ESP 3903: Creating Sensors

Creating Sensors
(Thermal Sensors)

A/P Chua Kian Jon Ernest
Mechanical Engineering Dept
Email: mpeckjei@nus.edu.sg
Room: E1-07-09, Tel.: 6516 2558

Module Details

Venue: Faraday Lab, E4-02-01

Time: Wednesday, 9am-1pm

Aim of the module

The aim of this module is for students to **design, make and test** their own sensor systems.

Assessment

Students will be divided into groups of **three/four** at the start of the module and assessment of the module will be made in the following way:

- **Mid-term presentation (30% of the mark)**
- **Final Presentation (70% of the mark)**

At their Mid-term/Final presentations, students will **present both as a group and individually** on the work they have carried out.

Other ESP staff (outside the ESP 3903 course) will be involved as examiners.

Module Details

Project Management: Students are free to purchase and acquire the materials they need for the project. A sum of up to 100 S$ per group will be allocated, and students should try to have their purchases for the project committed or spent by the end of February, contact ESP Admin Staff in the ESP office for more details on purchasing procedure.

The format of the course will be as follows:

W1: Lecture 1: Mechanical/Thermal sensors (Ernest)

Lecture 2: Sensors and Electronic Circuits (A. Khursheed)

Students to form their own groups, 3/4 students in each group

W2: Lecture 3: Summary of LabView (A. Bettiol), Wednesday 19 January at 10am

Laser Cutter Demo

W7: Mid-term Presentation (after the break week)

W12: Final Presentation

Module Details

Project Outline: Students are free to make a **sensor or energy harvester** of their own choice, however, they should **design and fabricate the main part of the system for themselves**. They should aim to use simple readily available materials. The sensor for example, might measure any one of the following: **temperature, pressure, humidity, electric/magnetic field strength, stress, strain, position, vibration, sound, light intensity, or any other parameter** important in science and engineering. Students are expected to design and make a suitable electrical circuit for the sensor, so that its output signals can be transferred to a computer, and stored in the form of data files that can be displayed in the form of graphs/maps. At the end of the project, students should be able to **demonstrate the effectiveness of their sensor**, typically comparing it to a professional one, and where possible, they are encouraged to make sensor arrays that can **directly monitor 2D/3D distributions in real time**. The projects fall under the following broad areas, such as, **medical sensors for improved health, energy saving sensors** for applications such as Green Buildings, and energy harvesting devices.

If an Energy Harvester project is selected, in addition to measuring the **electricity output**, students are still required to use LabView to monitor the output. Ideally, they should use the Energy Harvester system to drive devices.

Students must make up their own electrical circuits, using individual components, such as **resistors, capacitors, inductors, diodes, transistors and Op-Amps**. They will typically use LABVIEW software to transfer data to a computer. A **Laser cutter** and 3D Printer will be available to students in assisting them manufacture their sensors/harvesters and is located on the 4th floor in the WS2 building.

In some cases, it may be necessary to **use professional sensors/specialized ICs**. Light sensors are for instance, difficult to make with readily available materials, however, the **main part of the system** should still be **designed and fabricated by students themselves**. The main requirement from the project is that students design and fabricate something for themselves.

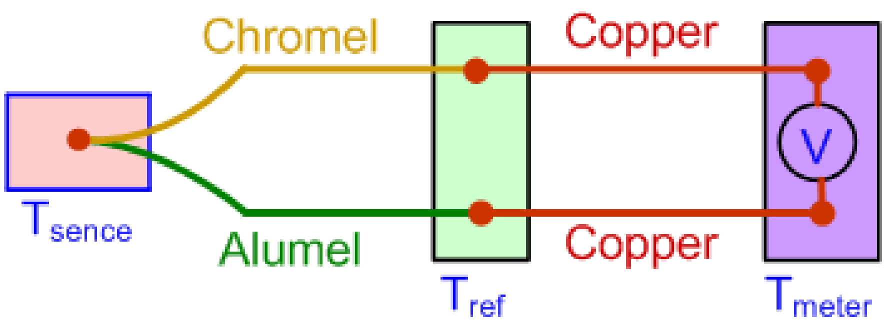
General Guidelines

Once students decide on their project, they should **consult with Ernest, Khursheed and Karuppiah**. They should also consult with Raisul, Ernest Chua and Karuppiah before the Mid-Term and Final Presentations. These consultations are mandatory. Khursheed, Ernest Chua and Karuppiah will be available for consultation in their respective offices.

An important part of the assessment will be how students manage their project. Students must themselves place limits on what they attempt. Often students are **too ambitious**, and attempt something for which they have **no background** (too complicated electronic circuits), or rely on **materials that are not available** (take too long to purchase/acquire). They themselves must set limits on their project, to what is realistic in the time-frame that they have. They must **not spend more than 10 hours per week** on the project, and restrict their project accordingly to what can be done within this time-frame. There is **no simulation requirement** in this project. No extra marks will be given for running simulation programs, unless it is essential for the design of the sensor. This is basically **a hands-on project**, where students are encouraged to source their own materials, fabricate things for themselves, and use only things that they themselves understand very well.

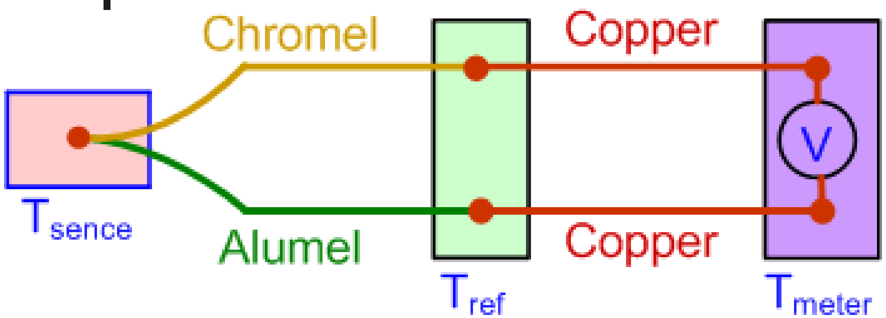
Temperature Measuring Sensors: Thermocouple

- **Seebeck Effect:** when any conductor is subjected to a thermal gradient, it will generate a voltage
- Under open-circuit conditions where there is no internal current flow, the gradient of voltage ∇V is directly proportional to the gradient of temperature ∇T.
- $\nabla V = S(T)\,\nabla T$ where S(T) is a temperature dependent metal property know as the Seebeck coefficient
- Thermocouple is developed based on Seebeck Effect. Typical configuration of thermocouple:



K-type thermocouple (Chromel–alumel) in the standard thermocouple measurement configuration. The measured voltage V can be used to calculate temperature T_{sence}, provided that temperature T_{ref} is known.

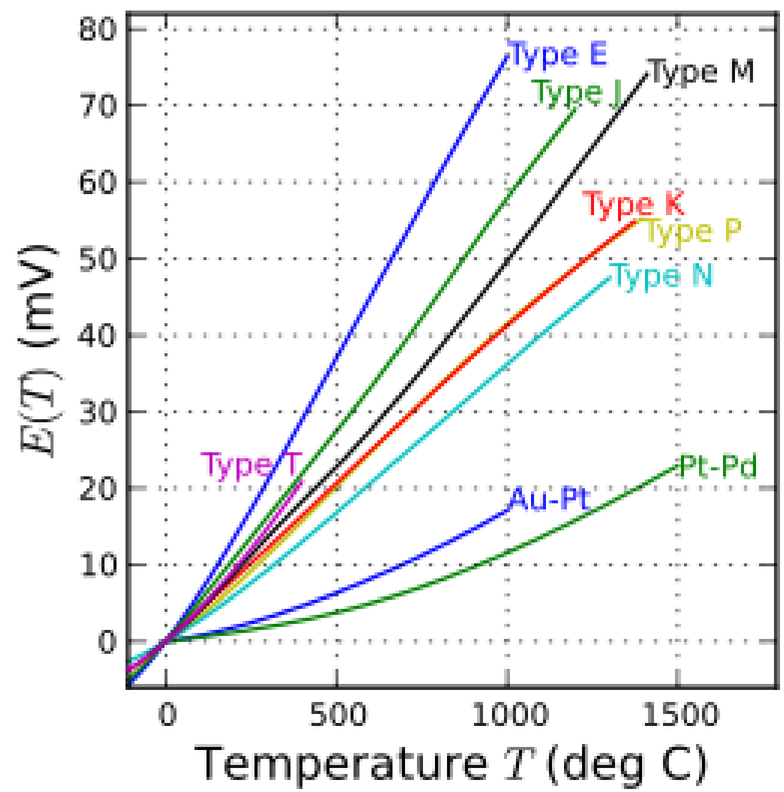
Temperature Measuring Sensors: Thermocouple



- Details are often hidden from the user since the reference junction block (with T_{ref} thermometer), voltmeter, and equation solver are combined into a single product.

- Common type thermocouples:

Type	Material	Measuring range	Sensitivity
E	Chromel – Constantan	−110 ºC to +740 ºC	About 68 µV/ºC
J	Iron – Constantan	−40 ºC to +750 ºC	About 50 µV/ºC
K	Chromel – Alumel	−200 ºC to +1350 ºC	About 41 µV/ºC
N	Nicrosil–Nisil	−270 ºC to +1300 ºC	About 39 µV/ºC
T	Copper – Constantan	−200 ºC to 350 ºC	About 43 µV/ºC



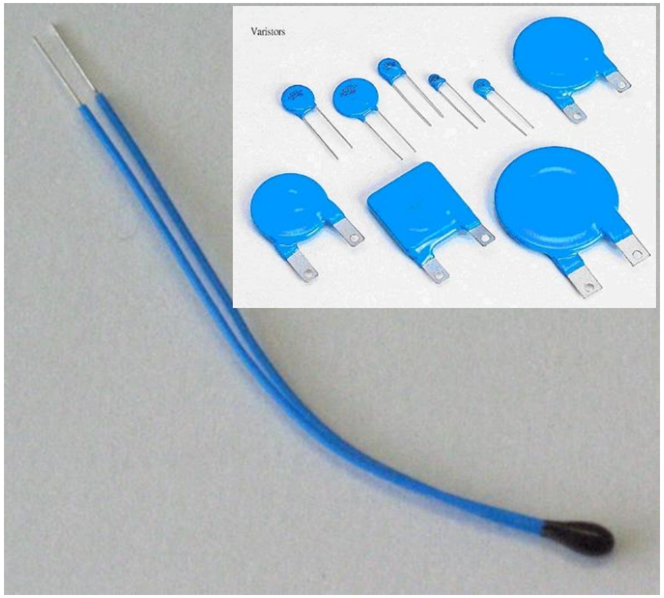
Temperature Measuring Sensors: RTD

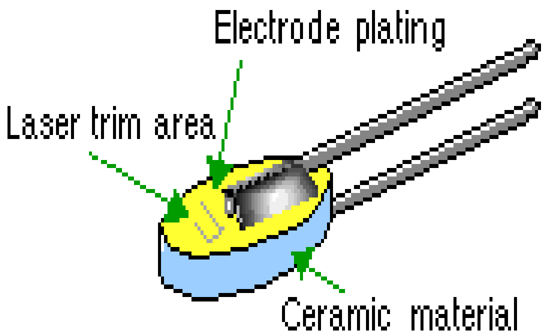
- RTD sensors: Resistance Temperature Detectors based sensors.
- Sensors (used to measure temperature) by correlating the resistance of the RTD element with temperature.
- Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core.
- Element is usually quite fragile, so it is often placed inside a sheathed probe to protect it
- Common resistance materials used for RTDs:
  - ✓ Platinum (most popular and accurate)
  - ✓ Nickel and
  - ✓ Copper

RTD Thermometer with probe

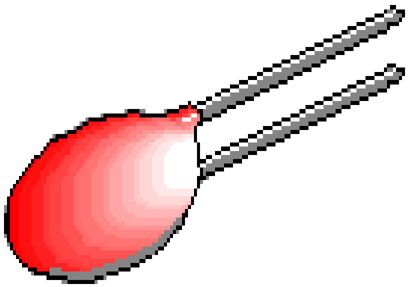
Temperature Measuring Sensors: Thermistor

- A thermistor is a resistor whose resistance varies significantly with temperature
- Material used in a thermistor is generally a ceramic, while RTDs use pure metals
- RTDs are useful over larger temperature ranges, while thermistors typically achieve a higher precision within a limited temperature range, typically $-90^{o}C$ to $130^{o}C$



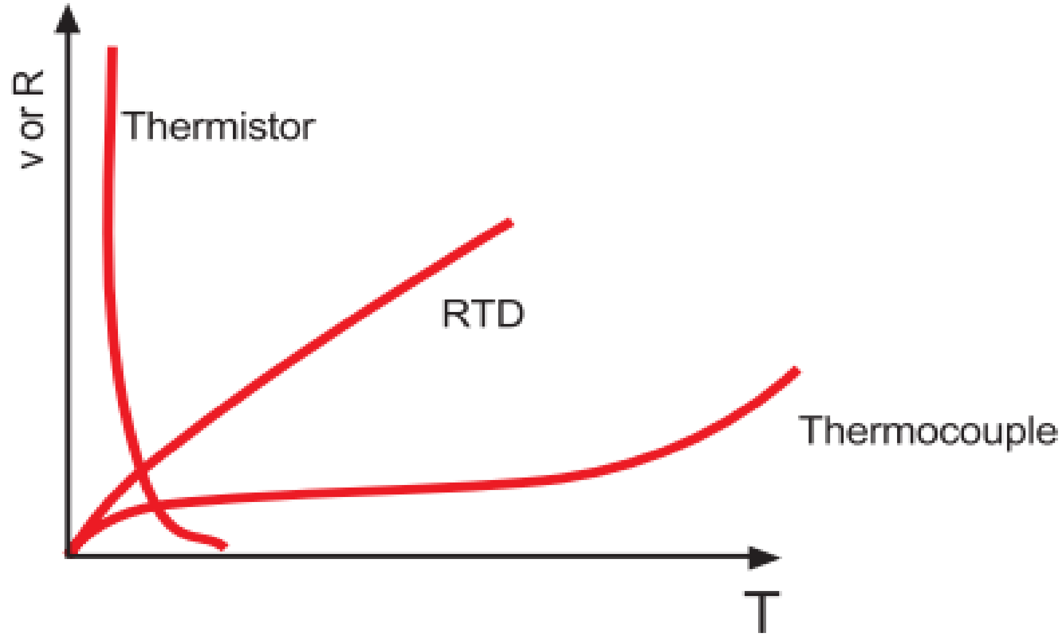


Thermistor without Encapsulation



Thermistor with Encapsulation

Comparison Among Different Temperature Sensors



- The word that best describes the thermistors is "Sensitive"

Thermocouple: Linear or non-linear equation

RTD: Callendar-Van Dusen equation

$$R_T = R_0\left[1 + AT + BT^3 + CT^3(T-100)\right]$$

R_0 = Resistance at 0°C

Thermistor: Steinhart–Hart equation

$$\frac{1}{T} = a + b\ln(R) + c\left[\ln(R)\right]^3$$

$a = 1.4 \times 10^{-3}$ $b = 2.37 \times 10^{-4}$

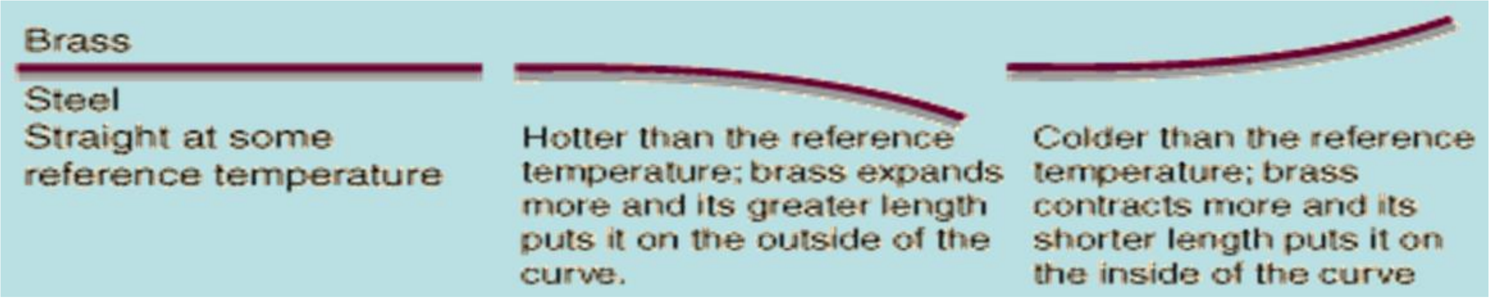
$c = 9.90 \times 10^{-8}$

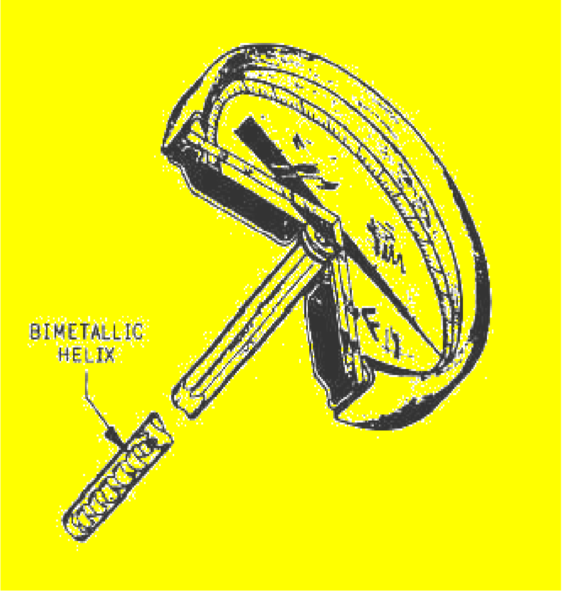
Portable Infrared Thermometer

- Infrared thermometers measure temperature using blackbody radiation (generally infrared) emitted from objects

- They are sometimes called laser thermometers if a laser is used to help aim the thermometer, or non-contact thermometers to describe the device’s ability to measure temperature from a distance.

Bimetallic Thermometer

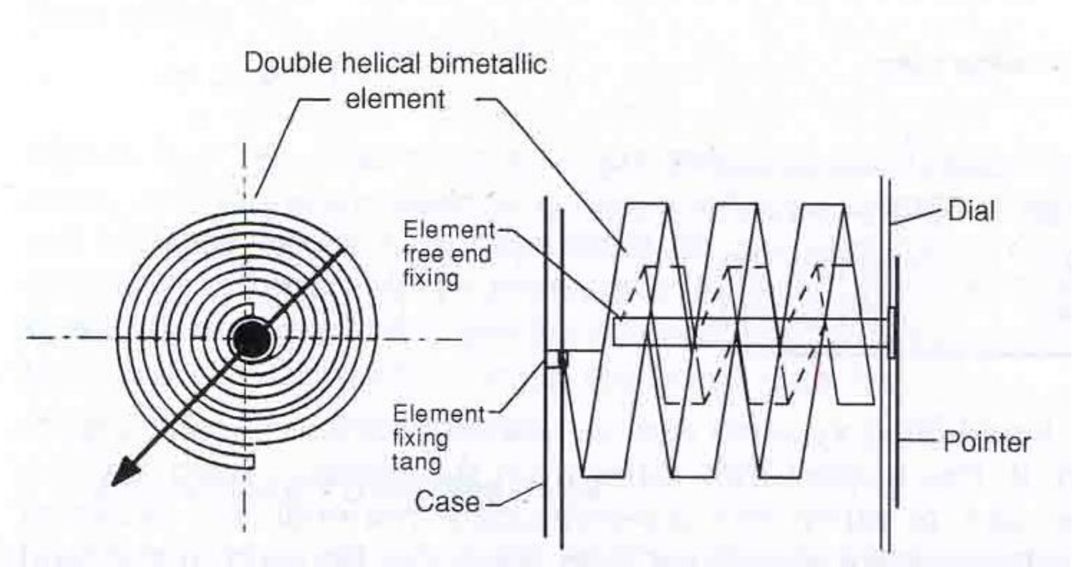




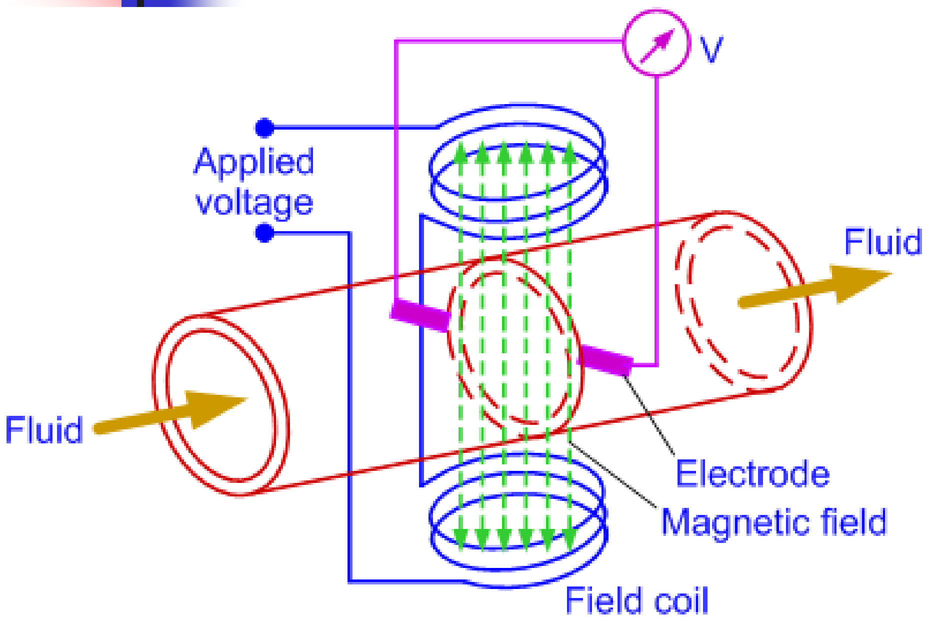
Bimetallic thermometer

Effect of unequal expansion of a bimetallic strip

- Different metals have difference coefficient.
- Configured as spiral or helix for compactness
- Can be used with a pointer to make an inexpensive compact rugged thermometer.



Electromagnetic Flowmeter

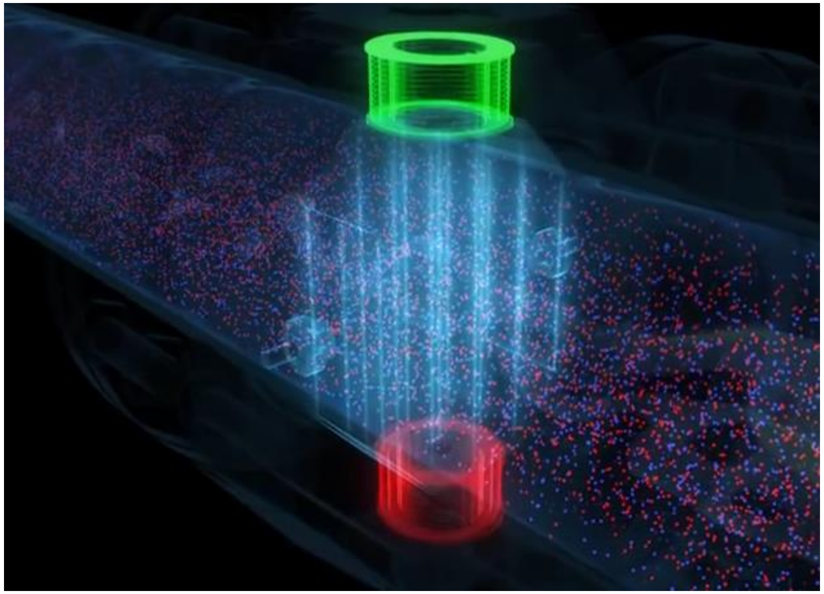


- Two field coils are installed that generate constant magnetic field over the entire cross section of the measuring pipe.
- Two electrodes which can pick up electrical voltage are installed at right angle on the wall of the tube
- As the conductive fluid starts to flow through the tube, the magnetic field applies force to the electrically charged particles. As result, positively and negatively changed particles are separated and collect on the opposite side of the pipe wall
- Now an electrical voltage forms which is detected and measured by the electrodes.
- Flow measuring error < ±1%

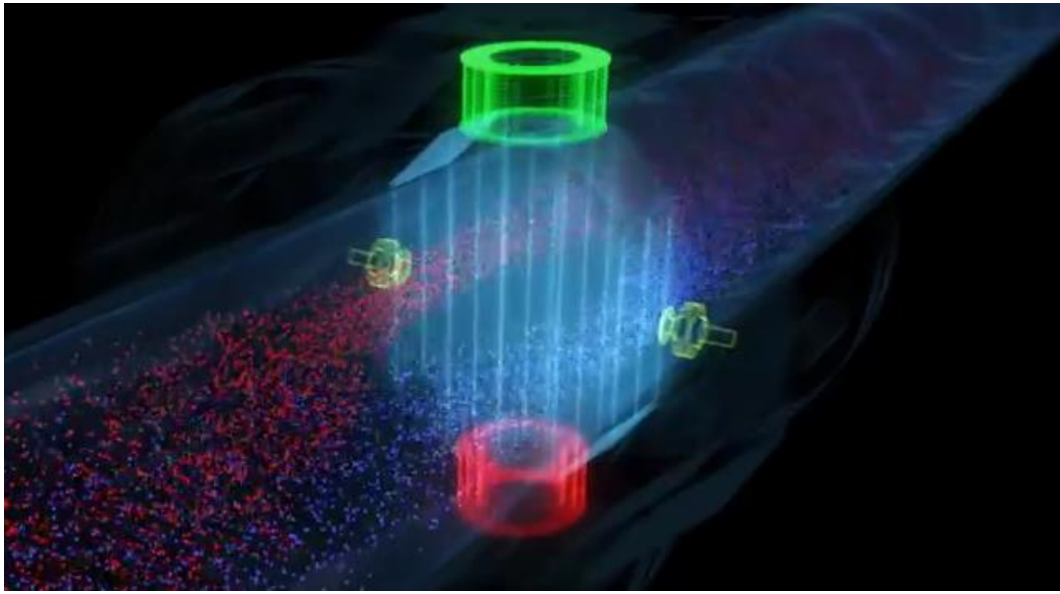
➢ No head loss by the flow meter

➢ Need to cut pipe for installation

Electromagnetic Flowmeter



Before starting fluid flow
(Positively and negatively changed particles are not separated)



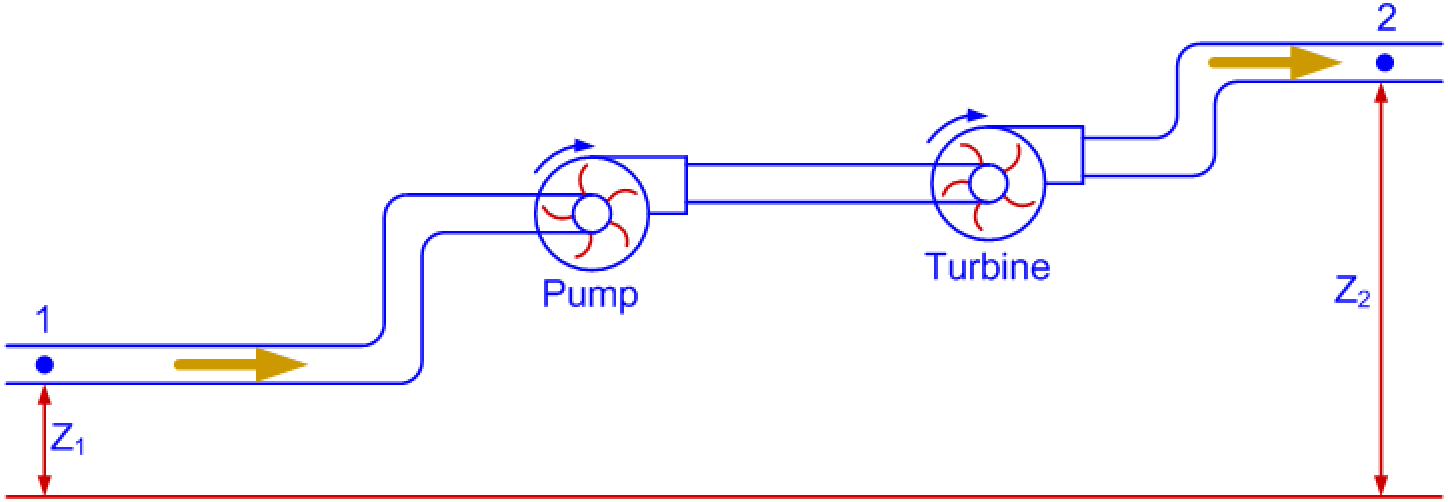
After starting fluid flow
(Positively and negatively changed particles are separated)

- Used to measure flow of conductive fluids such as water, chemicals, corrosive fluids, slurries

Insertion type:
Operate similarly

Bernoulli Equation

- Useful for fluid flow analysis and development of flow sensors



$$\frac{P_1}{\rho_1 g} + \frac{V_1^2}{2g} + Z_1 + \frac{W_{pump}}{g} = \frac{P_2}{\rho_2 g} + \frac{V_2^2}{2g} + Z_2 + \frac{W_{turbine}}{g} + e_{loss}$$

where P = Pressure, Pa

ρ = Density, kg/m^3

g = Acceleration due to gravity, 9.81 m/s^2

V = Velocity, m/s

Z = Height from datum line, m

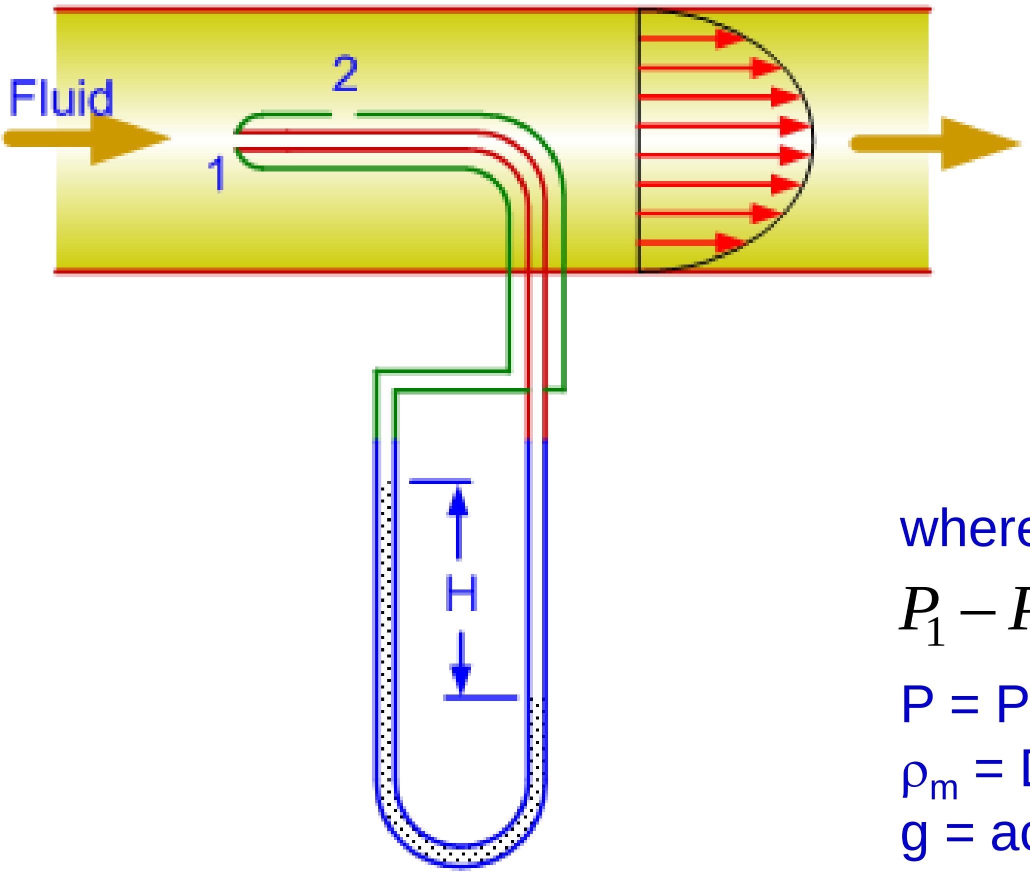
W_{pump} = Power input to pump for unit mass flow rate of fluid, W/(kg/s)

$W_{turbine}$ = Power output by generator for unit mass flow rate of fluid, W/(kg/s)

e_{loss} = Pressure loss in piping system, m

Pitot and Pitot-Static Probe

$$\frac{P_1}{\rho_1 g}+\frac{V_1^2}{2g}+Z_1+\frac{W_{pump}}{g}=\frac{P_2}{\rho_2 g}+\frac{V_2^2}{2g}+Z_2+\frac{W_{turbine}}{g}+e_{loss}$$



Bernoulli Eq. between point-1 (stagnation point) and point-2:

$$\frac{P_1}{\rho_1 g}=\frac{P_2}{\rho_2 g}+\frac{V_2^2}{2g}$$

$$V=\sqrt{\frac{2(P_1-P_2)}{\rho}}$$

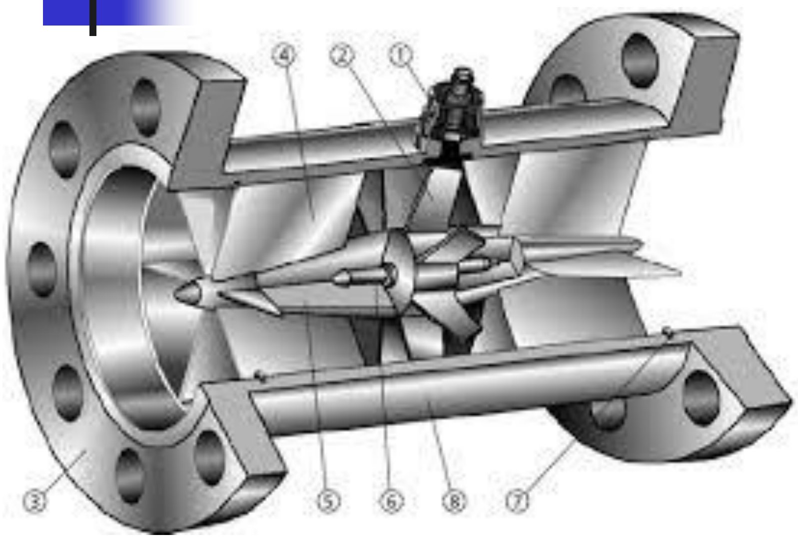
where:

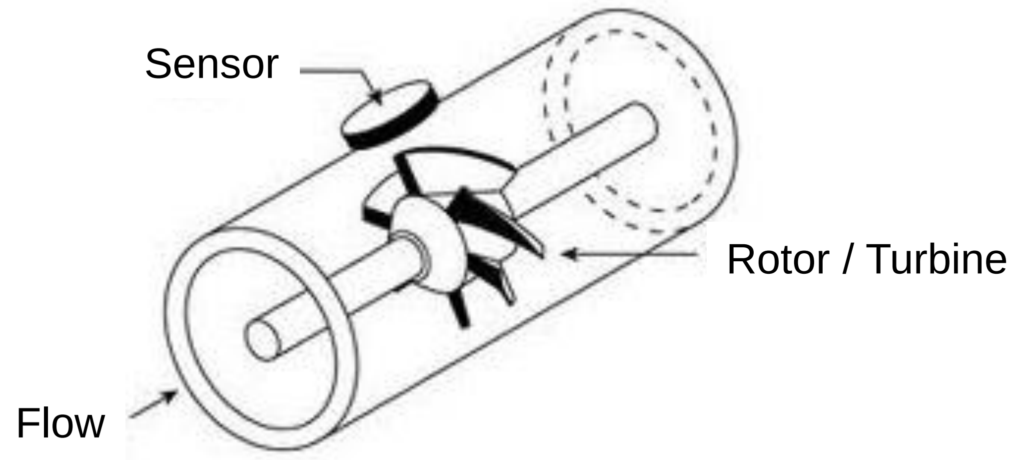
$$P_1-P_2=H\rho_m g$$

P = Pressure, Pa
ρ_m = Density of manometric fluid, kg/m^3
g = acceleration due to gravity, 9.81 m/s^2
V = Velocity, m/s

Differential pressure transducer or inclined manometer can also be used to measure (P_1-P_2)

Turbine Flowmeter





- Consists of a cylindrical flow section that houses a turbine (a vaned rotor) that is free to rotate
- Additional stationary vanes at the inlet to straighten the flow
- Sensor generates a pulse each time a marked point on the turbine passes by to determine the rate of rotation
- Rotational speed of the turbine is nearly proportional to the flow rate of the fluid
- Measuring error < ± 0.25% when calibrated properly

Vane Anemometer

Air flow velocity Air flow velocity, T & RH Small duct Wind speed

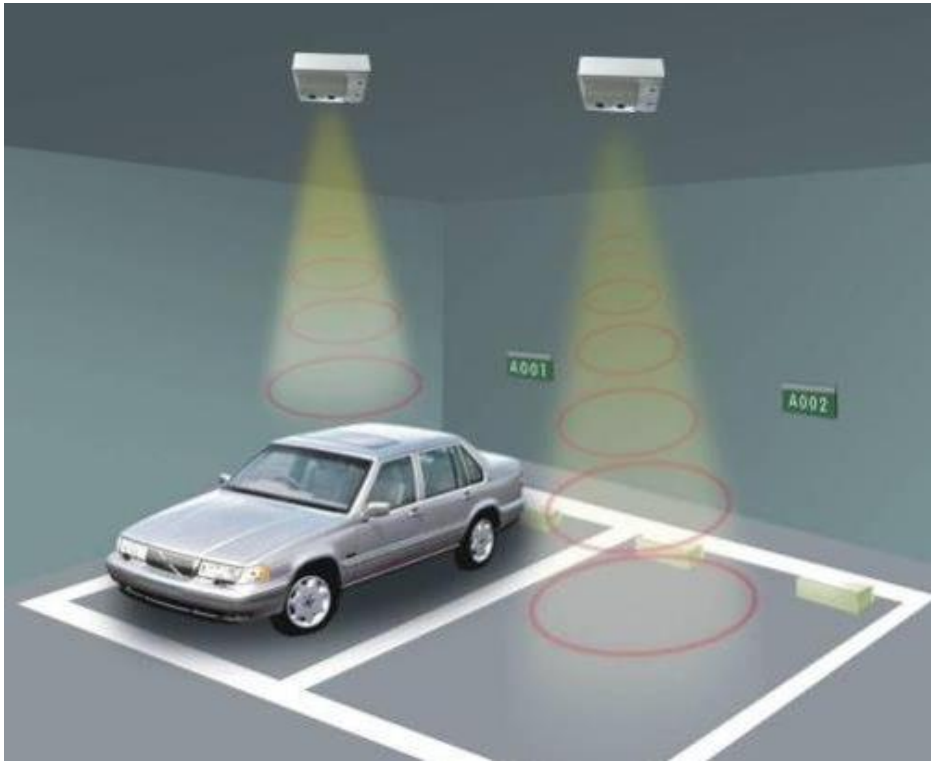
- Simple, low cost and good accuracy
- Can be used for wide range of flow conditions
- Commercially available for both liquid and gases and for pipes of practically of all sizes
- Also used to measure flow velocities in unconfined flows such as winds, rivers and ocean currents

Thermal (Hot-Wire and Hot-Film) Anemometer

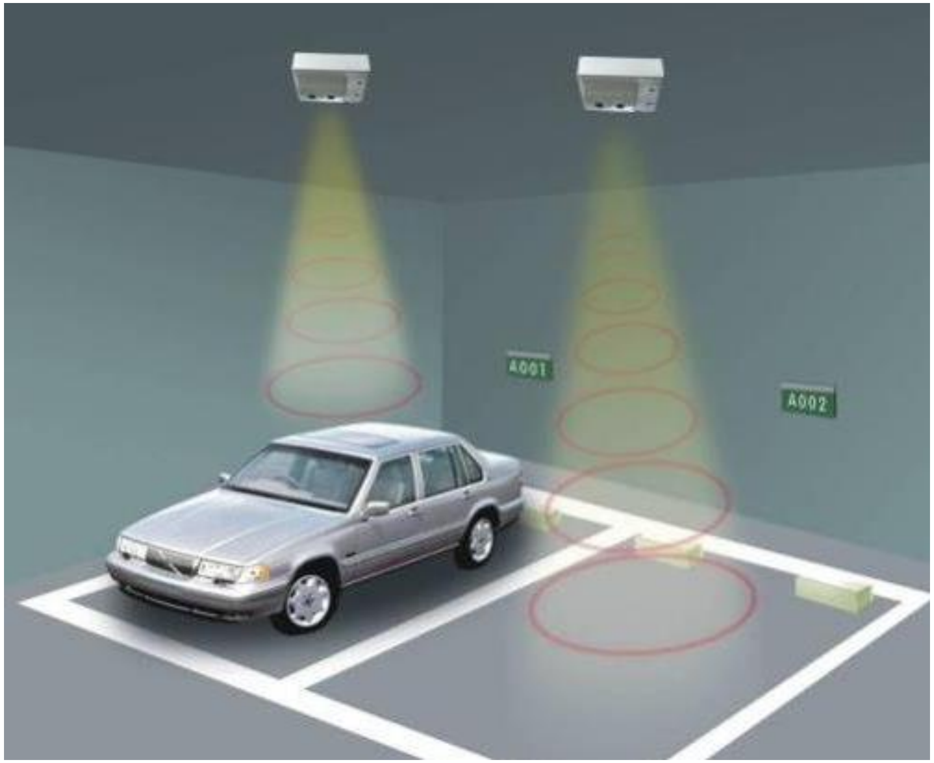
- Thermal anemometers involve an electrically heated sensor (about 5 μm dia and 1 mm length for hot-wire; less than 0.1 μm thick metallic film mounted on about 50 μm dia ceramic support for hot-film)
- Electronic controls maintain the sensor at a constant temperature by varying the electric current (by varying the voltage). The sensor tends to cool as it loses heat to the surrounding flowing fluid
- Relationship between electric current and flow velocity is developed
- Can be used to measure the instantaneous velocity at any point in the flow without appreciably disturbing the flow
- Can take thousands of velocity measurements per second – used to study the details of fluctuations in turbulent flow

Photograph of Motion Sensor

- Active ultrasonic sensors emit ultrasonic sound waves at a frequency above the range of human hearing.
- These waves bounce off objects in the immediate vicinity and return to the motion sensor.
- The sensor determines the distance between itself and the target by measuring the time between sending and receiving the signal



Photograph of Motion Sensor



- Can be used in seminar room, corridor, warehouse, carpark, toilet, staircase, lift and accelerator for controlling electrical loads

Relative Humidity Sensor

- Relative Humidity (RH) sensors usually rely on measurements of some other quantity such as temperature, pressure, mass or electrical change in a substance as moisture is absorbed.

- By calibration and calculation, these measured quantities can lead to a measurement of humidity

- Modern electronic devices use temperature of condensation (Dew point) or changes in electrical capacitance or resistance to measure humidity differences.

Different RH meters:

a) Metal-paper coil type: water vapour is absorbed by a salt-impregnated paper strip attached to a metal coil, causing the coil to change shape

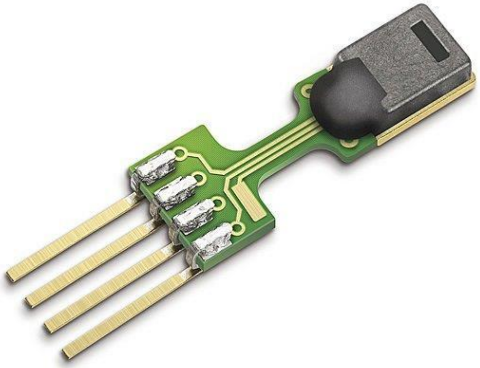
Relative Humidity Sensor

Different RH meters:

b) Sling Psychrometer: measure dry-bulb and the wet-bulb temperature

c) Resistive humidity sensors: change in electrical resistance of a material due to humidity

d) Thermal conductivity humidity sensors: change in thermal conductivity of air due to humidity



Describing Sensor Performance

- **Range**
  - maximum and minimum values that can be measured

- **Resolution or discrimination**
  - smallest visible change in the measured value

- **Error**
  - difference between the measured and actual values
    - **Random errors:** caused by unknown and unpredictable changes in the experiment. These changes may occur in the measuring instruments or in the environmental conditions
    - **Systematic errors:** usually come from the measuring instruments (something wrong with the instrument or its data handling system, instrument is wrongly used)

- **Accuracy, inaccuracy, uncertainty**
  - accuracy is a measure of the maximum expected error

Sensor Calibration

- **Sensors can exhibit non-ideal effects**
  - **Offset:** nominal output ≠ nominal parameter value
  - **Nonlinearity**: output not linear with parameter changes
  - **Cross parameter sensitivity:** secondary output variation with, e.g., temperature

- **Calibration:** adjusting output to match parameter
  - analog signal conditioning
  - look-up table
  - digital calibration
    - $T = a + bV + cV^2$,

      where T= temperature; V=sensor voltage;

      a,b,c = calibration coefficients

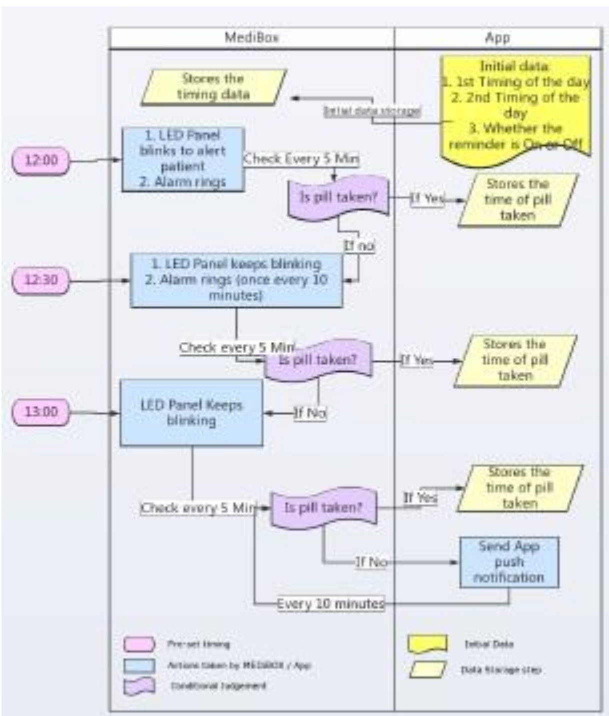
Selection of Projects

- Project has potential application / solve real world problem – Apply for award
- You can implement your **innovative / smart idea**
- You can design and fabricate your own sensor
- Sensor should show desired performance characteristics – linearity, repeatability
- Can fabricate using available resources and test performance within given time
- Search website – how to design, fabricate, test performance, fine tune
- Time management: Design, redesign and fabricate – 50% time; Test and fine tune – 50% time
- Proper allocation of jobs within group members: who will lead which job

Previous Projects

Smart Pill Box to Help Patient Remember to Take Medication

Scenario	Voltage
No Pill	(1.570 +/- 0.003) V
With Pill	(1.600 +/- 0.003) V



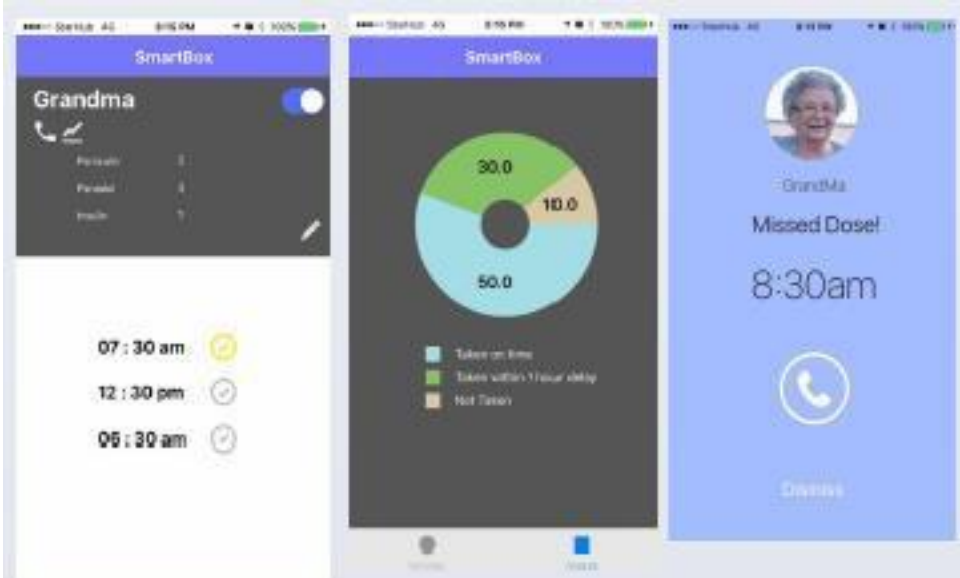


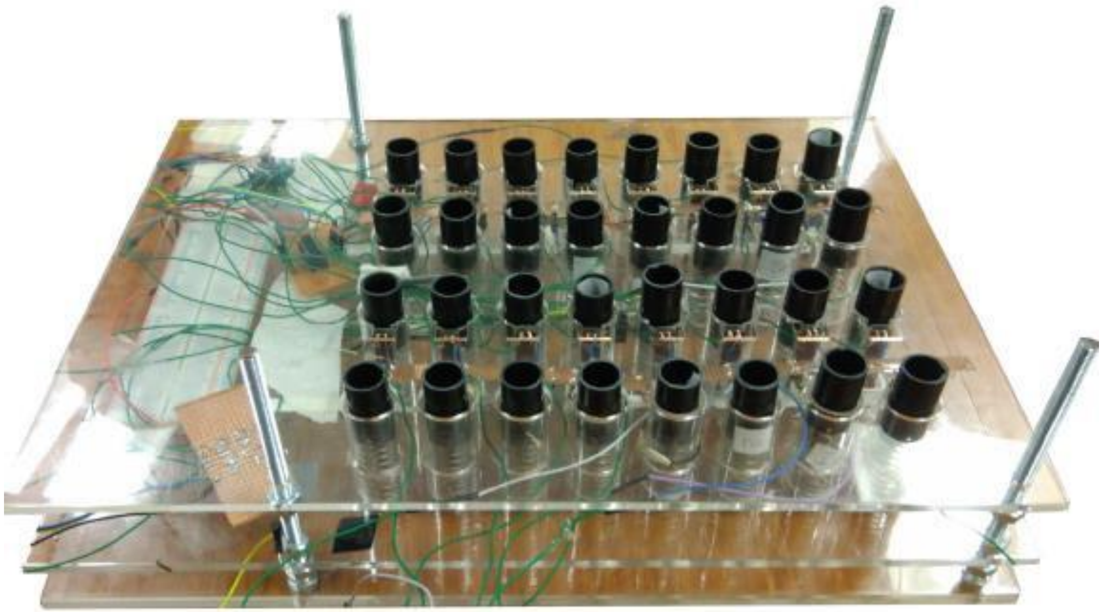
Figure 6 (a) Reminder Monitor Page

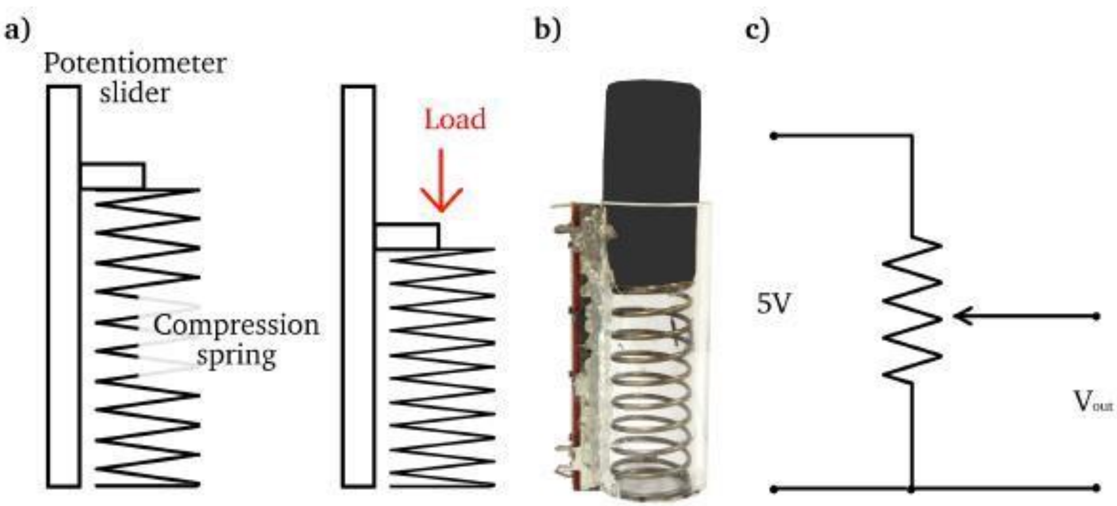
Figure 6 (b) Data analysis page

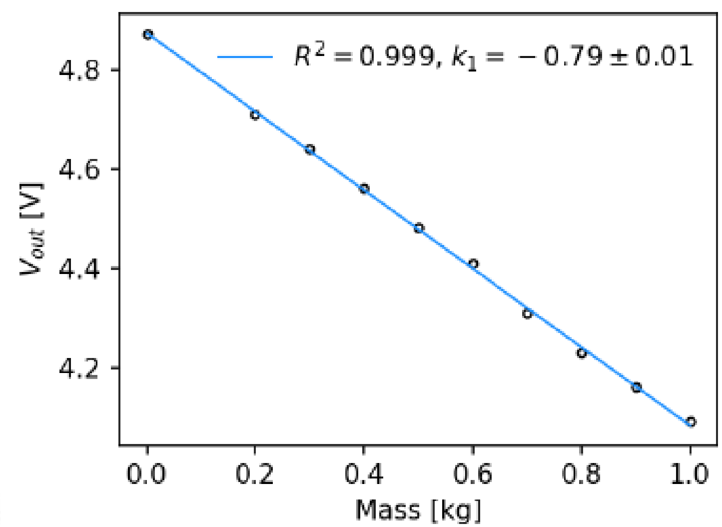
Figure 6 (c) Push Notification

Previous Projects

Pressure-Mapping Sensor Array for Bed-Ridden Patents



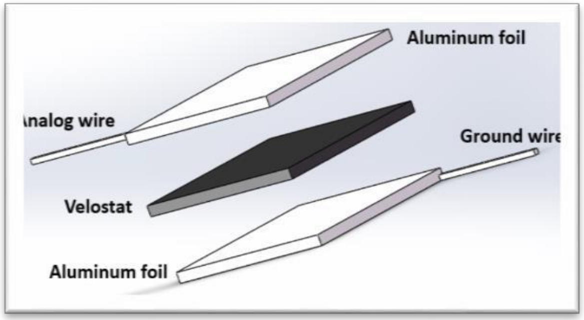




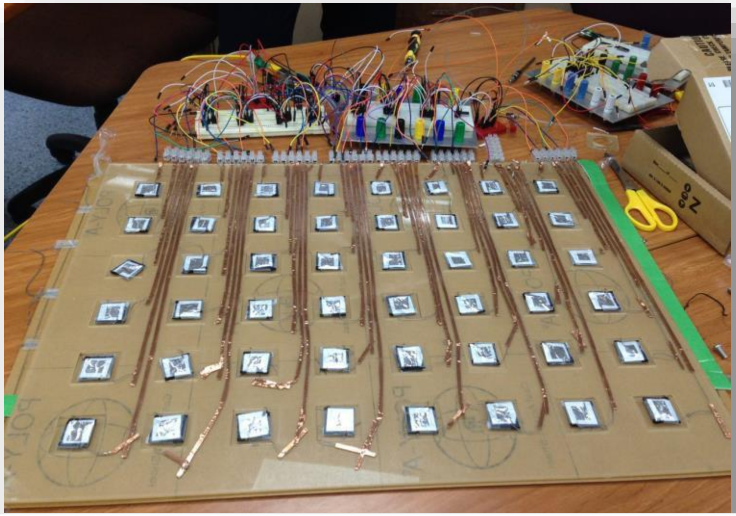
Potentiometer

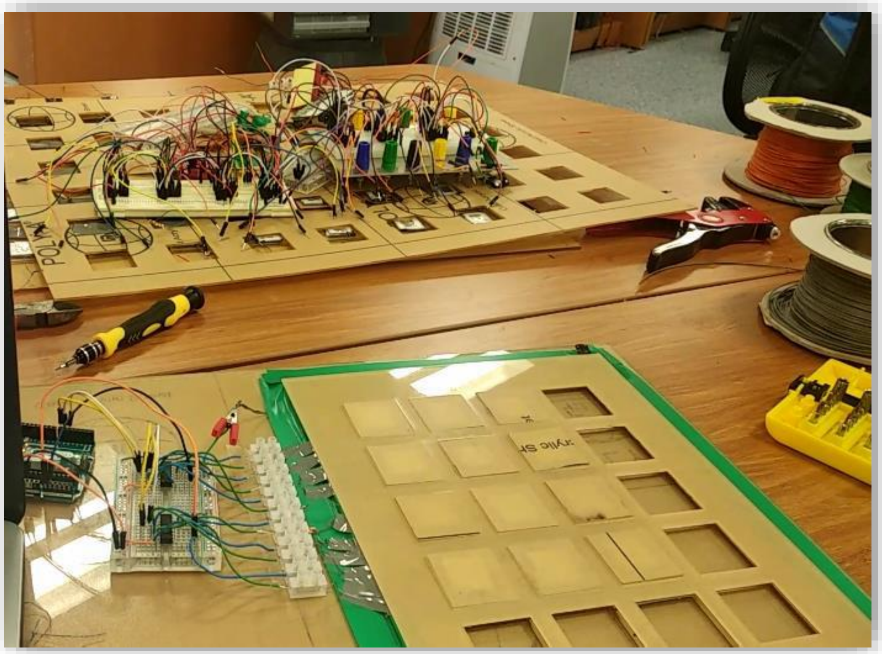
Previous Projects

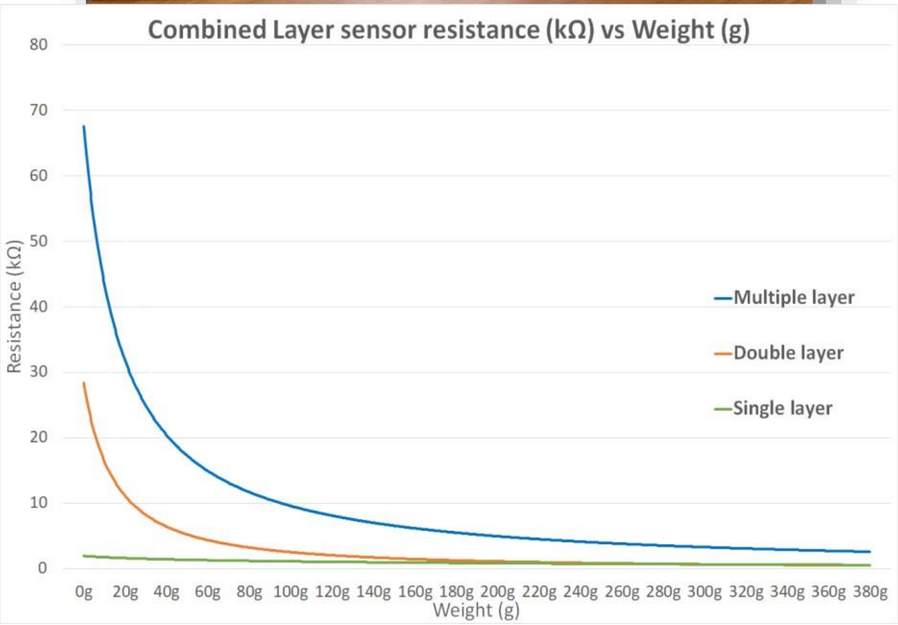
Pressure-Mapping Sensor Array for Bed-Ridden Patents



Velostat is an electrically conductive material that has lower resistance when compressed.

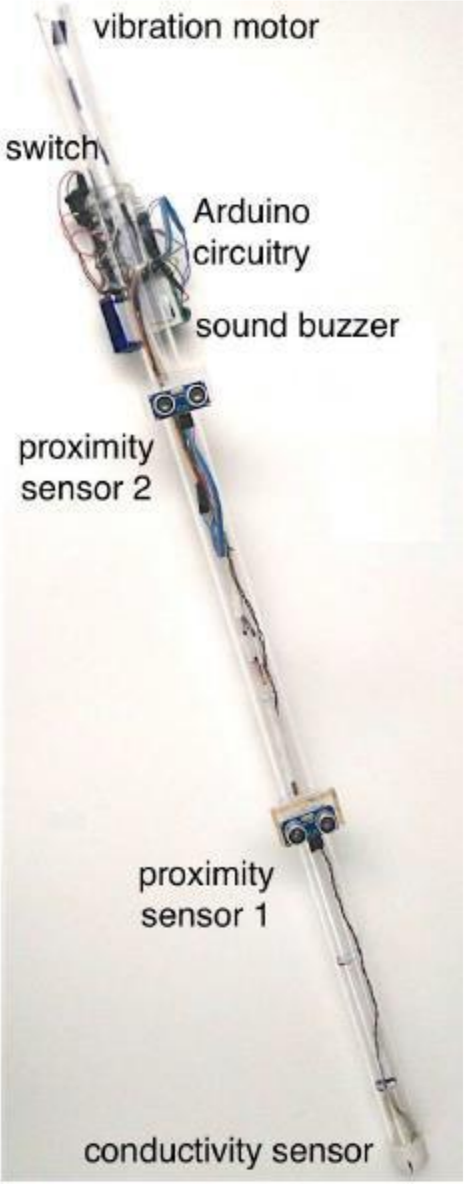


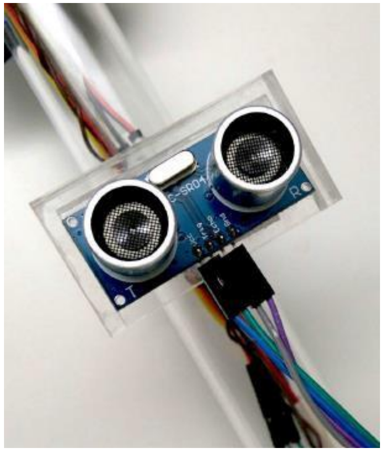




Previous Projects

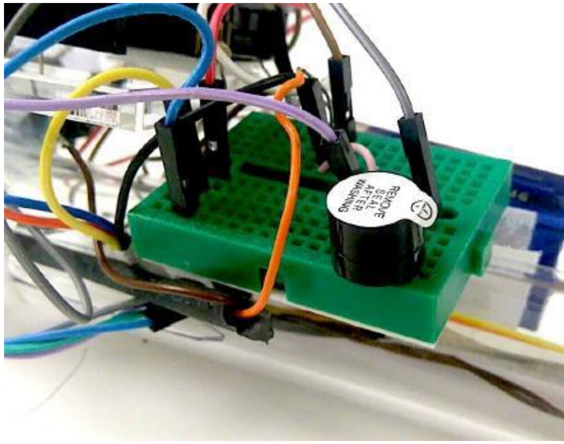
Smart Walking Cane with Obstacle and Wet Surface Detection Functionalities





Ultrasonic transceiver

Vibration Motor



Buzzer

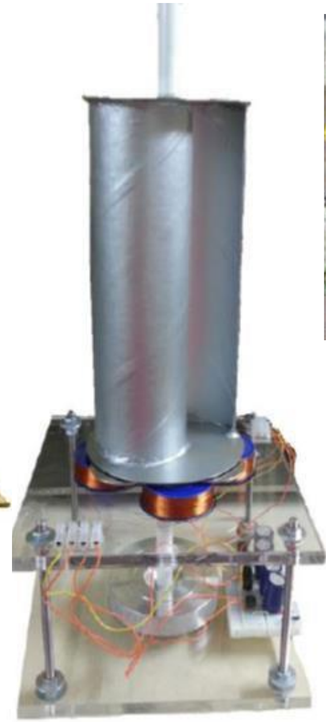
Conductivity Sensor at Cane Tip

Testing performance

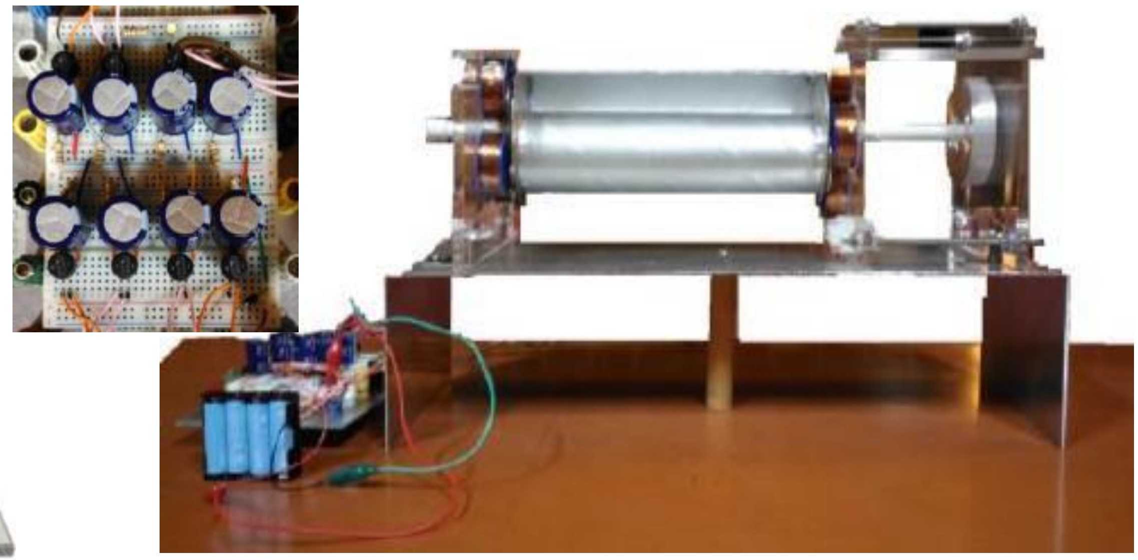
Previous Projects

Energy Harvester: Vertical Axis Wind Turbine

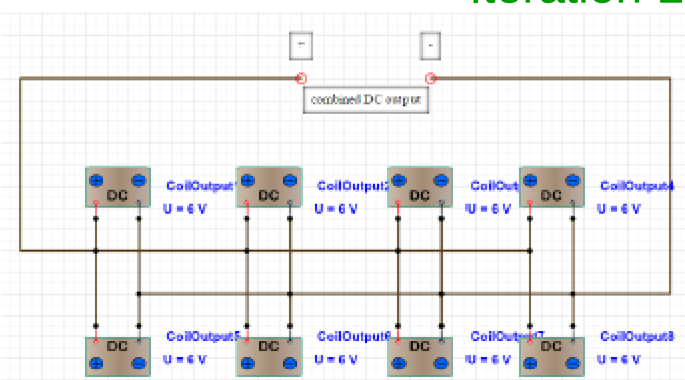
Iteration-1



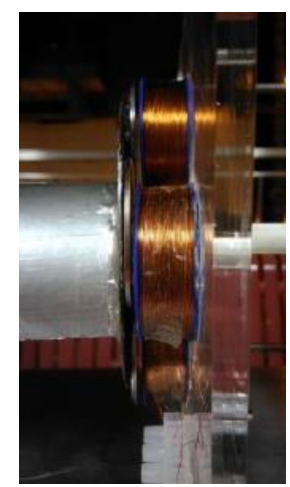
Iteration-2



Final iteration



DC output



System in front of Daikin condenser

Previous Projects

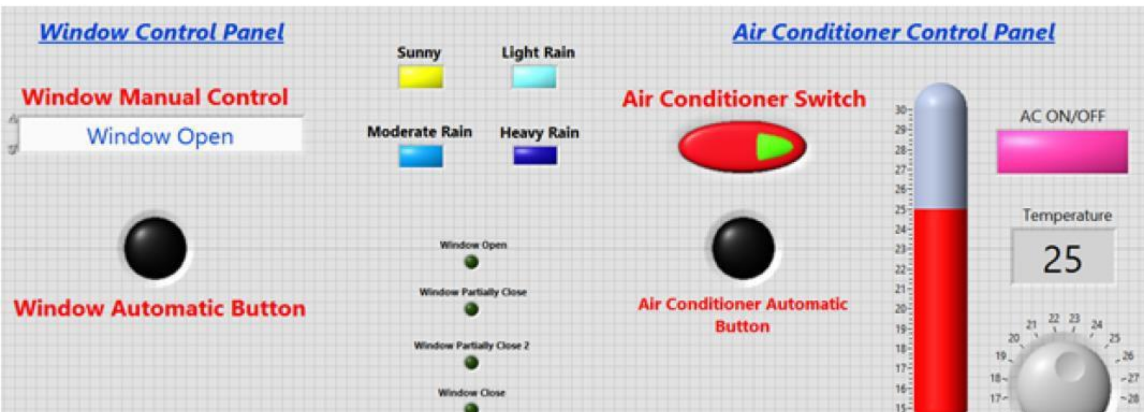
Automated Light and Rain Sensing Window

Light & Rain Sensors

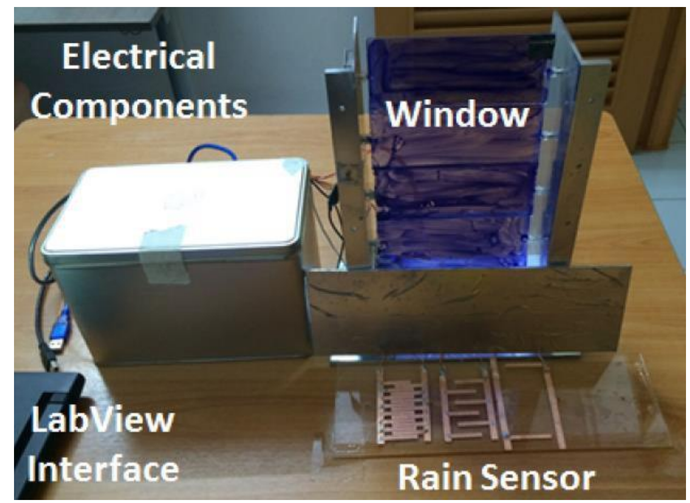
USB 6008 DAQ Card

Arduino Uno Microcontroller

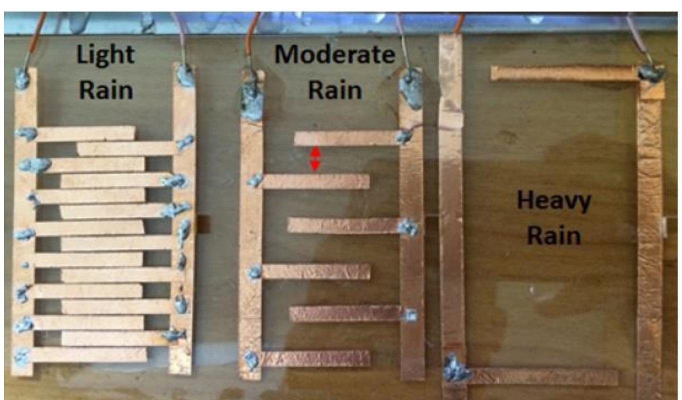
Stepper Motor



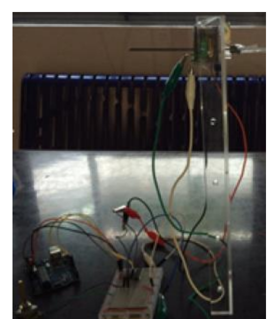
LabVIEW Control Interface



Final setup



Rain Sensor



Previous Projects

Thermal sensing and cooling system for laptops

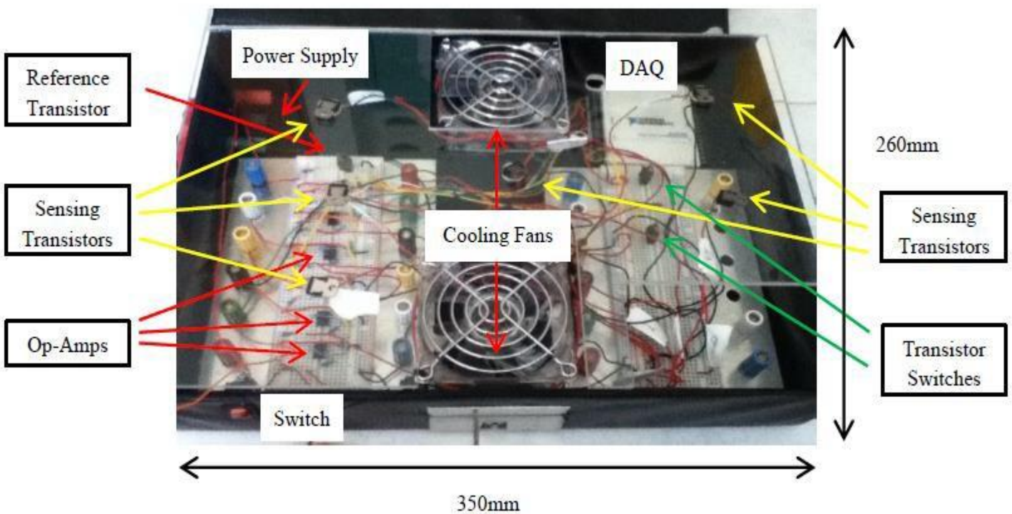


Fig. 2. Actual diagram of thermal sensing system

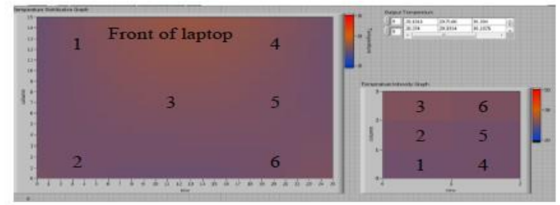


Fig. 9a. Temperature intensity graph at room temperature

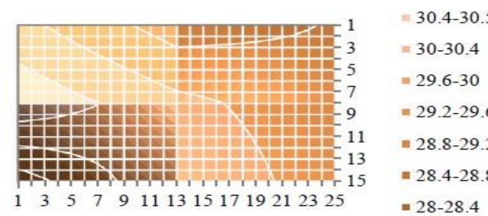


Fig. 9b. Temperature contours at room temperature

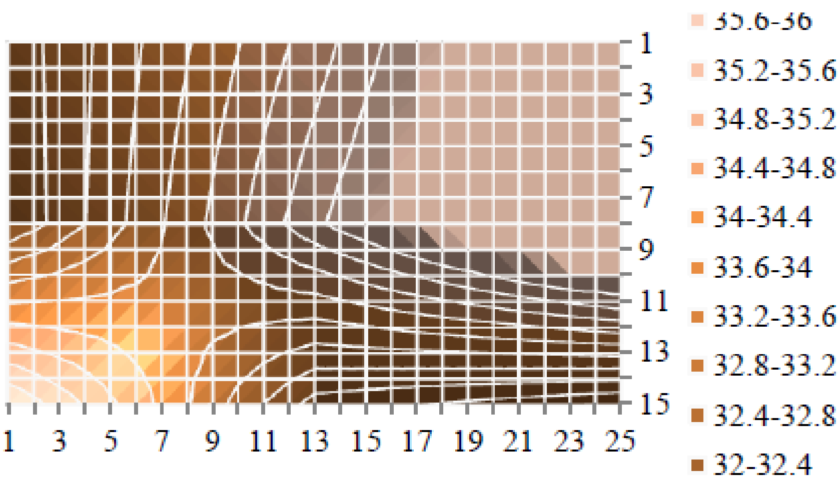


Fig. 11b. Temperature contours after cooling fans are on

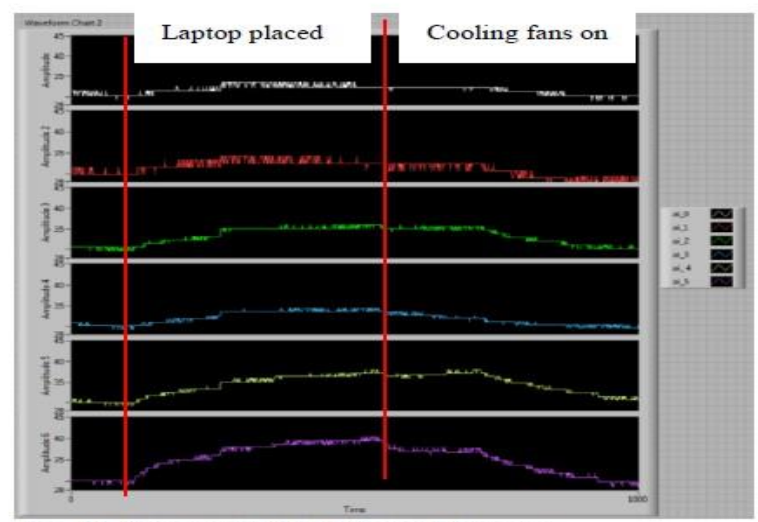


Fig. 12. Temperature time history of 6 sensors

Previous Projects

Automated Window Shutter System in Energy Efficient Building Designs

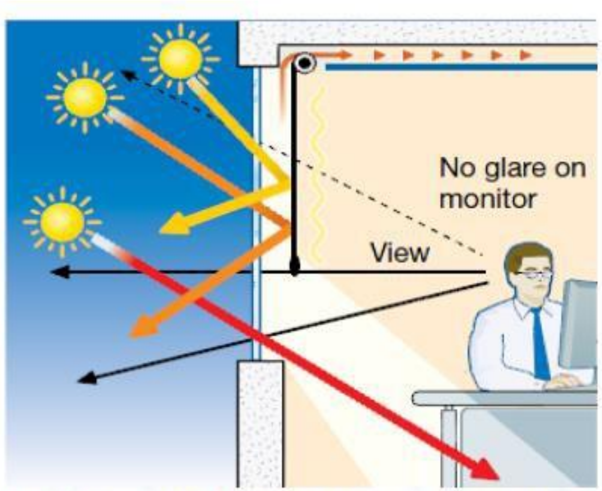


Fig. 2. Solar shade to achieve partial lighting with UV reflection on the top half and preservation of natural view at the bottom half. Natural lighting is known to induce alertness/awakeness in humans.

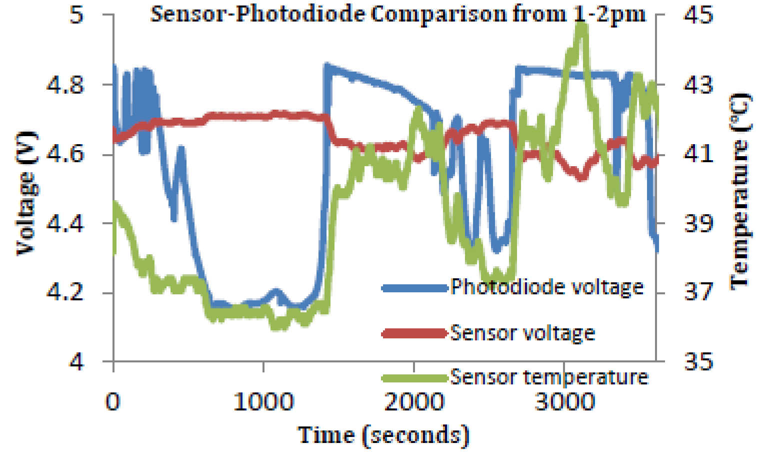


Fig. 12. Graph shows comparison of a photodiode with sensor output voltage. Measurements taken on 28/3/2012 from 1-2pm on a day with scattered clouds with air temperature at 29°C and humidity at

$$ETTV=SF(WWR)(CF)(SC_{external+glazing}-SC_{glazing})=25W/m^2$$

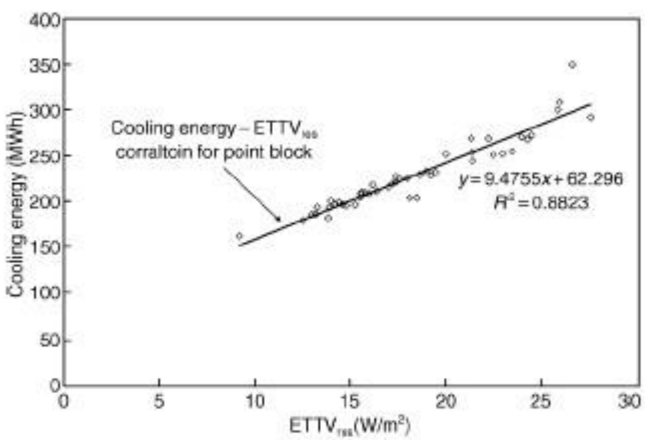
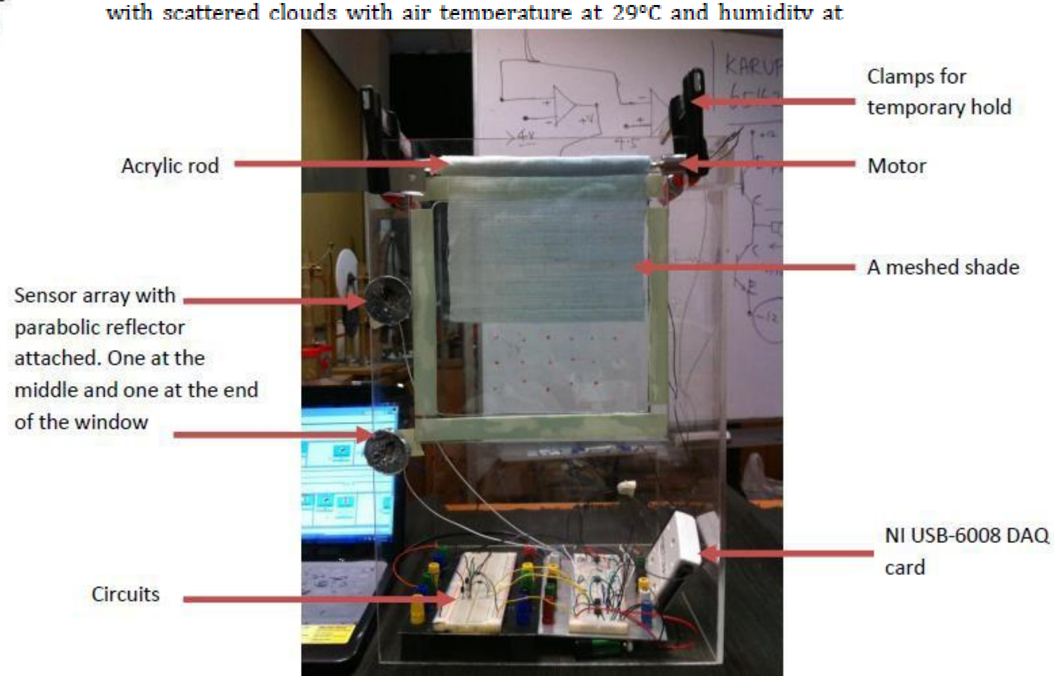
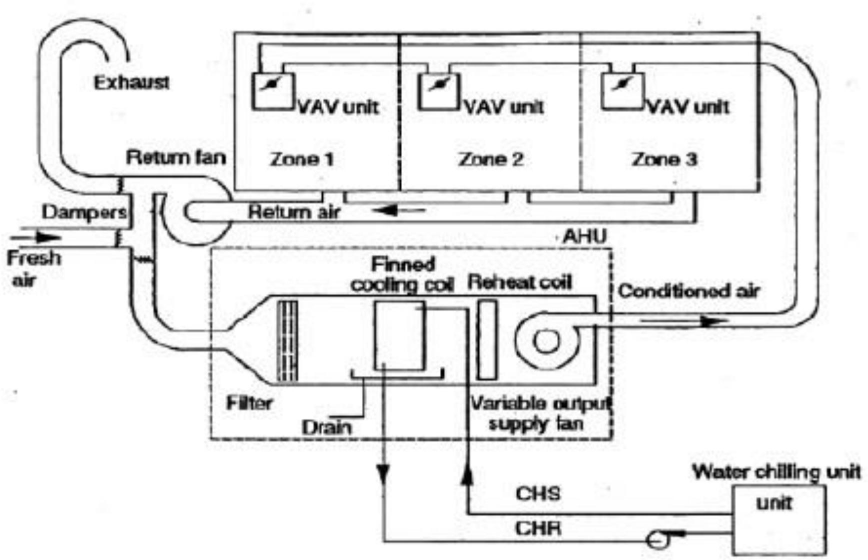


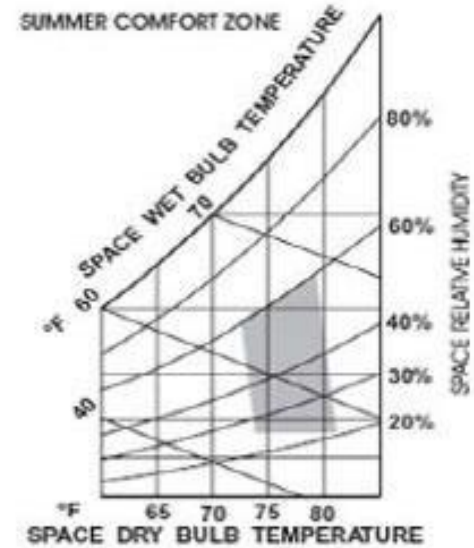
Fig.4. ETTV graph correlating cooling energy to ETTV value.



Previous Projects

Humidity and Thermal Sensors for Human Comfort Control in Green Buildings





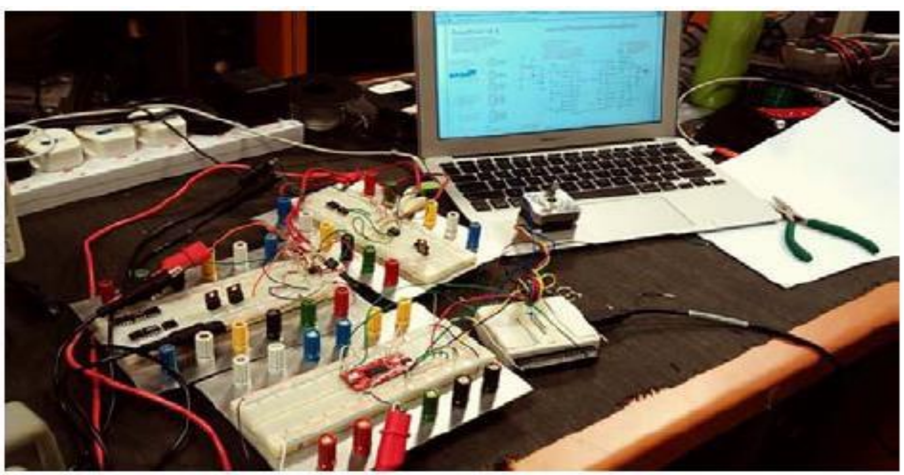
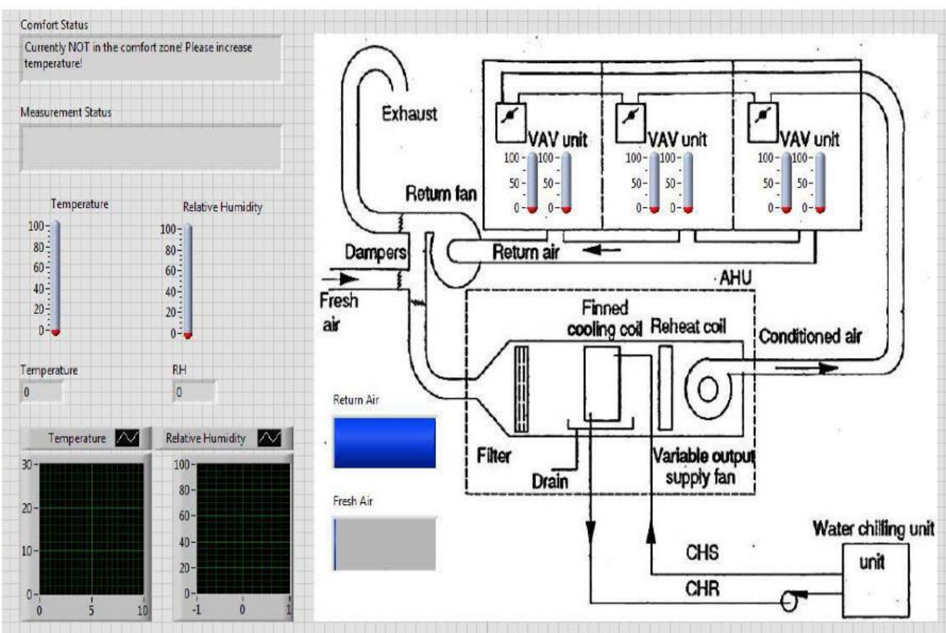


Fig. 28. Temperature and humidity sensors for motor control for use in model VAV system



Potential Projects

- Differential pressure sensor: Positive or negative pressure inside spaces
- Cooling tower water saving: measure acidity / alkalinity / conductivity and regulate chemical dosing & blow down
- Sensors to count number of people in a room
- AHU off coil RH by measuring T_{db} & T_{wb}: Energy savings
- Cheap T, RH, CO and CO_2 sensors: Room IAQ and energy savings
- Cheap O_2 or CO sensor: Combusting system energy savings
- Cheap and simple daylight sensor: Controlling window shading
- Energy harvesting: Cooling tower, Condenser water energy
- Reduction of food wastage inside refrigerator: Scanning barcode
- Recovery of PE & KE of flowing water
- Further improvement of previous potential projects