PH233 Lab 5: Characterizing a “PLANT” for a realistic feedback control system

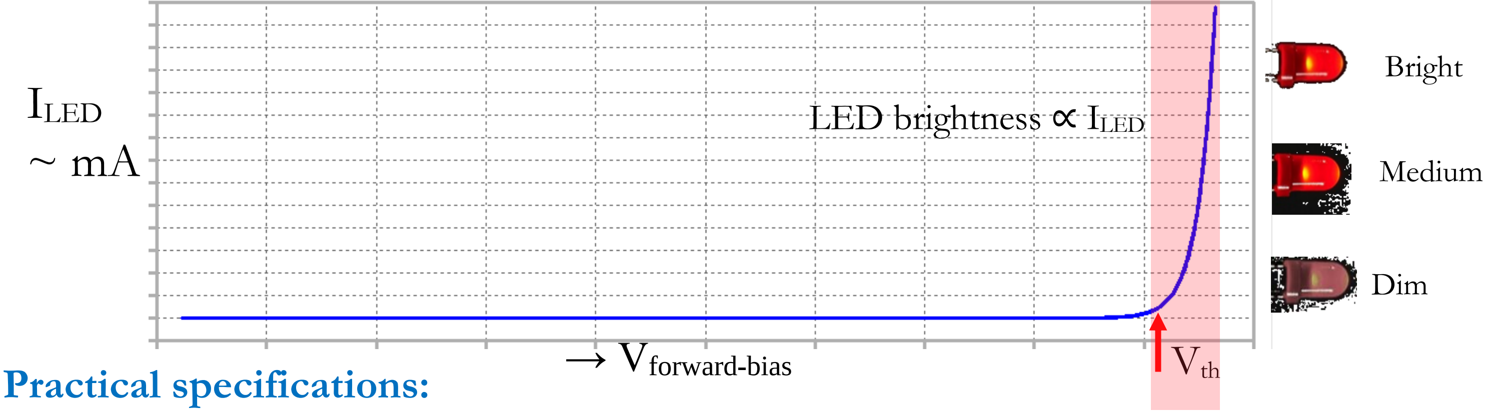
A(15) + B(5)

PART A: ACTUATOR 15

Setup a circuit that gives precise control of current through an LED such that brightness of light emitted by the LED can be precisely controlled.

An LED is a type of diode. As we have learnt, a diode I-V characteristics dictate that once the forward bias voltage across an LED exceeds a threshold voltage V_{th} it starts conducting. The brightness of light from the LED is proportional to the conduction current (we assume the relation is approximately linear for this experiment)

Fig 1: Typical LED I-V characteristic: The turn-on threshold voltage will vary depending on Red/Green LED’s and may be different for different LED’s. Aim of this module is to devise an opamp based LED driving circuit that operates in the shaded red band – I_{LED} is directly controlled, without caring about V_{th}



Practical specifications:

In earlier labs, we were mostly concerned with turning an LED ON or OFF, and putting a safety limit on the forward current with a series current limiting resistor.

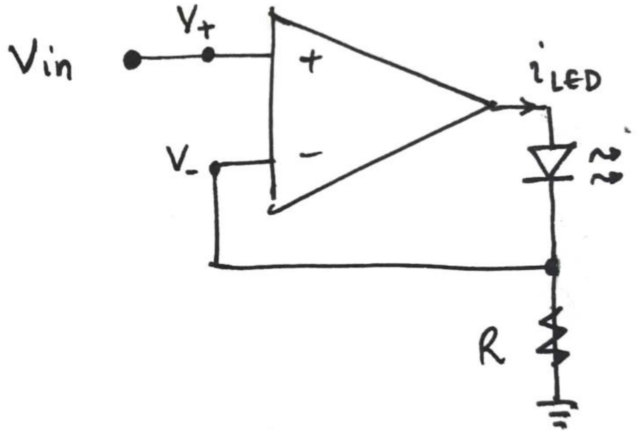
Our goal is *different* in this experiment. We want to control the brightness of the LED which is (approximately) proportional to I_{LED} in forward bias after turn on.
We will be working with voltage levels between modules of the overall feedback system. So we don’t want to waste V_{th} (~1.8V for red LED) simply to turn it on and then have a very narrow band of voltage control highlighted in red in Fig 1 to control its current.

Circuit Design: **5**

Use the following ingredients to design and build a circuit that controls the brightness of a red LED by precisely controlling the current I_{LED} in the red band highlighted in Fig 1. i.e. I_{LED} is directly controlled (not V_{LED})

1. Single Opamp LM741 must be used
2. Input voltage to the circuit $V_{in|actuator}$ must span 0V to 4V. LED must turn on immediately when $V_{in|actuator}$ rises above 0V and its brightness ($\propto I_{LED}$) must increase approximately linearly up to $V_{in|actuator} = 4V$
   i.e. V_{LED} must not come directly from V_{CC}
3. A series resistor can be used as a probe for measuring I_{LED} in circuit. One end of the resistor must be at GND, so as to not disturb the circuit characteristics.
4. **Main circuit idea:** All the above can be done by including the LED in your opamp feedback loop. Configure the circuit with LED in the feedback loop. Prove mathematically that your circuit design will work as per requirement.
   [Note: this hint looks similar to one of the quiz questions, but the solution is different!]

2 marks(design) + **3** marks(proof)



We apply the idealizations that:

1) $V_+ \simeq V_-$

2) $i_+ \simeq i_- = 0$ (current flowing into either Op-Amp pins)

Kirchhoff current rule:

$$i_- + \frac{V_-}{R} = i_{LED} \Rightarrow i_{LED} = \frac{V_-}{R} \quad (i_- = 0)$$

$$i_{LED} = \frac{V_+}{R} = \frac{V_{in}}{R} \Rightarrow \boldsymbol{i_{LED} \propto V_{in}}$$

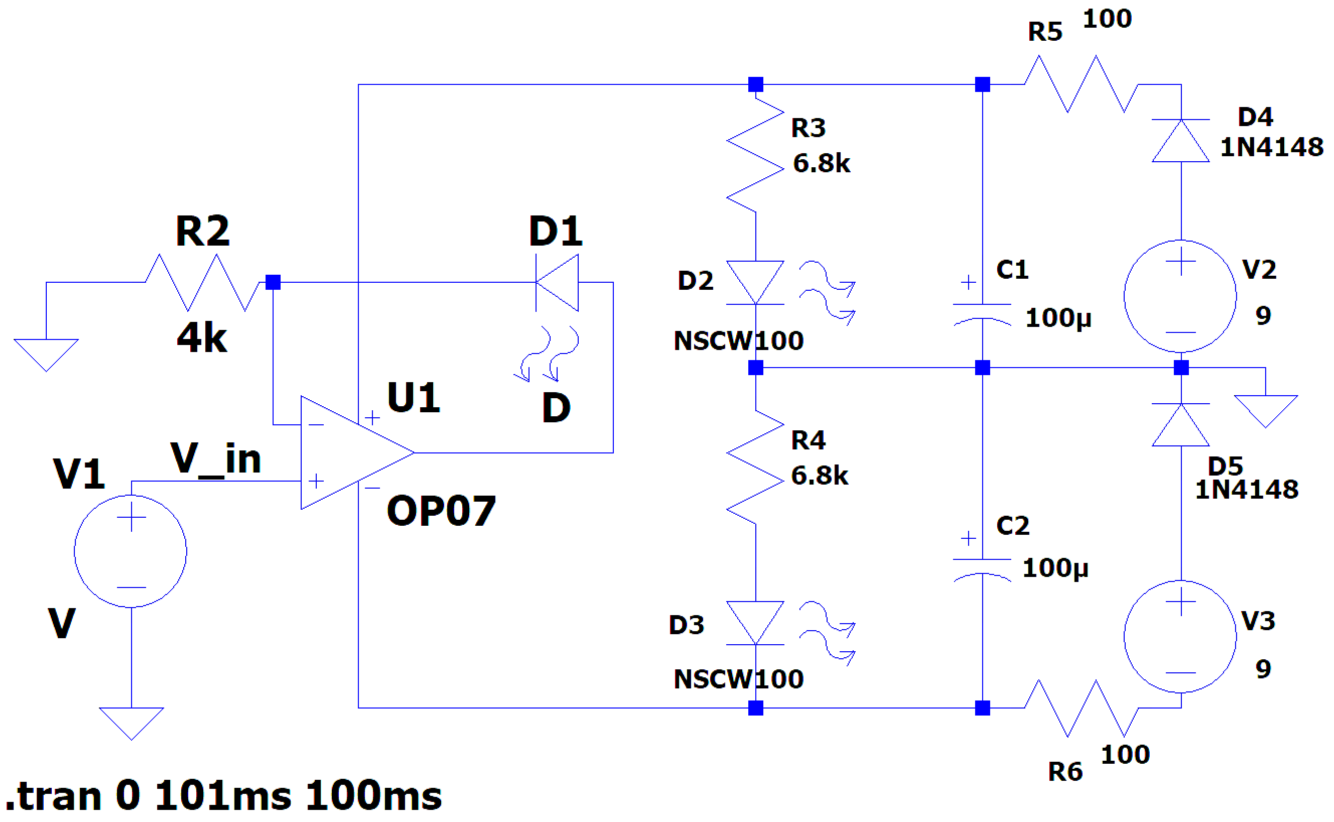
The resistor value must be chosen such that when we vary V_{in} the current through LED makes LED burn with max brightness ($i_{LED|max} \sim 10mA$).

We can safely apply these approximations because the Op-Amp is operating with feedback-closed loop. This is also confirmed by LTSpice simulations.

Simulation: 5

Simulate your circuit in LTSpice. Provide a circuit diagram and simulation plot of I_{LED}(y-axis) v/s $V_{in|actuator}$(x-axis) validating the control range of your circuit.

Use component values such that $I_{LED|max}$ ~ 10 mA well within the maximum current that can be supplied by the opamp. Measure the voltage across a suitably connected resistor to probe I_{LED} when you build the circuit.



Here V_{in} will be drawn from the power line V_{CC} via a Potentiometer- for adjustments between 0-4V.

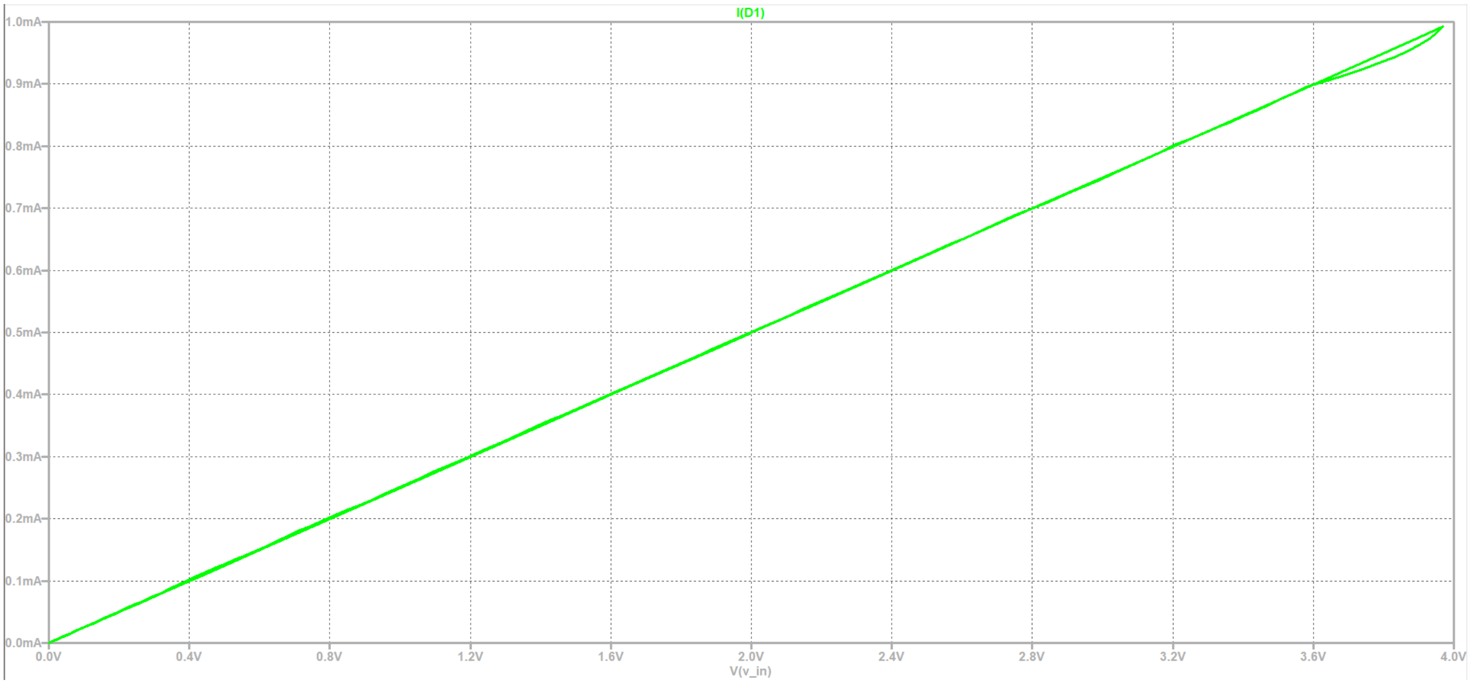
$$i_{LED|max} = \frac{V_{in|max}}{R} = \frac{4V}{R} = 1mA \Rightarrow R = 4k\Omega$$

I have used $2k\Omega + 2k\Omega$

Plots:

$i_{LED}\ v/s\ V_{in}$:

(Here we also observe slight hysteresis at the peak voltage because a sinusoidal source is used for a 0-4V sweep)



Demo 5

Build your circuit as per the above design. Use a 10kΩ potentiometer to vary DC voltage input $V_{in|actuator}$ to your circuit. Measure $V_{in|actuator}$ and I_{LED} with DMM
Fill the following table listing your measurements for a few settings between 0V and 4V

$V_{in|actuator}$ = 0V I_{LED} =?

$V_{in|actuator}$ = 1V I_{LED} =?

$V_{in|actuator}$ = 2V I_{LED} =?

$V_{in|actuator}$ = 3V I_{LED} =?

$V_{in|actuator}$ = 4V I_{LED} =?

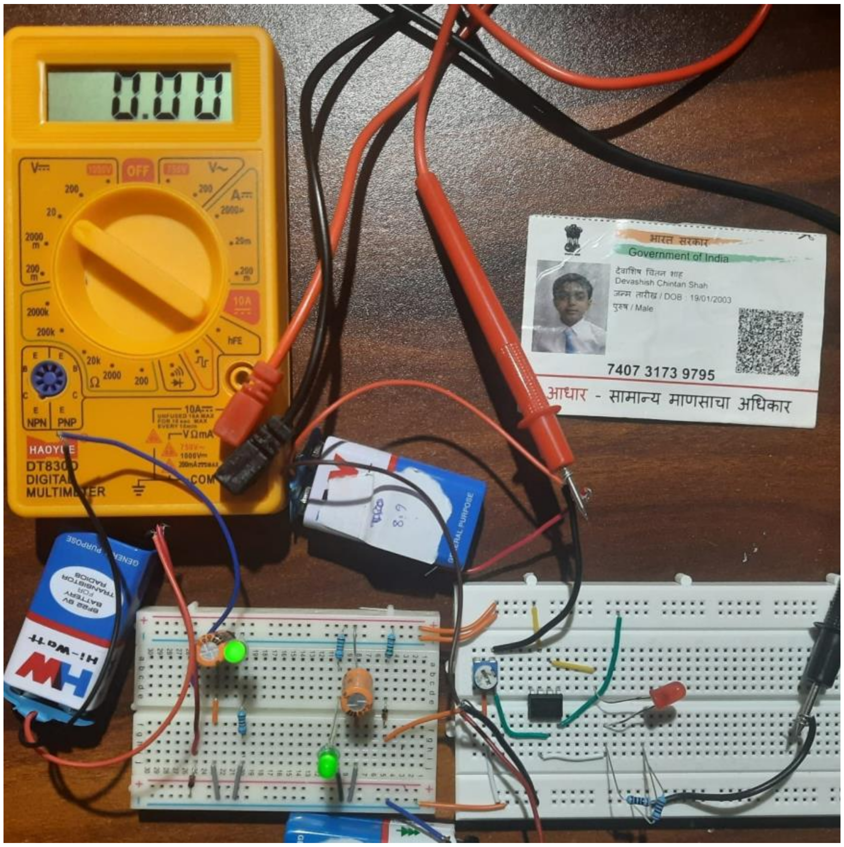
Post a sequence of photos for the above measurements, indicating $V_{in|actuator}$ applied (measured with DMM), and the corresponding I_{LED} measured as voltage V_{shunt} by DMM across the shunt resistor. Obviously as a sanity check, the perceived brightness of the LED should also change accordingly as per I_{LED}.

V_{in}	V_R	$I_{LED} = \frac{V_R}{R}$
0.00V	0.00V	0.00mA
0.99V	0.98V	0.245mA
2.00V	2.03V	0.508mA
2.99V	3.08V	0.77mA
3.98V	3.24V	0.81mA

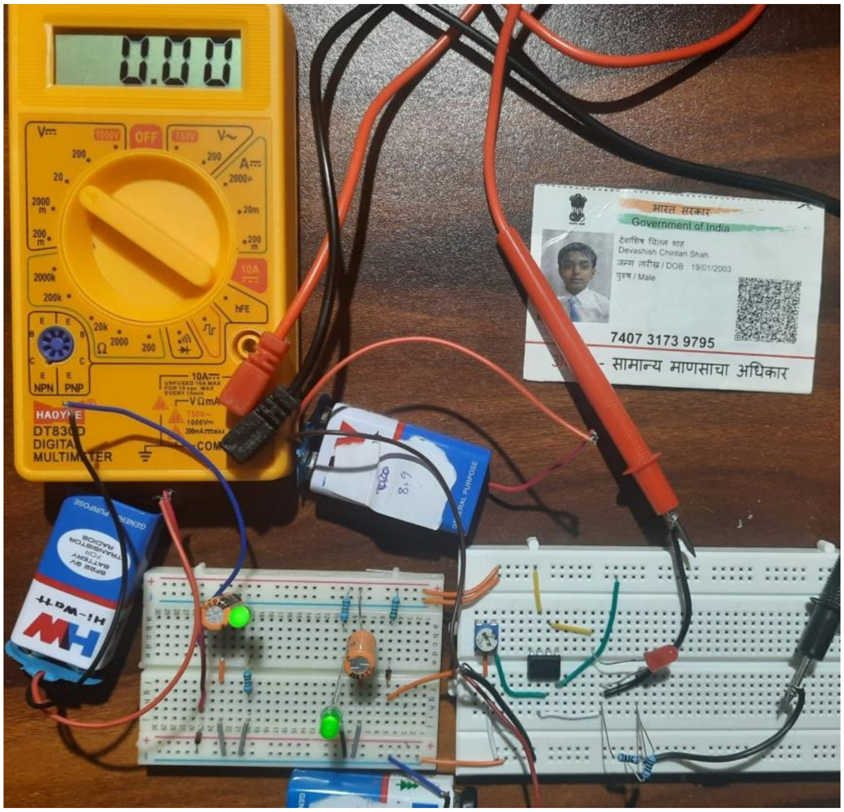
We indeed observe:

$$I_{LED} \propto V_{in}$$

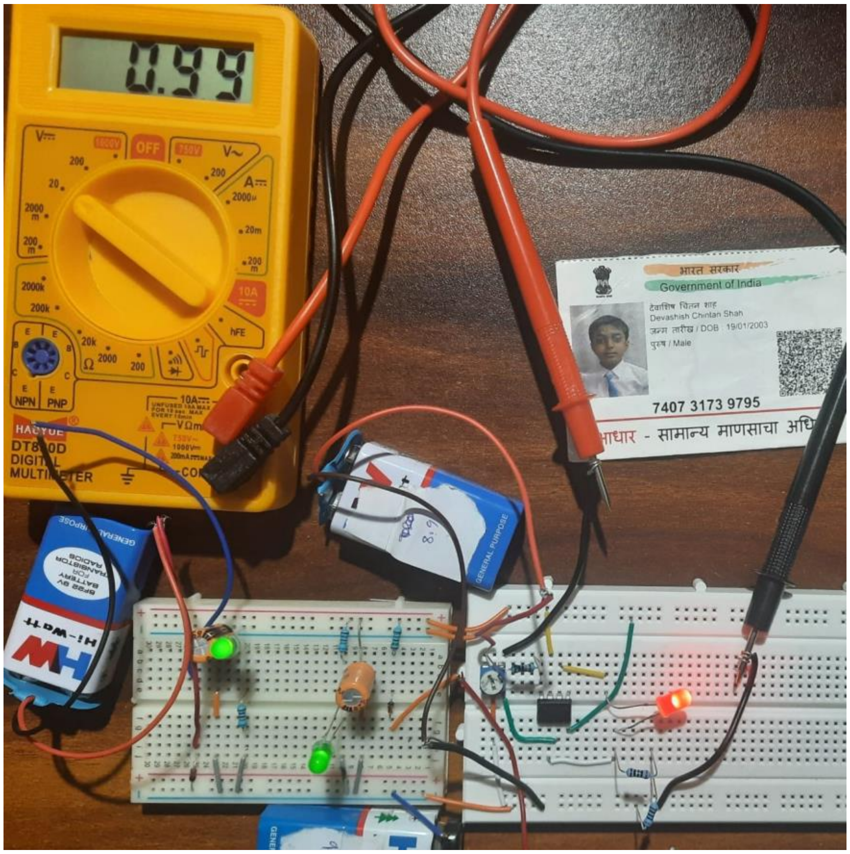
$$V_{in} = 0.00V$$



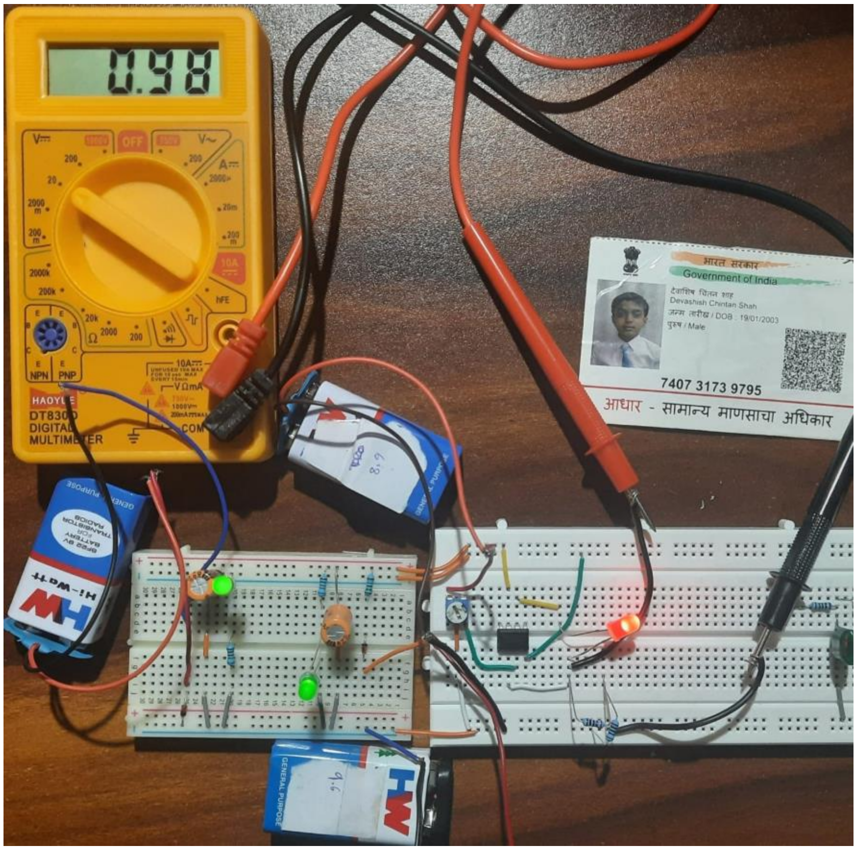
$$V_{shunt} = 0.00V$$



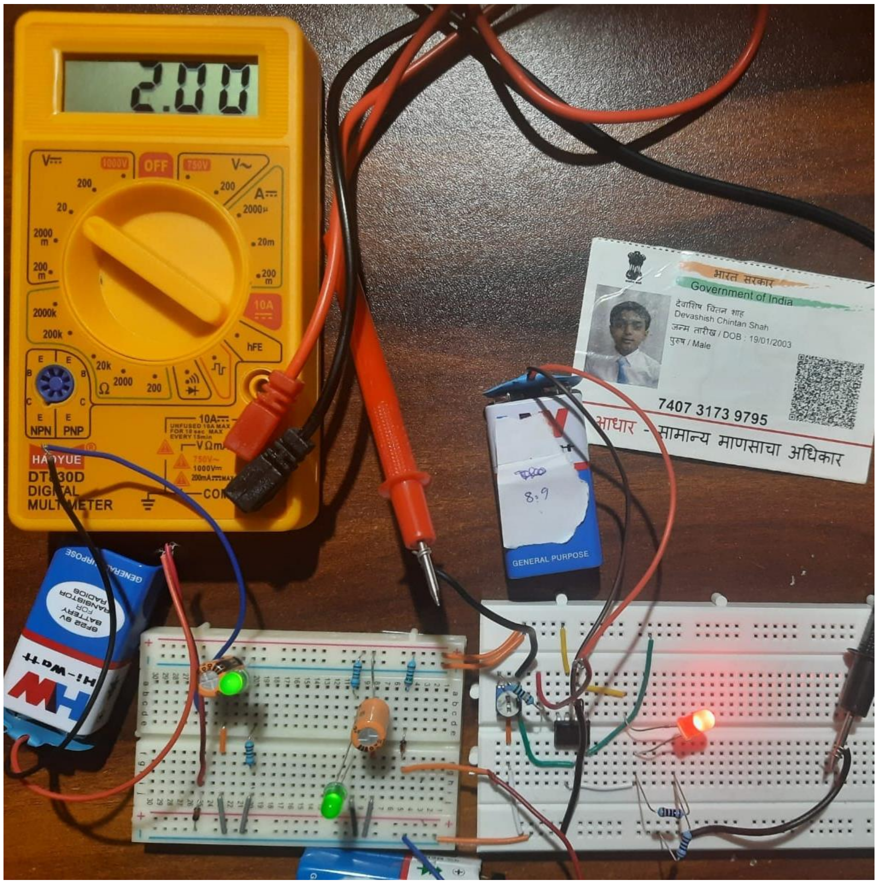
$$V_{in} = 0.99V$$



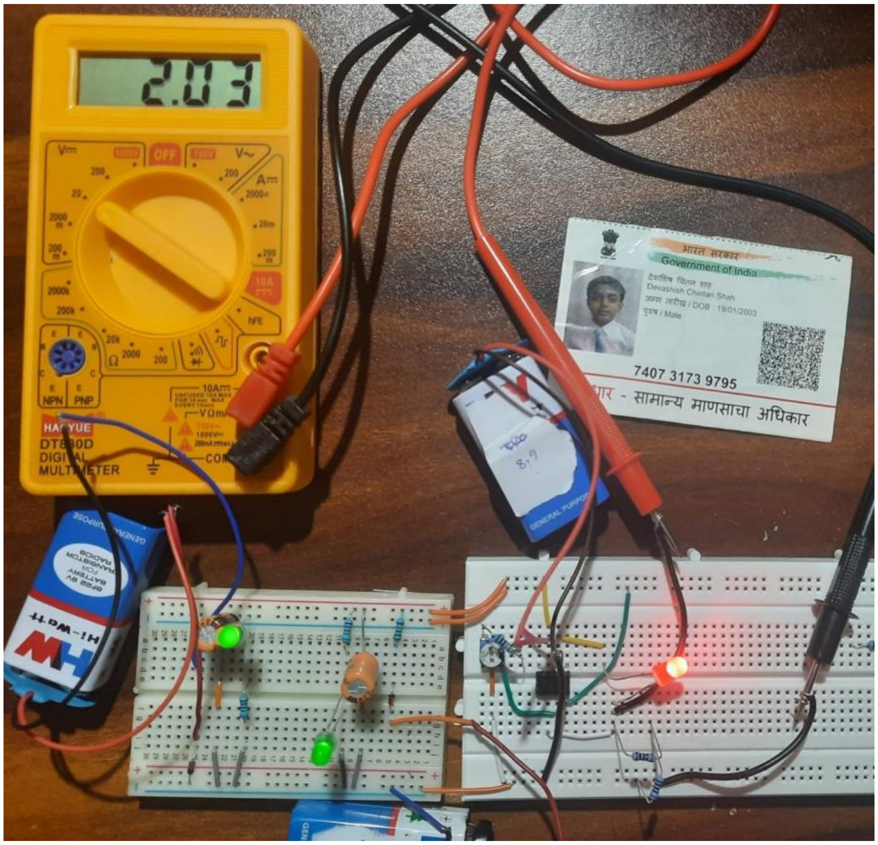
$$V_{shunt} = 0.98V$$



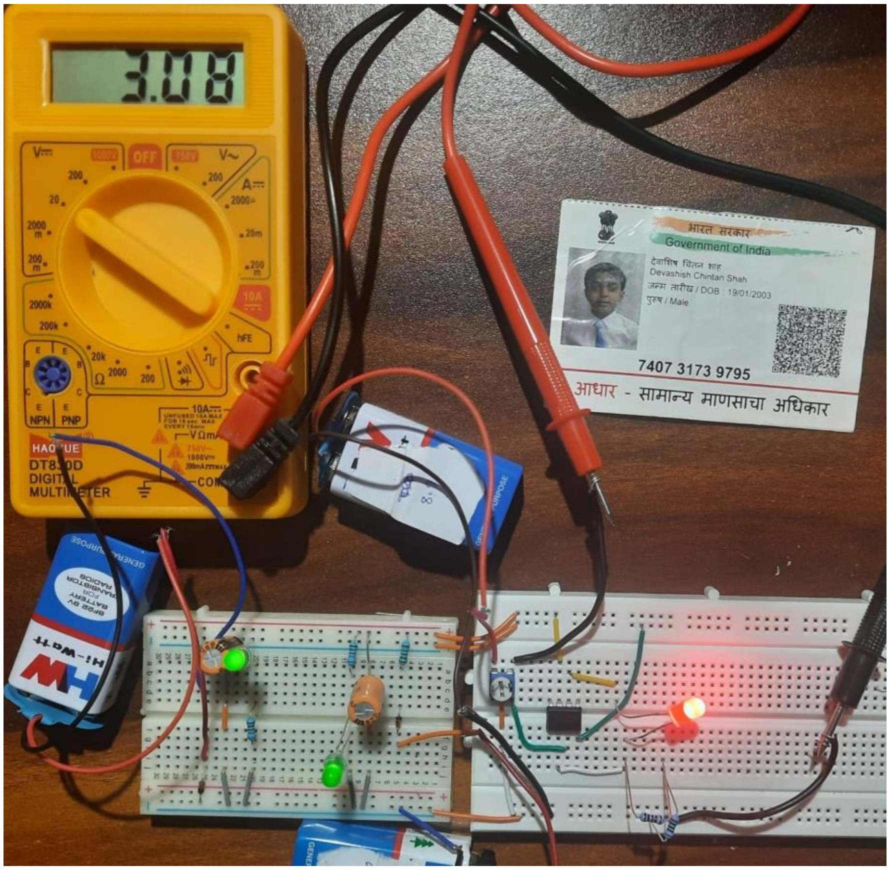
$$V_{in} = 2.00V$$



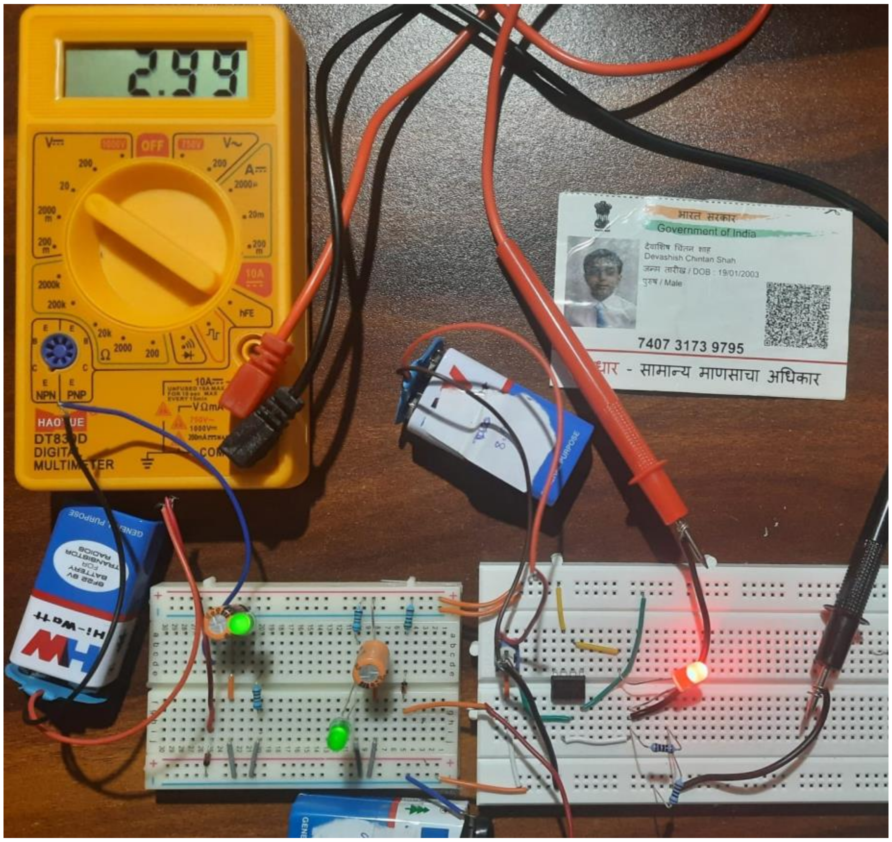
$$V_{shunt} = 2.03V$$



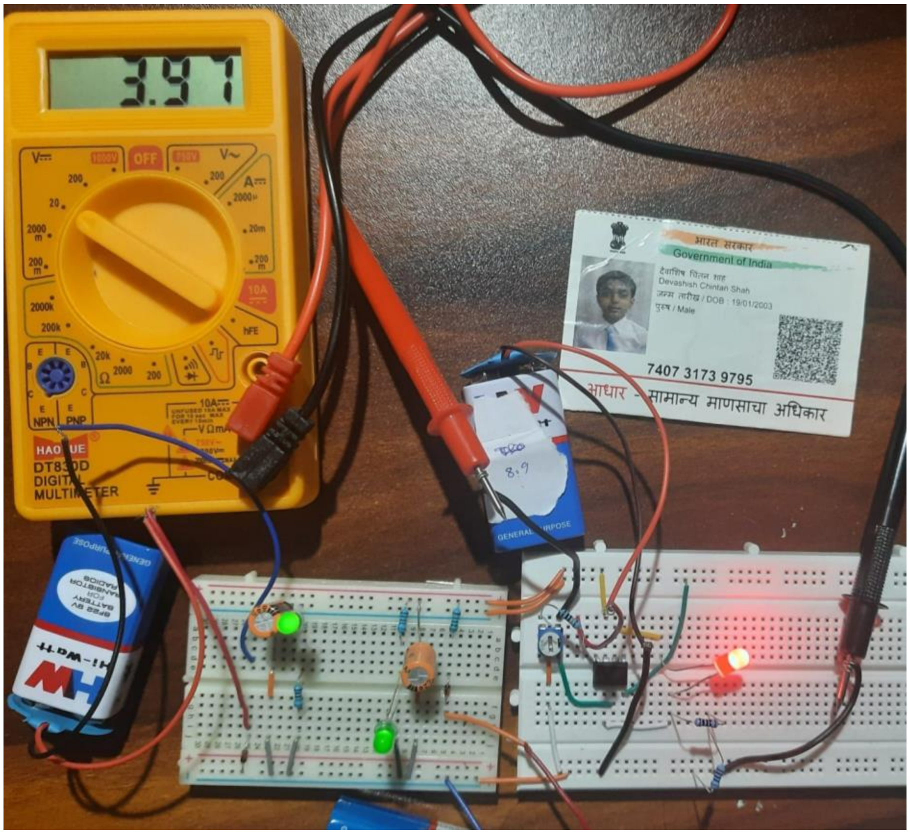
$$V_{in} = 3.08V$$



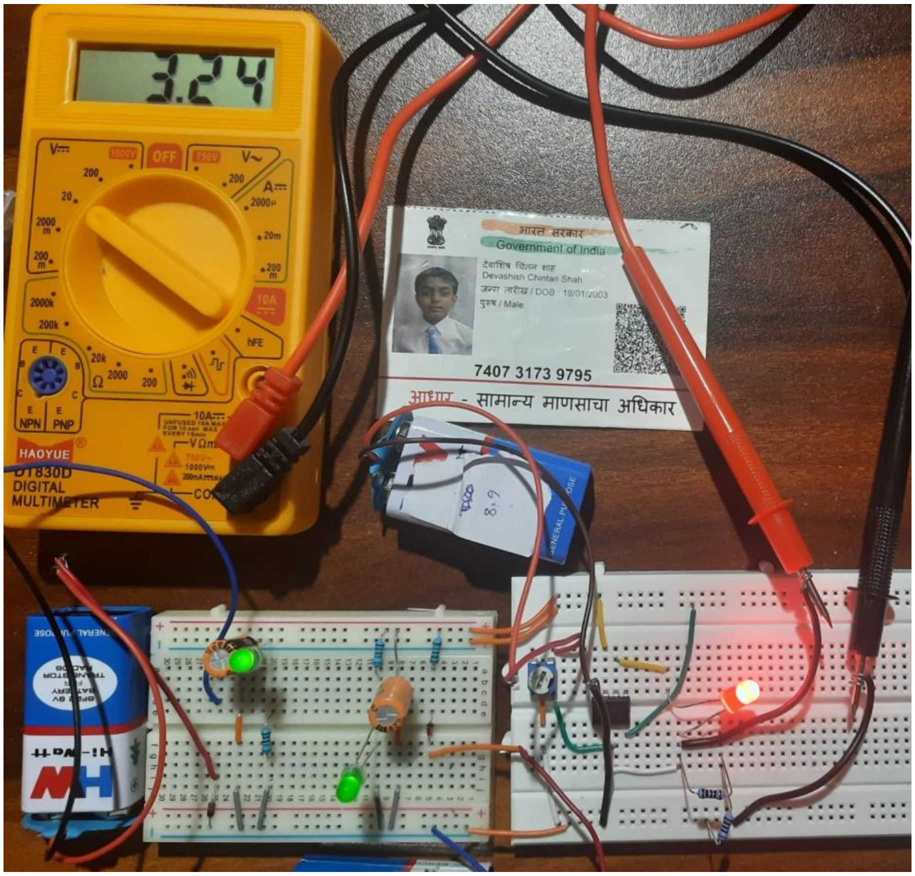
$$V_{shunt} = 2.99V$$



$$V_{in} = 3.97V$$



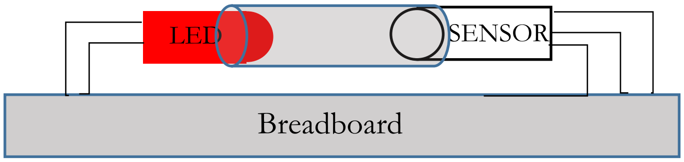
$$V_{shunt} = 3.24V$$



PART B: SENSOR 5

The photo-transistor is our sensor for the final feedback system. Setup the photo-transistor on your breadboard directly facing the LED as done earlier in Lab 4. The LED and photo-transistor must be directly facing each other as close as possible such that the 60° emission and acceptance light cones overlap maximally. To reject stray external light, you can wrap the LED + photo-transistor combo with a piece of straw colored black as shown below:

Fig 2: Piece of straw painted black slipped onto your LED and sensor at each end helps to reject external light disturbance on your setup during characterization



Connect Collector of photo-transistor to V_{CC} and a probe resistor at the Emitter to convert the photo-current produced by incident light into a voltage – we call this $V_{out|sensor}$

Choose a suitable value of emitter resistor R_E and configure your setup such that:

1. When $V_{in|actuator}$ is minimum → $V_{out|sensor}$ is minimum
2. When $V_{in|actuator}$ is maximum → $V_{out|sensor}$ is maximum *and not saturated*
3. The relation between $V_{in|actuator}$ and $V_{out|sensor}$ is approximately linear

The objective of this part is to fine-tune the experimental setup on your breadboard such that $V_{in|actuator}$ and $V_{out|sensor}$ span the maximum possible range, and the relation between them is linear over that range. Your choice of R_E may depend on the ambient light conditions in your work area – so choose a fixed location and time of the day. You will re-use this calibrated setup for the next lab.

Record your measurements as per the following pattern: 5

$V_{in|actuator}$ = 0V $V_{out|sensor}$ =?

$V_{in|actuator}$ = 1V $V_{out|sensor}$ =?

$V_{in|actuator}$ = 2V $V_{out|sensor}$ =?

$V_{in|actuator}$ = 3V $V_{out|sensor}$ =?

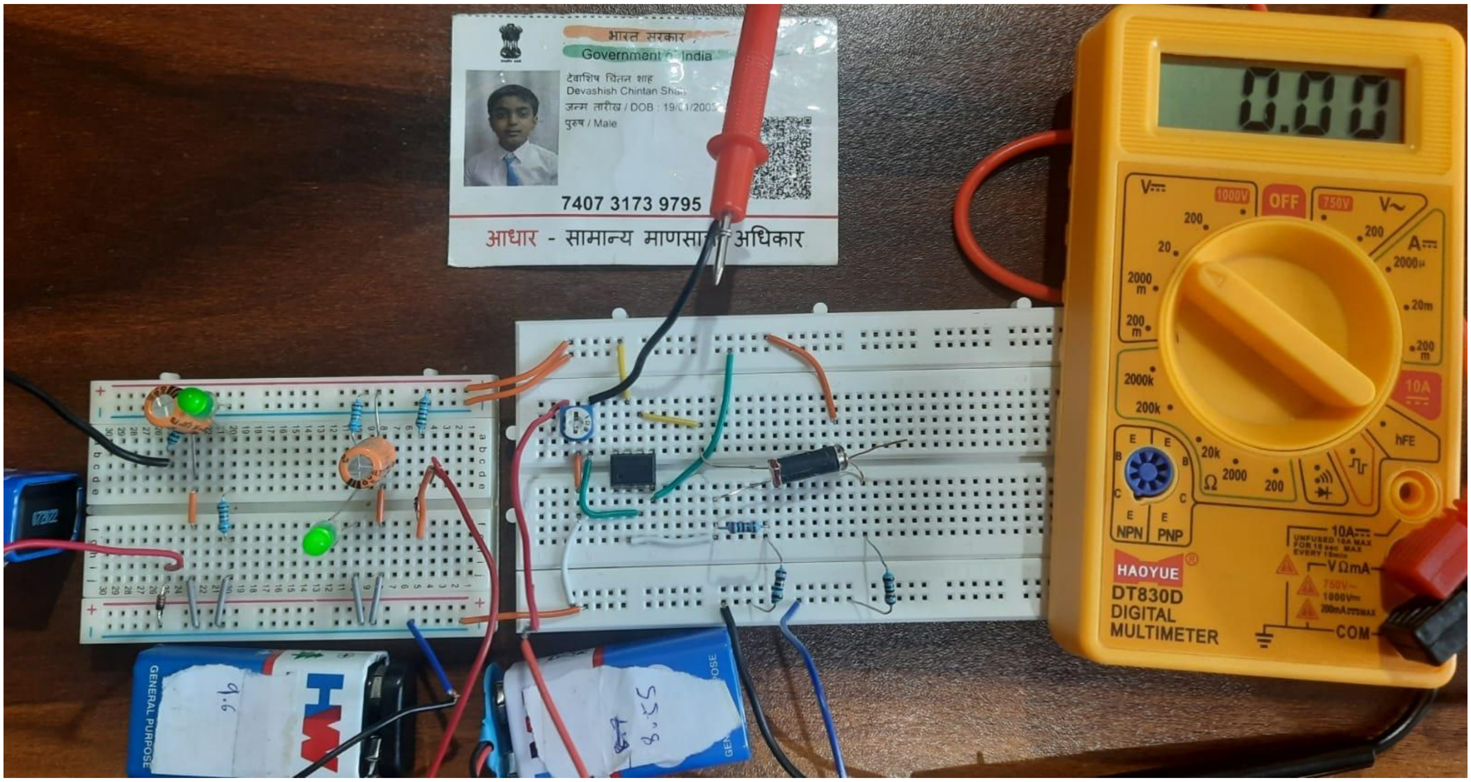
$V_{in|actuator}$ = 4V $V_{out|sensor}$ =?

$V_{in\vert actuator}$	$V_{out\vert sensor}$	$\frac{V_{in\vert acturator}}{V_{out\vert sensor} - V_{out\vert ambient}}$
0.00V	0.16V ($\neq 0$ because of ambient lighting)	-/-
1.02V	0.43V	3.7
1.99V	0.80V	3.1
3.02V	1.17V	3.0
4.14V	1.44V	3.2

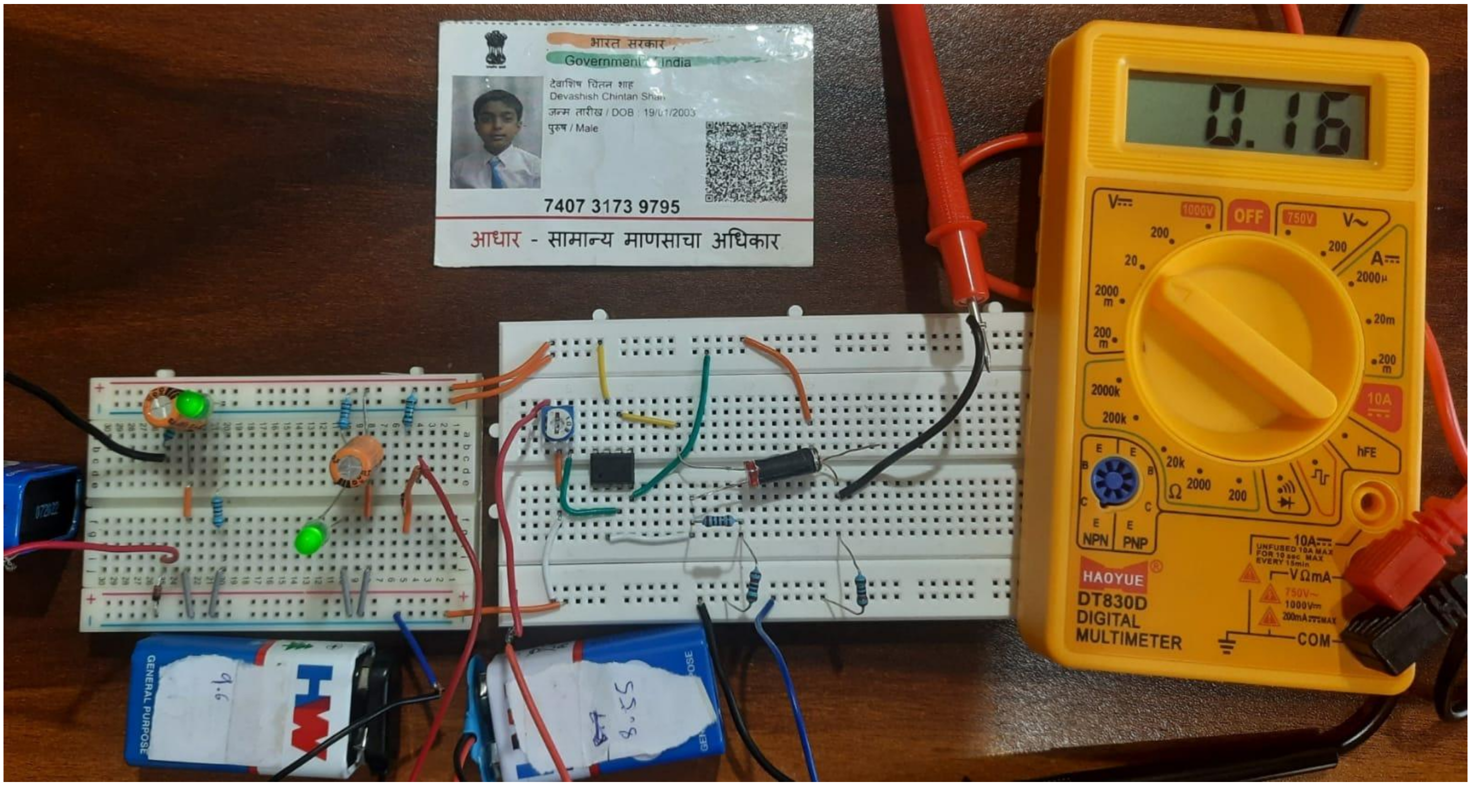
Thus, we actually observe

$$V_{out|sensor} \propto V_{in|actuator}$$

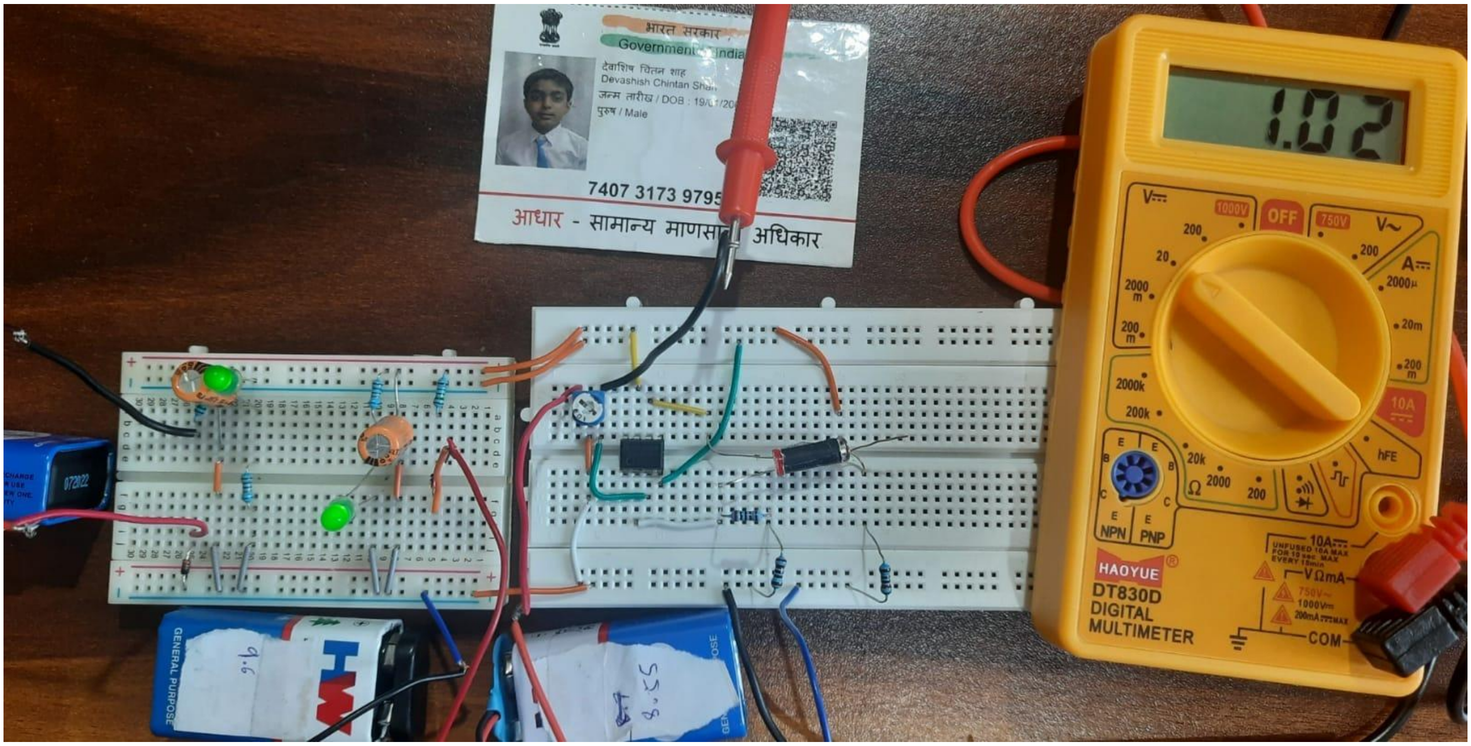
$$V_{in|acturator} = 0V$$



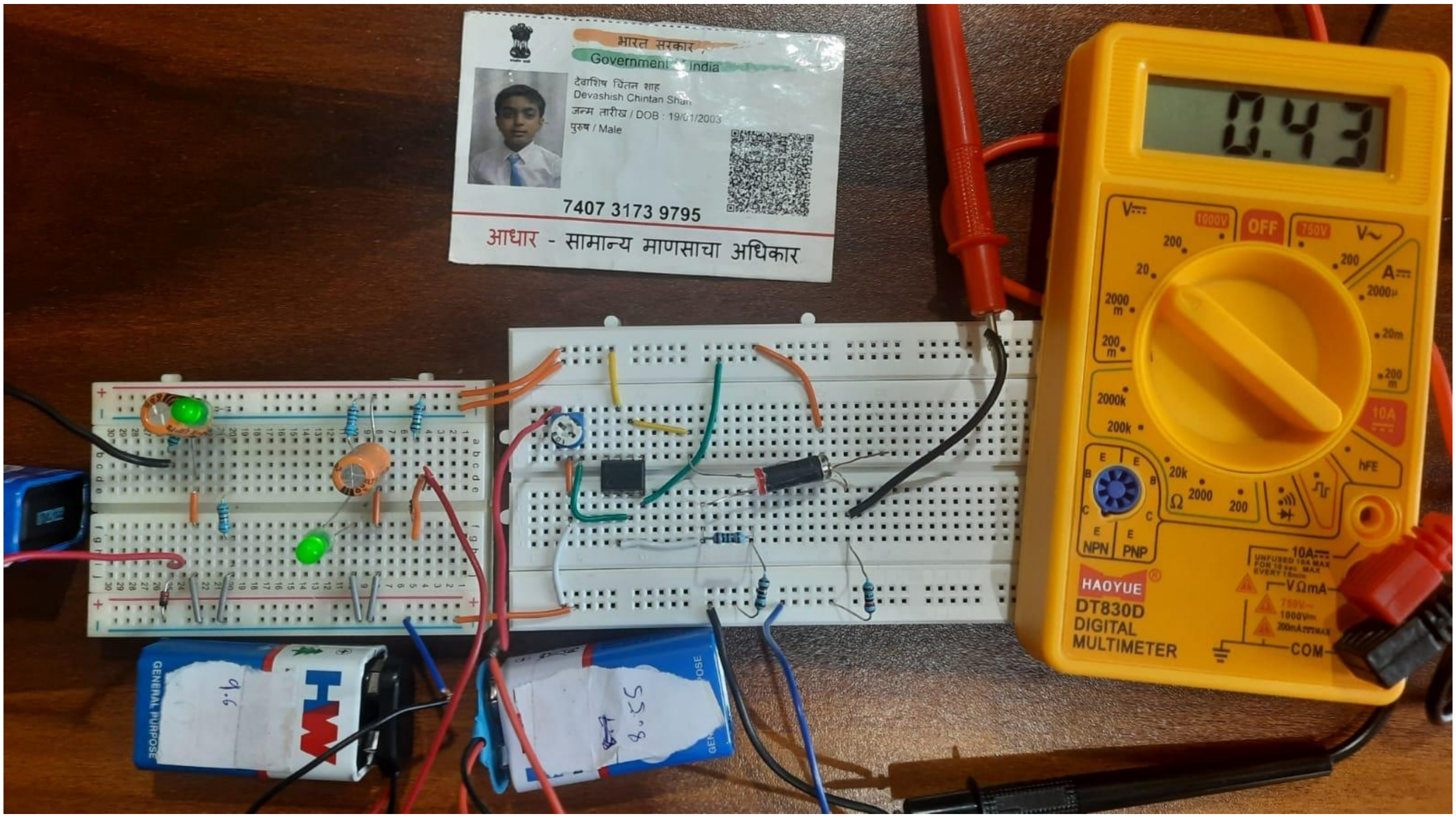
$$V_{out|sensor} = 0.16V$$



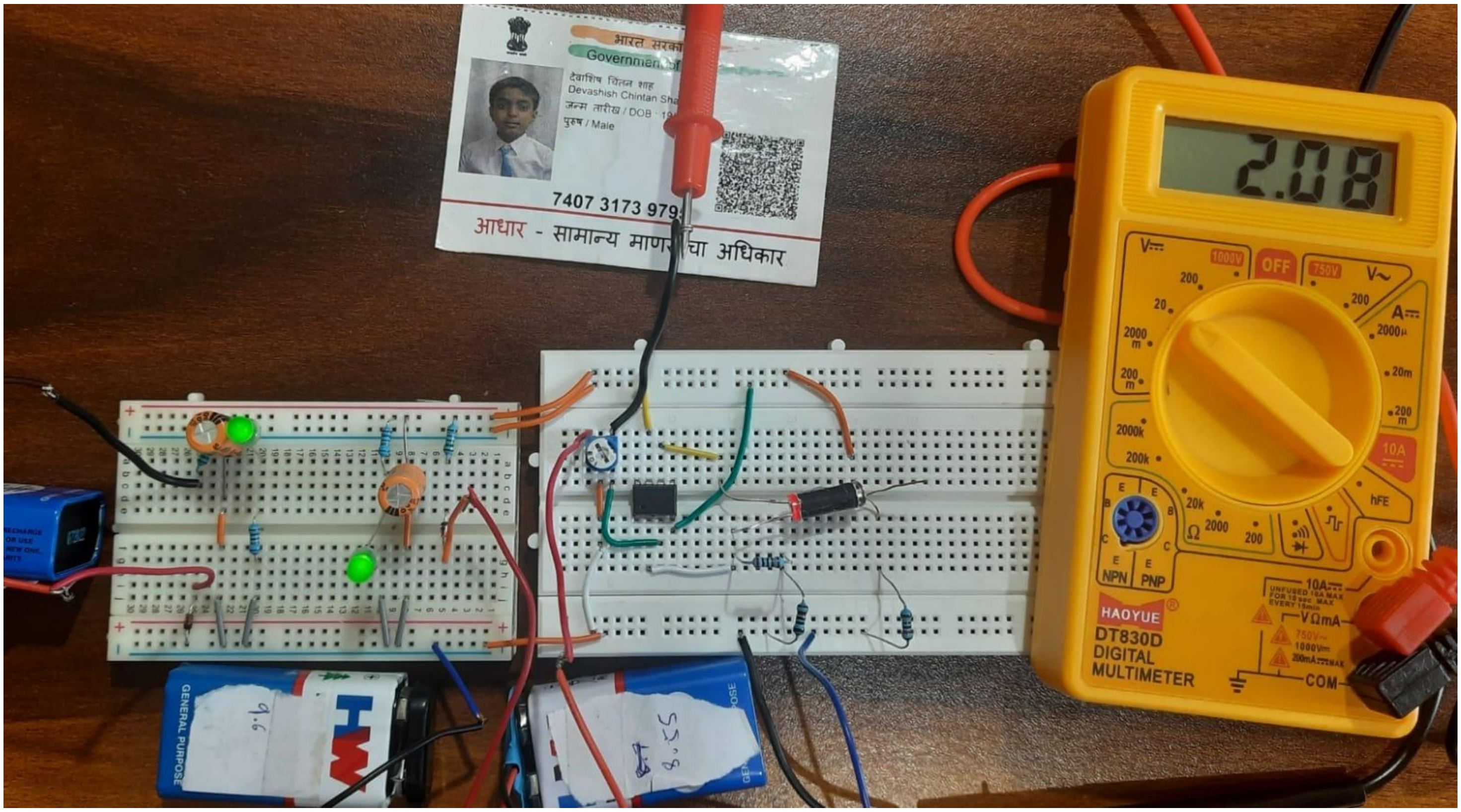
$$V_{in|acturator} = 1.02V$$



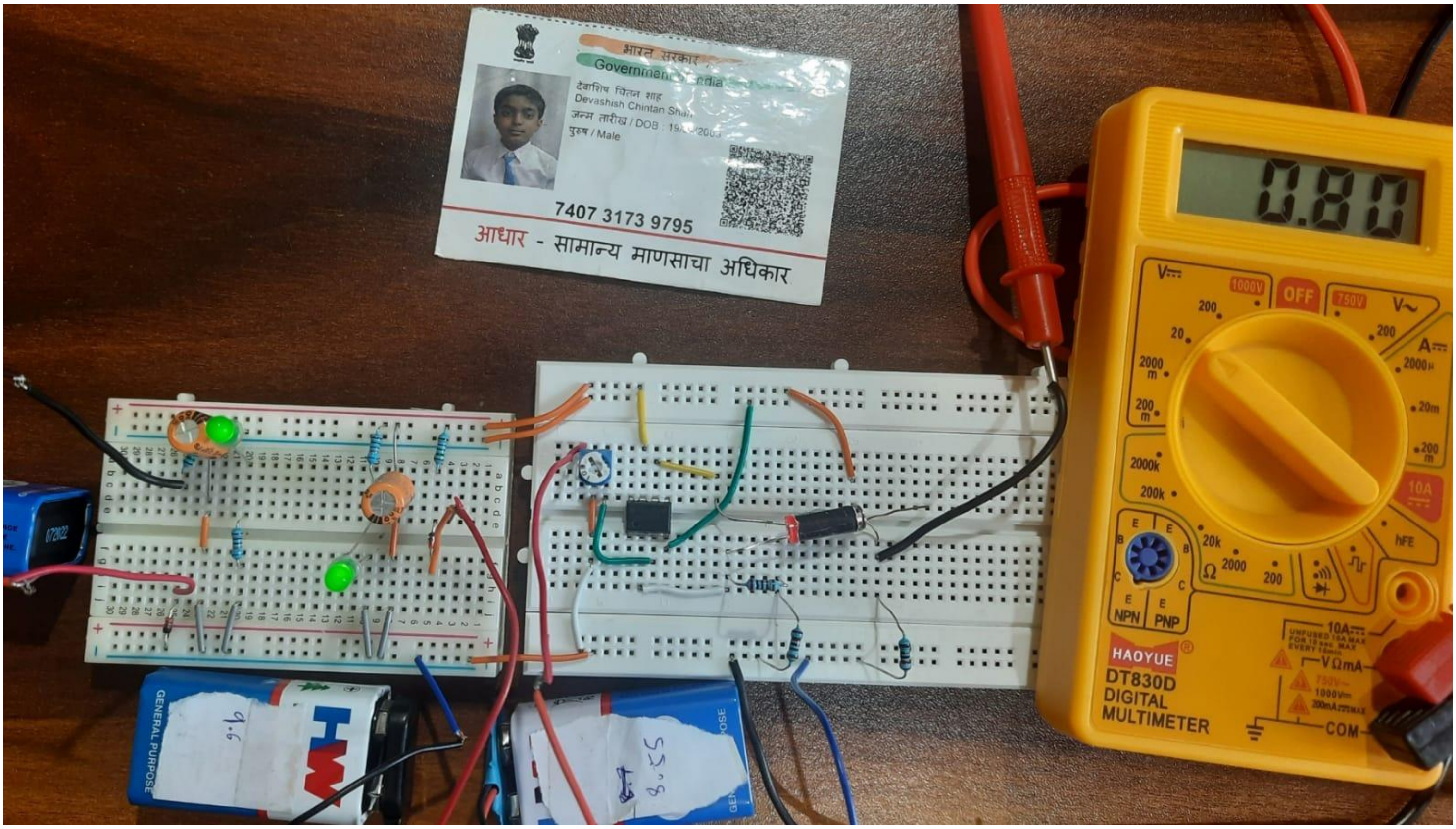
$$V_{out|sensor} = 0.43V$$



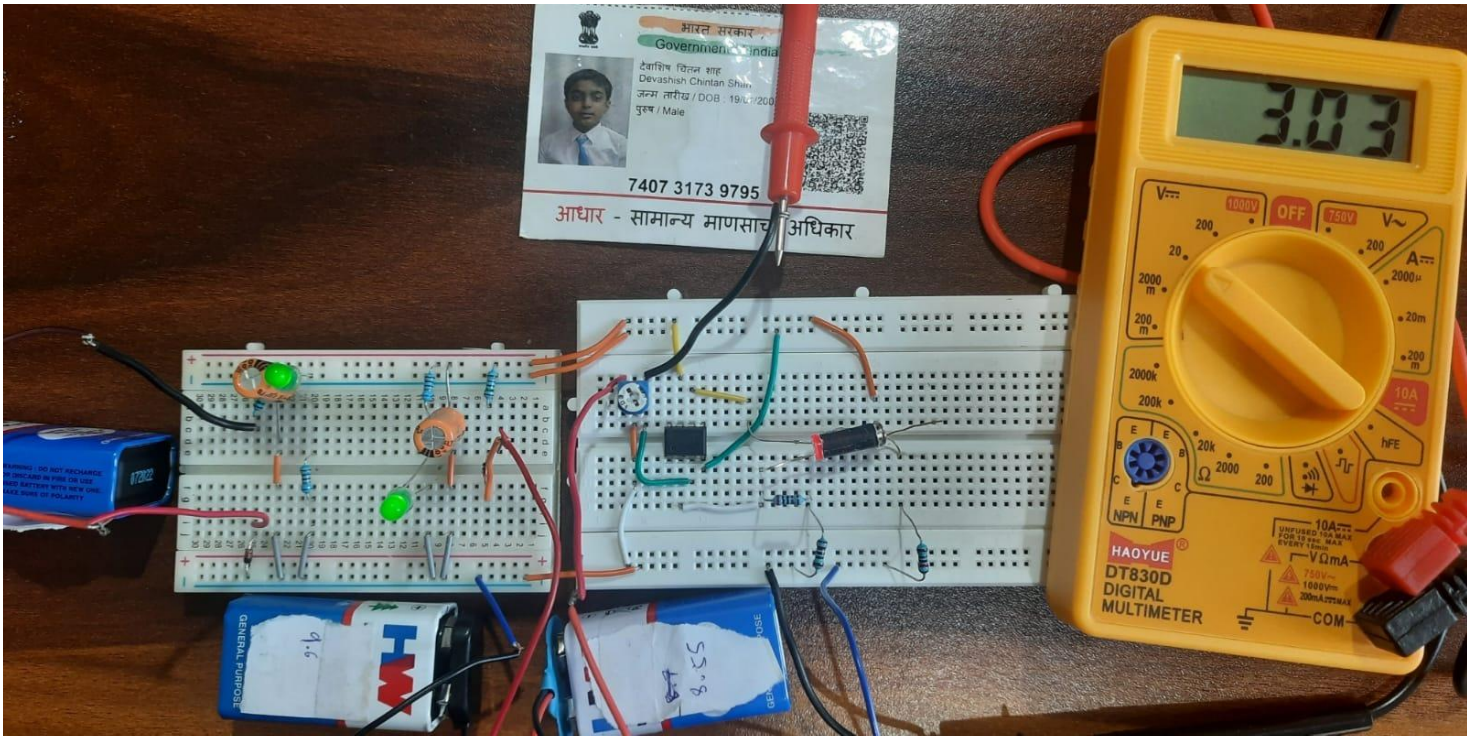
$$V_{in|acturator} = 2.08V$$



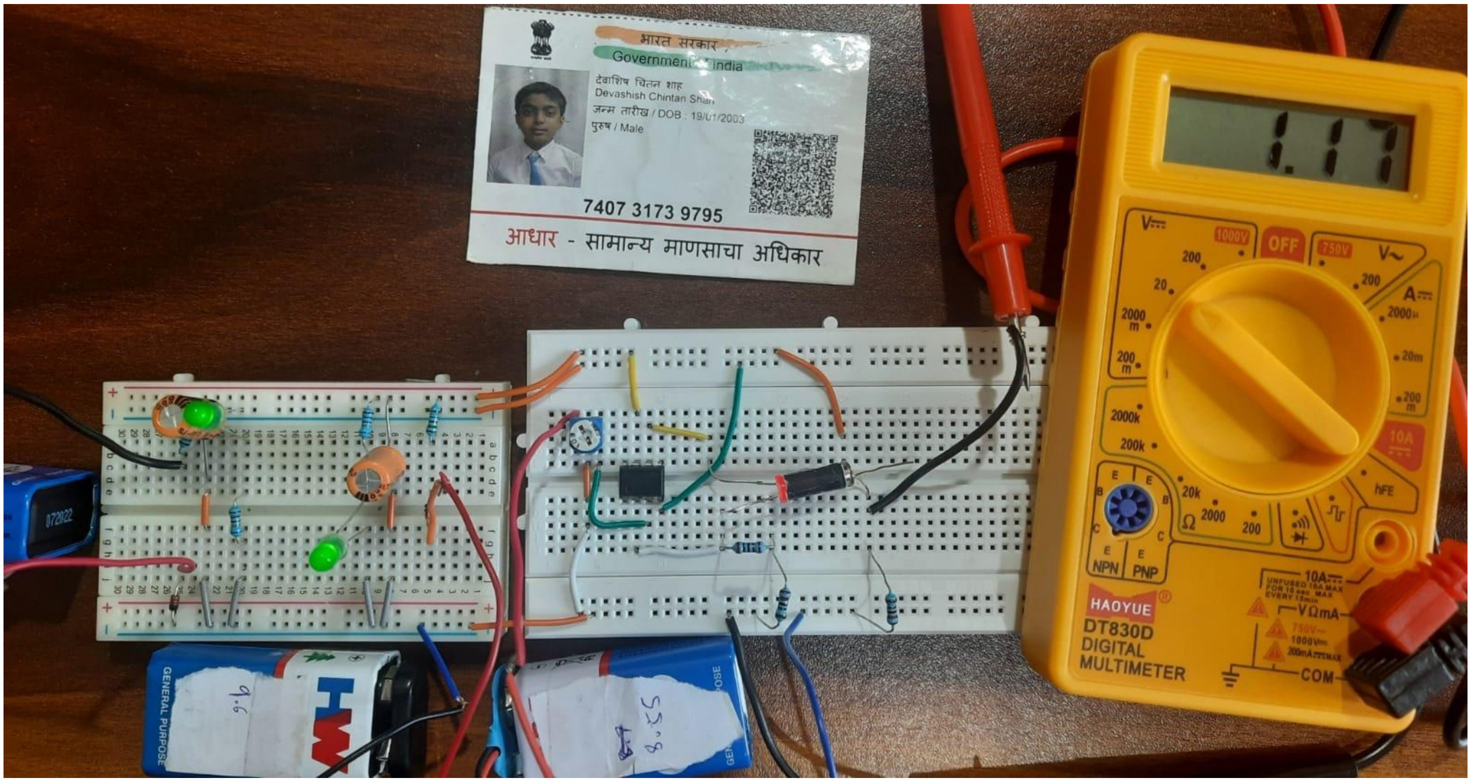
$$V_{out|sensor} = 0.80V$$



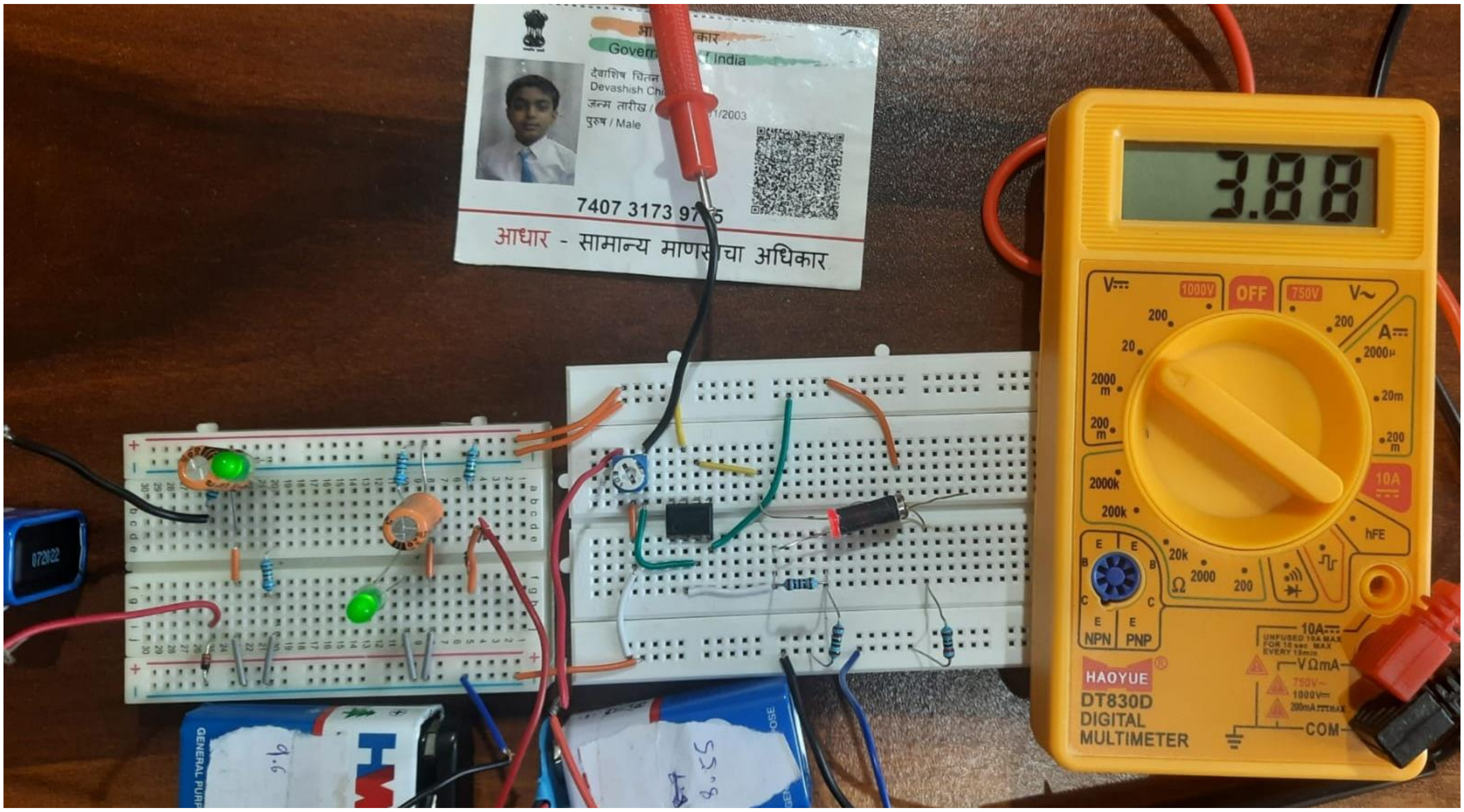
$$V_{in|acturator} = 3.03V$$



$$V_{out|sensor} = 1.17V$$



$$V_{in|acturator} = 3.88V$$



$$V_{out|sensor} = 1.44V$$