

## MECHANICAL ANALOG TO ION TRAP

**Abhishek. S. Dani, Dewang. M. Sukhadare\* and Neha. V. Nandi**

Department of Physics, VPM's B. N. Bandodkar College of Science,  
Chendani Bunder Road, Thane (W) 400 601  
Sukhadarewango38@gmail.com

### ABSTRACT

Many students may find visual analogies useful aids to intuition and understanding in more abstract areas of physical theory, especially when dealing with electricity and magnetism. For the sake of this project, I will focus on

- Studying the analogy of a ball moving on a spinning saddle as a mechanical representation of an ion in an RF-electric-quadrupole trap.
- Running Stimulation in Mathematica of Particular Saddle potential.
- 3d printing Saddle with known physical aspects.
- Building the Electronics Involved to vary speed of Saddle attached to DC motor and Measure RPM.

Although not a perfect analogue to the RF-electric-quadrupole ion trap, the spinning saddle has the advantage of being visible, tangible, and easy to manipulate without the need for complicated equipment.

**Keywords:** Ion Trap, Rotating Saddle Potential, IR Sensor, AT89S52, 555 Timer

### INTRODUCTION

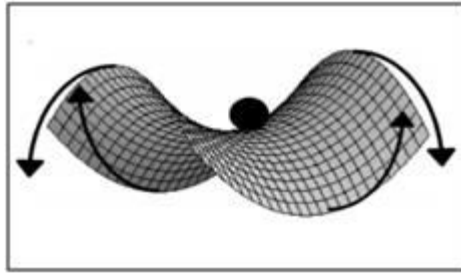
Ion traps allow just this sort of confinement: a charged atom can literally be trapped within a small radius, allowing more accurate study of its properties. In 1989, Wolfgang Paul received a share of the Nobel Prize in Physics for his development of the RF-electric-quadrupole ion trap. This type of trap is especially useful in determining atomic masses—the trap itself can be used as a mass spectrometer.

### DERIVATION OF ION TRAP POTENTIAL (Paul, 1989)

In order to confine an ion to an area, it is necessary to subject the ion to a restoring force that will draw it back to the system's origin. The simplest example of such a force is analogous to the spring force and takes the form

$$F = -cr \quad (1)$$

where  $F$  is the force acting on the ion,  $r$  is the position vector of the ion, and  $c$  is an arbitrary constant. Following the derivation of Thompson, Harmon, and Ball [4], I will recall that the force on a charged particle is proportional to the electric field and integrate (1) to find



$$\phi(x,y,z)=\phi_0/(2r_0^2)(\alpha x^2+\beta y^2+\gamma z^2) \quad (2)$$

where  $\phi$  is the electric potential at a given point in the Cartesian plane,  $\phi_0$  is a constant defining the magnitude of the potential,  $r_0$  is the radius of confinement, and  $\alpha$ ,  $\beta$ , and  $\gamma$  are constants that serve to determine the shape of the potential. In order to ensure the negative sign in (1), it is necessary for  $\alpha$ ,  $\beta$ , and  $\gamma$  to be positive. Additionally, the application of Gauss' Law to free space requires that the integral of the electric field over a sphere must be zero. Thus

$$\alpha+\beta+\gamma=0 \quad (3)$$

It appears impossible to satisfy (3) while still ensuring a trapping potential. There is, however, still the possibility of an arrangement, as I have not yet attempted to vary the potential with time. After setting  $\alpha = -\beta = 0$  and  $\gamma = 0$ , and allowing  $\phi_0$  to vary sinusoidally with time, (2) becomes

$$\phi(x,y,z,t)=(U_{RF} \cos[\Omega t])/(r_0^2)(x^2-y^2) \quad (4)$$

where  $U_{RF}$  is the amplitude of the ac component of the electric field applied to create the trap, and  $\Omega$  is the frequency of variation. This field can be visualized as a "flapping saddle"—a quadrupole potential in which extrema oscillate between being peaks and being valleys. In order to predict the motion of the ion, Newton's laws can be applied to (4) to produce the following differential equations:

$$m \frac{d^2}{dt^2} x = (-2eU_{RF})/(r_0^2) \cos[\Omega t]x \quad (5)$$

$$m \frac{d^2}{dt^2} y = (-2eU_{RF})/(r_0^2) \cos[\Omega t]y \quad (6)$$

where  $m$  is the mass of the ion and  $e$  is the electron charge. These equations are of the form of the Mathieu differential equations and admit stable solutions whenever [4]

$$|(4eU_{RF})/(mr_0^2 \Omega^2)| < 0.908 \quad (7)$$

It is interesting to notice that this stability condition is independent of the initial position and velocity of the trapped ion, depending only on the shape of the trap and the frequency of oscillation. (Thompson, *et al.*, 2002)

### THE SPINNING SADDLE POTENTIAL

In place of the ion moving within an electric quadrupole potential, I will now consider the problem of a ball moving within a gravitational quadrupole potential of the form

$$U(x,y)=mgh/(r_0^2) (x^2-y^2) \quad (8)$$

where  $U$  is the gravitational potential,  $m$  is the mass of the particle,  $g$  is the acceleration due to gravity,  $r_0$  is the radius of the saddle, and  $h_0$  is the maximum height at that radius, measured from the inflection point of the saddle. It is difficult to create a flapping saddle on which the ball can move, but the time-dependent potential of a saddle spinning at angular frequency  $\Omega$  is similar enough to the flapping potential as to be useful [4].

$$U(x,y,t)=mgh/(r_0^2) [x^2-y^2 \cos(2\Omega t)+2xy \sin(2\Omega t)] \quad (9)$$

Again, following the derivation of Thompson, Harmon, and Ball [4], I apply Newton's laws to get the coupled differential equations:

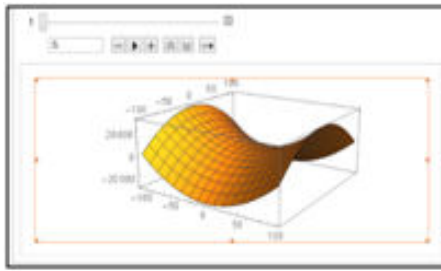
$$\begin{aligned} (d^2 x)/(d\tau^2)+2q[x \cos(2\tau)+y \sin(2\tau)] &=0 \\ \text{And} \quad (d^2 y)/(d\tau^2)+2q[y \cos(2\tau)+x \sin(2\tau)] &=0 \end{aligned} \quad (10)$$

where  $\tau=\Omega t$  and  $q=gh/(r_0^2 \Omega^2)$ . These equations differ from the ion trap equations only by the coupled sin term and their solutions are similar in that they predict stable motion for [4] regardless of the initial position and velocity of the ball (Thompson, *et al.*, 2002)

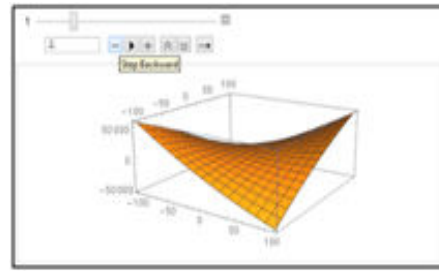
$$q \leq 1/2 \quad (11)$$

### STIMULATIONS IN MATHEMATICA 11.2

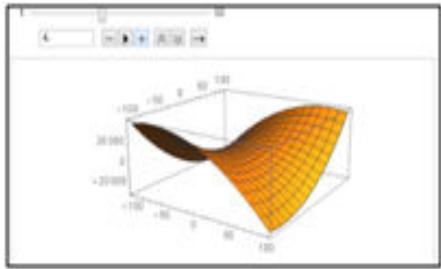
For the sake of this project, I used the saddle potential equation and plotted a 3D graph in Wolfram Mathematica 11.2 software with different heights and radii. Also, with the time variable  $t$  set to vary from 0 to 10 seconds, I was able to watch how the potential rotates as the time progresses (Wolfram Research, Inc., 2018).



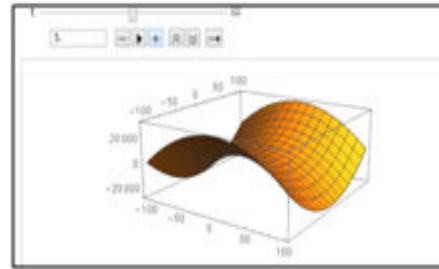
Time t = 0s



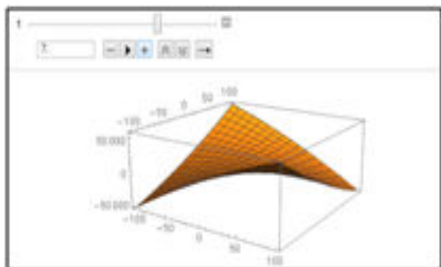
Time t = 2s



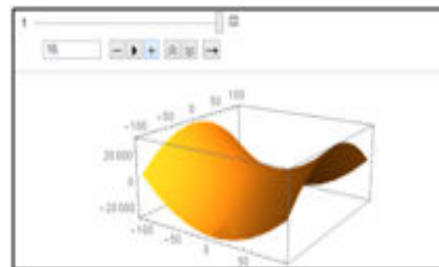
Time t=4s



Time t= 5s

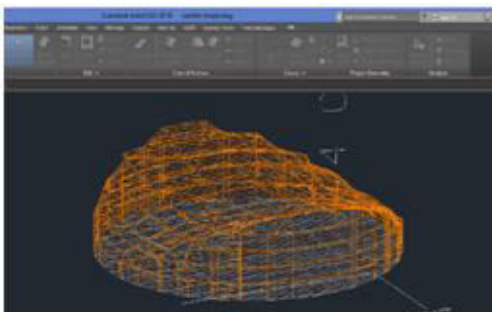


Saddle potential rotating stimulation in Mathematica 11.2



### 3D PRINTING THE SADDLE POTENTIAL

A hyperbolic paraboloid with dimensions  $r_0 = 7.5$  cm and  $h_0 = 1.25$  cm was modeled by using Mathematica 11.2 [6] to plot the intersection of  $z \leq 1.45(x^2 - y^2)$  and  $x^2 + y^2 \leq 7.5$ . This graphic was then exported and 3D printed using a CubePro Duo two-headed printer.



Modelling in Adobe AutoCAD



Final 3D printed Saddle Potential Model

## REQUIRED

In this experiment, the saddle potential must be connected to a DC motor and we need to calculate the minimum rotational velocity of the saddle required to trap a ball of particular density. For those purposes, we need to build two electronics circuits as follows:

1. PWM DC Motor Speed Controller using IC 555 Timer.
2. Contactless Digital Tachometer (RPM counter) using 8051 Microcontroller.

### 1. PWM DC MOTOR SPEED CONTROLLER USING IC 555 TIMER

We can control the speed of the DC motor by controlling the input voltage of the motor. For that purpose, we can use PWM (pulse width modulation.). PWM is a method through which we can generate variable voltage by turning on and off the power that's going to the electronic device at a fast rate.

### 555 TIMER PWM GENERATOR CIRCUIT

The 555 Timer is capable of generating PWM signal when set up in an astable mode. The output of the 555 timer can sink or source a current of 200mA to the load. So, if the motor that we want to control exceeds this rating we need to use a transistor or a MOSFET for driving the motor. In this example, I used a (TIP122) Darlington transistor which can handle a current up to 5A. The output of the IC needs to be connected to the base of the transistor through a resistor, and in my case, I used 1k resistor. For preventing any voltage spikes produced by the motor we need to use a fly back diode which is connected in parallel with the motor.

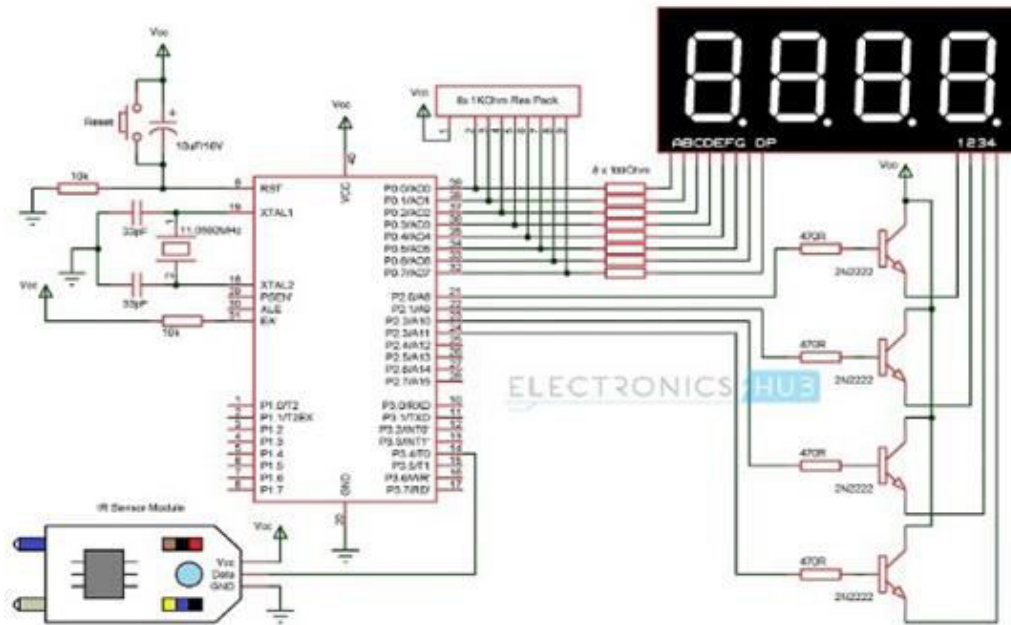
### COMPONENTS USED

1. NE555P Timer IC
2.  $R1 = R2 = 1k \text{ Ohm}$
3.  $C1 = C2 = 100nF$
4.  $D1 = D2 = D3 = 1N4004$
5. Potentiometer = 100k Ohm
6. Transistor – Darlington TIP122

### 2. DIGITAL TACHOMETER USING 8051 MICROCONTROLLER

A Tachometer is a device which measures the speed of a rotating object like an electric motor or a crank shaft of a vehicle engine. Speed is measured in RPM (Revolutions per Minute).

Here, in this project, we designed a simple Non – Contact or Contactless Digital Tachometer using 8051 Microcontroller, which can measure speed with an accuracy of 1 rev/sec (Administrator, 2017).



Circuit Diagram of Digital Tachometer

### COMPONENTS USED

1. 8051 Microcontroller
2. 8051 Microcontroller Programmer
3. IR Sensor Module (Reflective Type)
4. 4 – Digit 7 – Segment Display
5. 4 x 2N2222 NPN Transistors
6. 4 x 470Ω Resistors (1/4 Watt)
7. 8 x 100Ω Resistors (1/4 Watt)
8. 11.0592 MHz Quartz Crystal
9. 2 x 33pF Ceramic Capacitors
10. 2 x 10 KΩ Resistor (1/4 Watt)
11. 10 μF Capacitor (Polarized)
12. Push Button
13. 1 KΩ x 8 Resistor Pack

### IR SENSOR

IR receiver used in the project is a photo diode and it must be connected in reverse bias. The negative terminal or cathode is connected to 5V supply and the positive terminal or anode is connected to ground through a current limiting resistor of 10KΩ. And finally, the output of the IR receiver is given to the comparator. The comparator compares the input from the IR

receiver with a reference value (which is given through a 10K $\Omega$  Potentiometer). If the input from the IR receiver is greater than the reference value, the output of the comparator will be HIGH or else, the output will be LOW.

### **CONTROLLER CIRCUIT DESIGN**

The controller circuit consists of the microcontroller and its interfaces. Here, we chose the AT89S52 microcontroller. The AT89S52 is a low-power, high-performance CMOS 8-bit microcontroller with 8K bytes of in-system programmable Flash memory. The device is manufactured using Atmel's high-density nonvolatile memory technology and is compatible with the industry-standard 80C51 instruction set and pinout (Dejan, n.d.).

In our project, the Microcontroller reset circuit consists of a push button, a resistor and a capacitor with values such that the voltage at the reset pin doesn't fall below 1.2V and the timing constant is never less than 100ms. Here, we selected a 10 K $\Omega$  resistor and 10 $\mu$ F capacitor. Since the oscillating frequency of the microcontroller is 11.0592MHz, we selected the values of ceramic capacitors to be 33pF. The EA' pin must be pulled high via a 10K $\Omega$  resistor as we are not using any external memory.

### **MICROCONTROLLER CODE**

Once the circuit is designed and drawn on a piece of paper, the next step is to write and compile the code. Here, we used the Keil  $\mu$ Vision software to write the program in C language. Once the code is compiled, a hex file is created. In the next step, we use Proteus software to draw the circuit. The code is dumped into the microcontroller using an 8051 Microcontroller Programmer and the software associated with it.

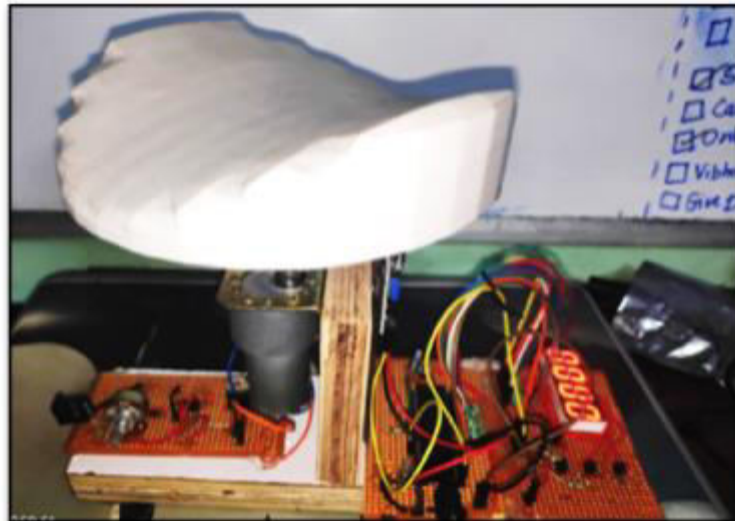
### **WORKING OF FINAL SETUP**

When the IR sensor is powered, the IR transmitter starts emitting IR rays. A motor is placed in front of the IR sensor, with its shafted marked with a white dot.

As the motor shaft rotates such that the white spots come in contact with the sensor, the IR rays are reflected by the dot and falls on the IR receiver. The photo diode, which is used as the IR receiver, starts conducting whenever the IR rays are reflected. At this point, the output of the IR sensor is given to the comparator and the output of the comparator is HIGH when the IR rays are reflected and the output of the comparator is LOW when there are no reflections. Hence, the output of the comparator is in the form of an ON-OFF pulse. This

pulse is given to the microcontroller as a timer input and the microcontroller is programmed to calculate the number of times the motor rotates in a second.

The speed of the motor is calculated by multiplying the value of final count by 60 to get the speed in revolutions per minute. This value is then displayed on the 4-digit 7-segment display.



Final Experimental Setup

## OBSERVATIONS

1. The IR Sensor needs to be calibrated according to the setup and to make it show the right RPM value, it was calibrated using Motor with known RPM (120 RPM) at stable 4V input.
2. Speed calculation may be affected by the varying duty cycle of the timer inside 8051. It was observed that the value of RPM of the motor shown on the 7-Segment Display fluctuates continuously within a range of +/- 50 RPM around Original RPM value.
3. Use of 16x2 LCD display is suggested as then we can program the controller to also display the Mean RPM value and the deviations from original value simultaneously.
4. The Vibration of the Motor also affects the data as the IR Sensor is kept highly sensitive and close to the motor for better accuracy. Use of Solid Base and Support for the motor is absolute necessity.
5. The Weight of 3D printed Saddle on the Motor Shaft also affects the ability of the PWM speed controller to rotate at lower speeds as motor draws more power from the circuit. Hence high power MOSFET like IRF540 could have been used instead of TIP 122 transistors for faster switching and ability to handle high power operations.



6. Also, for better accuracy and more adjusting abilities, we could have used 8051 along with L298N motor driver IC for Pulse Width Modulation.

### DISCUSSION AND FUTURE WORK

1. To examine how deviation from the expected critical frequency depends on the dimensions of the saddle.
2. Use Mathematica to graph theoretical trajectories of the ball on the saddle as well as to study the effect of friction and initial conditions.
3. Using a High Speed Camera to track motion of ball on the saddle and plot experimental trajectories.
4. Additionally, in order to achieve a more accurate comparison of experimental and theoretical trajectories, it would be useful to develop a method of experimentally quantifying the value of the coefficient of sliding friction.
5. An experiment testing the trapping lifetimes of balls of the same mass and material but with differing radii would be particularly interesting.

### REFERENCES

1. Paul, W. (1989). Electromagnetic traps for charged and neutral particles. Nobel Lecture. 601-622.
2. Thompson, R.I., Harmon, T.J., and Ball, M.G. (2002). The rotating saddle trap: a mechanical analogy to RF-electric-quadrupole ion trapping? *Can. J. Phys.*, 80(12): 1433-1448.
3. Wolfram Research, Inc., Mathematica, Version 11.2, Champaign, IL (2018).
4. Administrator (2017). Contactless digital tachometer  
<https://www.electronicshub.org/contactless-digital-tachometer-using-8051-microcontroller/>
5. Dejan (n.d.). PWM speed control using 555 Timer: <https://howtomechatronics.com/how-it-works/electronics/how-to-make-pwm-dc-motor-speed-controller-using-555-timer-ic/>
6. Earlier Research done at Cornell university in 2015  
<https://www.cornellcollege.edu/physics-and-engineering/pdfs/phy-312/2015-2016/Motion-Ball-Spinning-Saddle.pdf>