PCB. When the controller detects that UI mode has been enabled (left-most button held down), the current time is read from the RTC and shown on the displays. The displays then start blinking to indicate that user-input mode is enabled. At this point, the user can hold down the middle or the right push button to increase the hours or minutes, respectively. When the leftmost button is released the UI mode is exited and the user set-time is saved to the RTC.

Demo Mode Software Implementation

A demo mode was implemented for the completed system design. The demo mode provides a display which is sped up 60 times from real-time. This mode can be entered by the user by depressing all three pushbuttons on the user interface simultaneously and can be exited by depressing any of the buttons on the user interface. When in demo mode, the microprocessor reads from the RTC every second, then sets the RTC to the current time plus one minute. This causes the displays to increase the minutes every second, thus increasing the hours every minute (60x faster than real-time). The mode provides a convenient way to test the full functionality of the clock over the course of 12 minutes instead of 12 hours.

Solenoid Drivers

The solenoid drivers are designed through the use of Power MOSFETs, linear regulators, potentiometers, and signals from the microcontroller. The power MOSFETs are the crux, essentially acting as an electrical current switch between the power supply and ground. When the MOSFET detects a signal to switch ON, current will be able to flow from the power supply through the solenoid to ground. When current flows through the solenoid a magnetic field is generated which creates an upward force toward the top of the bolt to the levitating object. Each solenoid may have slight variation in resistance, which is why it is necessary to have potentiometers to fine tune the DC supply voltage for each.

Levitating Object

The levitating object was fabricated from light-weight but high-density foam whose center was hollowed out to leave space for a high-strength neodymium magnet (also known as rare-earth magnets). The orientation was chosen such that it would oppose the solenoid’s magnetic field when in the “on” state.

Main Casing/Frame

An important aspect of this product is the aesthetics, thus the frame design was quite important. The final design chosen was one built from cherry-wood with a transparent finish so that the natural grain of the wood could be easily distinguished. Glass tubes were used to stabilize the levitating object along its vertical axis with 3D printed plastic rings securing said tubes to the top of the frame. The frame was split into two pieces so that all cabling and PCBs could be secured before attaching the shell to the base. There are no user-serviceable parts so access to the interior of the product requires unscrewing the bottom piece from the top piece. A small gap was placed at the bottom of the frame to allow for the RGB LED to be seen as well as to allow for some moderate air flow without compromising aesthetics. Figure 6 shows a picture of the final product.

Figure 6: Clock Displaying 5:20

Discussion

Throughout the process of designing and assembling this clock, many problems were encountered and subsequently overcome. The first problem was a mismatch between BOM and PCBs. This occurred due to last minute design changes that were, due to group oversight, omitted from the final BOM and thus the parts ordering. If this had not been caught at time of assembly, a 5V regulator would have replaced the required 3.3V regulator which could, conceivably, destroy most of the parts on the board (since many had a maximum supply voltage under 5V). Another issue was found in the PCB layout where a ground trace was missing on one part of the board which required an unsightly rework wire; not exactly ideal for a project that centers around aesthetics.

Second concern was heat dissipation due to the solenoids. Since each coil consumes 750 mA and, at worst case, one coil is on for four hours, there is quite a bit of generated heat. Due to the design of the frame itself, all of the heat gets “trapped” near the top which could cause a large rise in the internal temperature. This is an issue because the glue used to create the individual layers of the frame is limited to a maximum temperature of 65℃. If the internal ambient temperature were to rise above that value, the frame would begin to lose structural integrity. Currently, no testing has shown that the ambient internal temperature will rise to that value; however, all testing has only been done in a climate controlled area which ignores external environmental effects.

Another problem that was encountered when assembling this clock was the use of Molex KK connectors. First of all, crimps are required for the assembly of the cable, which require an expensive tool. Without purchasing the tool, crimping these connectors by hand was very difficult and can easily be messed up. After the clock was fully assembled, any hardware issue could be traced back to loose crimp connections, causing debugging headaches. The user interface, since it was the only cable utilizing the KK connectors, was, thankfully, the only component of the clock affected.

Coil winding was an additional problem. The winding method used throughout the project required three people and an electric drill. One person is required to operate and hold down the drill, while the other two made sure that the magnet wire was fed into the coil properly. A winding counter was used to count the number of turns in the coil to eliminate as much user error as possible, but this method was not ideal. The winding process was quite tedious as well as imprecise, which means a better procedure should be implemented in the future.

Due to cost concerns, a last minute change was made wherein the support rings for the glass tubes were modified from brass to plastic. The reason for this was purely cost-driven as printing the rings in plastic via a 3D printer was significantly more cost effective than having them hand-made in brass.

Finally, a problem was encountered with the Main Control Board PCB where the mounting holes were inadvertently omitted from the final design. This posed a serious problem in terms of securing the PCB to the frame. Luckily, the PCB design called for #4 sized screws to fasten the Power MOSFETs to the board. Since parts of the screws were exposed on the bottom of the frame, it was decided that these would serve a dual purpose: fasten the Power MOSFETs to the board, and secure the PCB to the frame. To do this, four holes (appropriately spaced) were drilled into mounting point on the frame with a drill bit slightly larger than that of the #4 screws. This allowed for the PCB to be snuggly fit into the bottom of the frame with no chance of displacement short of manually prying the board out of the holes. This method proved to be very clean and effective and required no extra components (just a little extra manual labor).

Conclusions and Recommendations

The finished clock is both aesthetically pleasing and capable of displaying the time within 10 minute accuracy. The project was designed by three electrical engineering students and one industrial design student and combines the skill sets of both engineers and artists. Particular engineering effort was focused toward the design of the circuitry to achieve the levitation. The clock is definitely something that both engineers and artists can relate to and is a nice piece of for display in any interior settings.

If the project is attempted again or a second revision is designed, there are a few issues which should be considered. The first recommendation would be that a better casing should be designed for the heat dissipation of the clock. The second is that coil winding should be done professionally or a bit more precisely. The third suggestion would be to possibly have the clock display both hours and minutes using a levitation mechanism.

Acknowledgements
We would like to thank our advisors Leo Farnand and Vince Burolla whose constant guidance and encouragement directly contributed to the success of this project. We would also like to thank Mark Smith for providing funding to this project. Thanks to James Paulius (Industrial Design) for the frame design and artistic guidance throughout MSD I and Byron Conn for producing the high-quality frame which helps to tie the artistic and engineering aspects of this project together. Thanks to Tom Zogas for cutting and annealing the glass tubes used in the hour display.