International Journal of Engineering Research and General Science Volume 4, Issue 3, May-June, 2016
ISSN 2091-2730

Capacitive Sensing & Its Applications

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Abstract— The paper includes the study of the capacitive sensing technology and its applications in modern technology. The subject describes the behavior of electric field induced due to a capacitor. Capacitors are the basic building blocks of the electronic world. Capacitance is the ability of a capacitor to store an electrical charge. The sense of touch is an important human sensory channel. During interaction with physical objects, pets and human beings, touch (physical contact) constitutes an extremely significant event. The technology used to respond to such a physical touch is termed as **capacitive sensing.** In this paper we are going to define the capacitive sensing technology in the production of new age devices. Such device uses the human body capacitance as their input and according to the sensory feedback they provide output. These devices have a major role in the current scenario. Such devices are used to overcome accidents, which are a major cause in the present time. In this paper we are also going to define the use of such technology to design such king of helmet that can reduce the percentage of road accidents. When the driver wears that helmet then only his/her vehicle will be activated. This helmet uses the capacitance of the human ear as input. Now a days capacitive sensing has many applications, as such it is used in the smart phones used widely in the whole world. Many types of sensors use this technique. The major applications include the sensors used to measure or detect proximity, position or displacement, humidity, fluid level & acceleration. Capacitive sensing is different from that of the inductive sensing and its main advantage is that it can sense different kind of materials like skin, plastic, metal & liquid.

Keywords— proximity sensing, capacitive sensing, electrodes, traces.

INTRODUCTION:

In 1831, **Michael Faraday** discovered electro-magnetic induction. Essentially, he found that moving a conductor through a magnetic field creates voltage that is directly proportional to the speed of the movement—the faster the conductor moves, the higher the voltage induces. Today, inductive proximity sensors use ***Faraday's Law of Electromagnetic Induction*** to detect the nearness of conductive materials without actually coming into contact with them. The primary deficiency of these sensors, however, is that they only detect metal conductors and different metal types can affect the detection range.

Capacitive sensors, on the other hand, adhere to the same principle but can detect anything that is either conductive or has different dielectric properties than the sensor's electrodes surroundings. Proximity capacitive sensors have become increasingly popular as more user/machine interfaces are designed using touch panels to reliably respond to commands.

Capacitors are the basic building blocks of the electronic world. To understand how capacitive sensors operate, it is important to understand the fundamental properties and principles of capacitance.

Capacitance is the ability of a capacitor to store an electrical charge. A common form – *a parallel plate capacitor* whose capacitance is calculated by **C = Q / V**, where C is the capacitance related by the stored charge Q at a given voltage V. The capacitance (measured in Farads) of a parallel plate capacitor consists of two conductor plates.

The sense of touch is an important human sensory channel. During interaction with physical objects, pets and human beings, touch (physical contact) constitutes an extremely significant event. The technology used to respond to such a physical touch is termed as **capacitive sensing.** Now a days capacitive sensing has many applications, as such it is used in the smart phones used widely in the whole world.

Capacitive sensing depends on the phenomenon of the capacitive coupling. In this technique the input to the system is human body capacitance. Capacitive sensors can detect anything. The only condition for the detection is that the object must be conductive or it has a dielectric different from that of air.

Many types of sensors use this technique. The major applications include the sensors used to measure or detect proximity, position or displacement, humidity, fluid level & acceleration. Digital audio players, mobile phones & tablet computer use capacitive sensing touchscreens as input devices. Capacitive sensors can also replace mechanical buttons.

ADVANTAGES OF CAPACITIVE SENSING

1. It can sense different kinds of materials like skin, plastic, metal, liquid.
2. It is contactless and wear-free.
3. It has the ability to sense up to a large distance with small sensor sizes.
4. It is a low power solution.

POINTS TO BE KEPT IN MIND WHILE DESIGNING A CAPACITIVE SENSOR

1. Design electrode plates to measure the desired variable. Maximize capacitance with large-area, close-spaced plates.
2. Surround the sensor with appropriate guard or shield electrodes to handle stray capacitance and crosstalk from other circuits.
3. Calculate sensor capacitance, stray capacitance and output signal swing.
4. Choose an excitation frequency high enough for low noise. As excitation frequency increases, external and circuit-generated noise decreases.
5. Design circuit to meet accuracy specifications and provide immunity to environmental challenges.

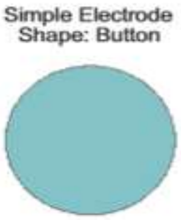
APPLICATIONS OF CAPACITIVE SENSING

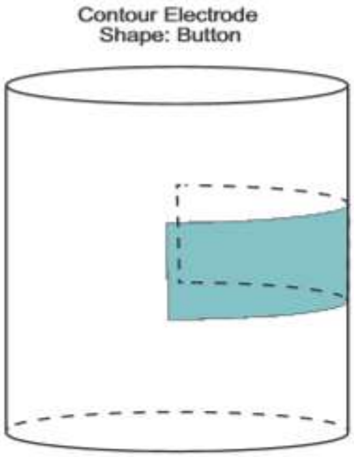
1. **Flow:** Many types of flow meters convert flow to pressure or displacement, using an orifice for volume flow. Capacitive sensors can then measure the displacement.
2. **Pressure:** A diaphragm with stable deflection properties can measure pressure with a spacing-sensitive detector.
3. **Liquid Level:** Capacitive liquid level detectors sense the liquid level in a reservoir by measuring changes in capacitance between conducting plates which are immersed in the liquid, or applied to the outside of a non-conducting tank.
4. **Spacing:** If a metal object is near a capacitor electrode, the mutual capacitance is a very sensitive measure of spacing.
5. **Scanned multi-plate sensor:** The single-plate spacing measurement can be extended to contour measurement by using many plates, each separately addressed. Both conductive and dielectric surfaces can be measured.
6. **Thickness measurement:** Two plates in contact with an insulator will measure the insulator thickness if its dielectric constant is known or the dielectric constant if the thickness is known.
7. **Ice detector:** Airplane wing icing can be detected using insulated metal strips in wing leading edges.
8. **Shaft angle or linear position:** Capacitive sensors can measure angle or position with a multi-plate scheme giving high accuracy and digital output, or with an analog output with less absolute accuracy but faster response and simpler circuitry.
9. **Limit switch:** Limit switches can detect the proximity of a metal machine component as an increase in capacitance, or the proximity of a plastic component by virtue of its increased dielectric constant over air.
10. **Accelerometers:** Analog Devices has introduced integrated accelerometer ICs with a sensitivity of 1.5g. With this sensitivity, the device can be used as a tiltmeter.

CAPACITIVE TOUCH HARDWARE DESIGN

To design a good touch sensor, all about we require is the good study of the capacitive sensing. The purpose of this paper is to describe the design of such a capacitor sensor that can achieve maximum performance. By achieving maximum performance in the hardware, the capacitive touch software library can perform the capacitive touch measurements with the lowest power consumption. The design for the sensor includes the schematic as well as the mechanical part. The schematic and mechanicals are treated as design requirements that influence the PCB layout. This paper first describes requirements that might be found in the schematic and mechanical requirements of the product. These requirements have an effect on the layout and must be considered first. After the requirements of the product are understood, then the PCB layout can begin. The figure below shows an equivalent circuit that provides the basic concepts for understanding how the different aspects of the design contribute to the overall performance. Before discussing the equivalent circuit, it is important to understand the basic terminologies used for the designing of the capacitive sensors. These terminologies include **electrode, traces,** and **capacitance.** The little description about these three terminologies is explained below:

1. **Electrodes:** An electrode is the physical conductive structure that a person interacts with. This structure is typically thought of as the copper on a printed circuit board (PCB), but can also be made of transparent materials such as Indium Tin Oxide (ITO) or other conductive materials like silver. The electrode shape can be very simple (for buttons) or very complex (for interdigitating). The electrode does not necessarily need to be planar. One of the benefits of capacitive touch detection is that it allows an application to use buttons, wheels, or sliders that conform to the shape of irregular surfaces.





2. **Traces:** A trace is the conductive connection between the microcontroller and the electrode. Similar to the electrode, the trace is typically a copper trace on a PCB, but it could also be made of materials like ITO and silver.

3. **Capacitance**: Capacitance is the ability of the electrode to store an electrical charge. In the context of capacitive touch detection, there are two common categories of capacitance: **mutual capacitance** and **self-capacitance**. As the names imply, self-capacitance refers to the capacitance of one electrode, while mutual capacitance refers to the capacitance between two electrodes. Self-capacitance is the topic of this document, and the concepts described here pertain primarily to self-capacitance solutions.
   An important concept within capacitive touch detection is baseline capacitance. This represents the steady-state no-interaction capacitance seen by the microcontroller. The baseline capacitance is the sum of the parasitic capacitances, which include the electrode, trace, and parasitic capacitances associated with the microcontroller pins, solder pads, and any discrete components associated with the circuit. The baseline capacitance is important because sensitivity is a function of the relative change in capacitance. If the baseline capacitance is too large, then any change in capacitance caused by a touch or proximity event is very small and might not be distinguishable from the baseline.

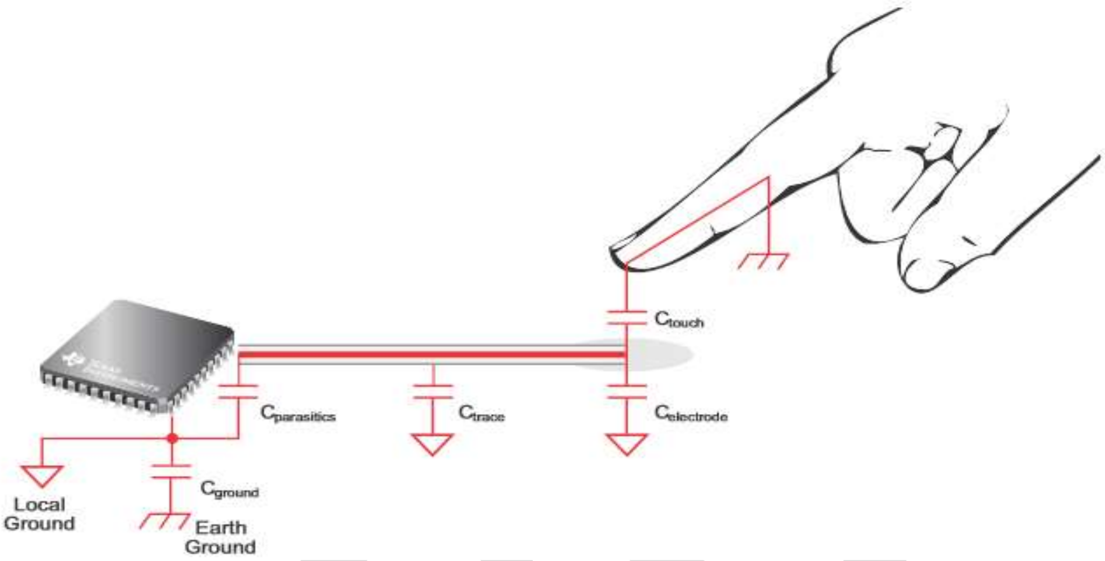
EQUIVALENT CIRCUIT

In the figure shown below, there are five capacitances –$\mathbf{C_{touch}}$, $\mathbf{C_{trace}}$, $\mathbf{C_{electrode}}$, $\mathbf{C_{parasitic}}$ & $\mathbf{C_{ground}}$.

1. $\mathbf{C_{ground}}$ is the capacitance between the device under test (DUT) ground and earth ground. In some applications, local and earth ground are connected when the DUT uses mains power, but typically the local ground is capacitive coupled back to earth ground.
2. $\mathbf{C_{trace}}$ and $\mathbf{C_{electrode}}$ is the capacitance between the trace and electrode structures back to the local ground. This capacitance is most directly affected by surrounding structures, typically ground pours, that are either on the same layer or on adjacent layers. Not shown is the capacitance between the trace and electrode structures and earth ground. These capacitances are not

without merit; however, for simplicity and in the context of this document, the design guidelines are given with the principle of affecting the local capacitance (that is, separation between local ground and the traces and electrodes).

3. The capacitance **$C_{parasitic}$** is a combination of the internal parasitic capacitance of the microcontroller and any components within the circuit. This capacitance is also referenced to local ground.
4. The touch capacitance, **C_{touch}**, is the parallel plate capacitance formed between the touch interaction and the electrode. In the example of a touch, as the finger presses against the overlay, the flattened surface of the finger forms the upper plate and the electrode forms the lower plate. The capacitance is a function of the area of the two plates, the distance between them, and the dielectric of the material that separates them.



PERFORMANCE PARAMETER ASSOCIATED WITH SIGNAL & NOISE

1. Signal & Noise: Capacitive touch detection is a type of analog-to-digital converter (ADC), specifically a capacitance to digital converter. As with most ADCs, the terms of interest are resolution, signal-to-noise ratio (SNR), and linearity, in the specific cases of wheels and sliders. Throughout this document, the design guidance helps to maximize signal, minimize noise, and address when these two goals are at odds.

2.Signal: The basis of capacitive touch detection is the ability to measure a change in capacitance. This change in capacitance is the signal that the capacitive touch solution identifies. The term **sensitivity** is often used to describe the signal strength—a more sensitive solution has a stronger signal.

Equation (1) serves as the basis for layout recommendations.

$$C = \varepsilon \times \left(\frac{A}{d}\right)$$

$$C = \varepsilon_r \times \varepsilon_0 \times \left(\frac{A}{d}\right) \ldots\ldots. (1)$$

The dielectric constant (ε), area (A), and distance (d) are described throughout this document with the intent of positively influencing the capacitance for a touch system.

3.Parasitic Capacitance: Although parasitic capacitance is presented separately, it is a part of the sensitivity and signal. As already mentioned, the capacitance of interest is the relative change in capacitance. The change in capacitance is based upon the touch interaction, but this change is perceived relative to the parasitic capacitance of the system. The parasitic capacitance is also called the steady-state capacitance or baseline capacitance. If the introduced change is 100fF, then the sensitivity, which is the relative change in capacitance, can be increased by decreasing the parasitic capacitance. The capacitances $\mathbf{C_{trace}}$, $\mathbf{C_{electrode}}$, and $\mathbf{C_{parasitic}}$ are generically referred to as parasitic capacitance.

4.Resolution: The term resolution can be used in several different contexts in capacitive touch detection. In the broadest sense, resolution is sensitivity and defined in terms of capacitance. A measurement system may be designed to resolve changes in capacitance in 0.1 pF steps and, therefore, the resolution is 0.1 pF

5.Linearity: The term linearity is often used to describe the performance of capacitive touch wheels and sliders. Similar to the linearity performance of ADC or digital to analog converter (DAC), the linearity is how well the reported position matching with the actual position.

6.Range: Range applies to proximity sensors. The range or distance is directly proportional to the sensitivity. The more sensitive the hardware design, the greater the distance or range can be achieved with a proximity sensor.

7.Noise: The signal is the change in capacitance that results in a meaningful change in counts. Noise, on the other hand, is any disturbance that does not change the capacitance but does change the counts. Most often these disturbances are the result of power supply switching noise, electrostatic discharge (ESD), electrically fast transients (EFTs), radiated noise, or some other type of electrical noise that couples into the system.

8.Signal-to-Noise Ratio (SNR): The SNR is a system-level specification and needs to be tested at the system level. Good layout alone is not adequate but is part of the overall design to achieve an acceptable SNR. The main idea in providing good sensitivity is to maximize the capacitance associated with a touch and minimize the parasitic capacitance. The noise must be mitigated and reduced with good design practices for noise immunity (for example, ESD, RF, or EMC).

SCHEMATIC OF CAPACITIVE SENSOR

At the schematic stage of development, the two key elements are noise and parasitic capacitances associated with components.

1. **Components used for Designing:** External components are not ideal with capacitive touch solutions because of the additional parasitic capacitance associated with any component. Therefore, components selected to be part of the capacitive touch circuit should have the smallest footprint area possible. Capacitance is directly proportional to area, so any reduction in footprint reduces capacitance. Typically, these external components are related to ESD protection such as current-limiting resistors placed between the microcontroller and the electrode. The concept of minimizing footprint also applies to connectors or any other component in the capacitive touch circuit. Ideally, any component would have a very low drift factor with temperature and time. While this is not a necessity, because the software has drift compensation, it is preferred to keep the touch circuit and all associated components as stable as possible over time and temperature.

2. **ESD Protection:** ESD protection should be designed with consideration of the laminate material that acts as a barrier between potential ESD strikes and the PCB. Relying on the high-dielectric breakdown voltage of the overlay is preferred to adding ESD components to the touch solution, because these components add parasitic capacitance to the circuit and reduce sensitivity. If additional ESD protection is required, small current-limiting resistors and low-capacitance clamps are recommended.

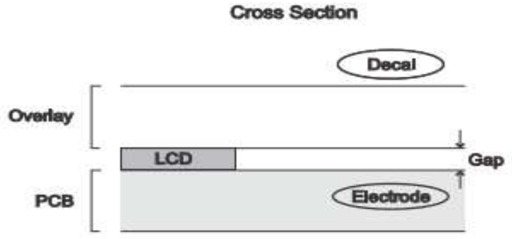
3. **Power:** The drift compensation found within the capacitive touch software library accounts for drift in VCC over time (this drift may be associated with battery decay in portable applications). More spurious shifts in VCC, such as those associated with noise spikes or ripple, can affect the measurement and even the drift compensation if the noise lasts for a long period of time. The most common method of reducing power supply noise is the use of filters. A PI filter is typically the filter of choice. An LDO can also be used to reduce power supply noise.

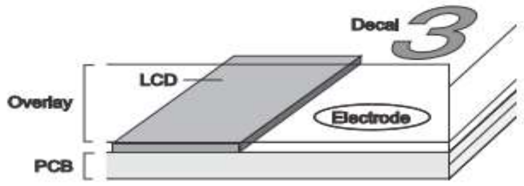
4. **Mechanical Parts:** The mechanicals are the mechanical characteristics of the design. The mechanicals include the overlay material, ink on top of the overlay, any adhesives used to bond the electrode to the overlay or enclosure, and any transition materials used to remove air gaps between the electrode and the overlay. Mechanicals also include the types of materials used for the electrodes. The mechanicals affect both the signal and the parasitic capacitance.

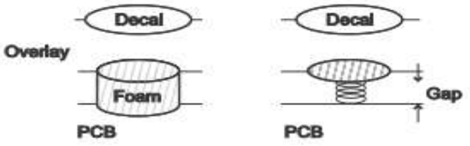
OTHER SITUATIONS

Not all applications fit into the typical category, and this section describes two special cases. The first is intentional air gaps that are greater than 2 mm between the electrode and the overlay material, and the second is the use of gloves.

Air gaps: In some applications, components are on the same layer as the electrode. This prevents the overlay from being directly applied to the electrode. A common example of this is when an LCD is mounted near the electrode (see Figure below). Another scenario is when the overlay material is not a uniform surface and, therefore, the electrode cannot make direct contact with the overlay. In either case, the gap must be filled or bridged with nonconductive filler (typically adhesive) or a conductive extension. When the gap is in excess of 2 mm, then a conductive extension, either foam or metal, should be used. The metal or foam must be malleable to conform to the shape of the surfaces and prevent the formation of gaps. As shown in Figure below, the area created by the foam or metal in contact with the overlay is now the area that influences the capacitance.







1. **Gloves:** Gloves are simply another layer of medium between the electrode and the finger, and the same principles of thickness and dielectric apply. The challenges with glove applications include the ability to support both gloved and ungloved hands as well as the variation in the types of gloves the application might require. Typical leather or plastic gloves have a dielectric constant in the range of 2 to 4, and fabric gloves and gloves with insulation can have a dielectric constant less than 2.

LAYOUT

After the mechanicals are understood, the electrodes can be sized and designed to provide the most signal. Independent of the mechanicals, the layout design is affected by the distance between the microcontroller and the electrodes, the PCB stackup (for example, one layer, two layer, or four layer), and other electrical circuits on the PCB.

The first item to consider relates to the schematic and the placement of any external components that are associated with the capacitive touch solution. This is typically found with the comparator solutions, and the resistor is part of the feedback path that creates the oscillator. Other examples are of ESD protection components. In all cases, the components should be kept as close as possible to the microcontroller. As the components move farther away from the microcontroller, the increased area correlates to an increased risk of noise or ESD conducting into the device.

ELECTRODE DESIGNING

The electrode design must accomplish two goals. First, the design must provide sufficient signal (change in capacitance with interaction). The design must project the e-field up and out so that the appropriate level of sensitivity is achieved at the desired distance. Understanding the stackup, thickness and dielectric, the electrode can be sized and shaped to provide the maximum signal. Second, the electrode design needs to have a minimal parasitic capacitance.

In the following sections the shape and area of the electrode are discussed with the intent of maximizing the signal for different implementations (buttons, sliders, and wheels). The basis for controlling the parasitic capacitance is common to different sensor implementations and is discussed here.

Figure below shows an example PCB cross-section and the important parameters that influence the parasitic capacitance. Similar to figure in the above section, the height, width, and separation have a direct effect on the parasitic capacitance of the electrode, $C_{electrode}$. The fundamental parameter area is not shown in Figure below, because this has a direct effect on both the touch capacitance (C_{touch}) and the parasitic capacitance ($C_{electrode}$). This section describes how changes to the height and separation can minimize the parasitic capacitance. The following sections describe how changes to the area can maximize C_{touch}.

1. **Proximity:** Proximity electrodes have a circular or square shape, the same as buttons. Proximity sensors require a higher degree of sensitivity than buttons, and this higher sensitivity is accomplished by increasing the area and the separation from other conductors.

2. **Wheels and sliders:** The concept of a wheel is identical to a slider with the exception that the slider needs to be terminated at the ends.

3. **Shape of the Electrode:** The capacitance of the electrode is a function of area, but the shape is important to consider, because the shape can influence the area.

4. **Buttons:** For buttons, the electrode shape is typically round or rectangular. One common mistake is to make the electrode the same shape as the icons printed (in nonconductive ink) on the overlay. As shown in Figure 11, this can lead to electrodes with odd shapes that create discontinuities and reduce surface area.

5. **Area of the electrode:** An important detail of designing the electrode shape is not to design shapes that have low surface area. The area of each electrode must provide the maximum Ctouch, which in turn produces the most signal (the change in capacitance) when a touch event occurs.

    a) **Proximity sensors:** Proximity sensors typically have a larger area in order to detect large surfaces (palm of the hand) at larger distances. In most applications the electrode size is limited by the end product dimensions. These applications depend heavily upon the measurement algorithm and longer measurement times to provide sufficient sensitivity. The longer measurement times translates into higher power consumption.

    b) **Sliders and wheels:** Sliders and wheels are different from buttons in that the interaction involves multiple electrodes. As shown in Figure 13 the area of the electrode is not as critical as the percentage of coverage across multiple electrodes.

c) **Electrode Material:** As discussed in the above sections, conductivity becomes an issue in more resistive materials like ITO. Although the transparency of ITO is very good, the resistivity is high when compared to materials like silver and copper. Typically the physical dimensions prohibit increasing the area of the ITO electrodes, and therefore any degradation in sensitivity must be compensated for in the firmware. This typically results in slightly longer measurement times and consequently increased power consumption.

d) **Spacing between the electrodes:** As mentioned previously, one of the unique features of the capacitive touch software library, 1, is that the electrodes are scanned sequentially. This and following the recommendation to drive the signals to GND as the default state of the electrodes allows neighbouring electrodes to be treated as an extension of the ground pour. Therefore, the spacing between the electrodes follows the same rules for spacing from ground. The goal is provide enough spacing so that the e-field propagates up and through the overlay material. A minimum spacing of one-half the laminate thickness has been found to provide sufficient signal (sensitivity).

VEHICLE ACTIVATING KIT BASED ON CAPACITIVE SENSING

Bike manufacturers are constantly launching newer, faster machines for the customers, but few include safety as a prime feature. Keeping this in mind, some students of the Veermata Jijabai Technological Institute (VJTI), Matunga, have developed the **'Smart Helmet'**, which not only ensures safer driving, but also activates the bike only when the rider puts on the helmet. The helmet has been developed by six students of 3rd year majoring in Electronics and Information Technology, in collaboration with a company called Creative Concept. One of the inventor, Saurabh Doiphode, said, "The smart helmet consists of a pressure sensor. When the user wears the helmet, this sensor gets activated, and is detected by the microcontroller placed on the helmet. This microcontroller sends a signal wirelessly through radio waves to the receiver present on the bike. It turns the ignition system on with the help of a relay circuit attached to the bike itself." The students have also changed the ignition circuit of the bike, which therefore, cannot be started with a push of the ignition button or a kick of the starter. The students have also added an LCD screen to the bike to guide the biker.

New in this technology: The smart helmet was based on the pressure sensing technology. The helmet which we are going to make is based on **Capacitive Sensing Technology.** There will be a proximity sensor placed inside the helmet which takes the capacitance value of the ear of humans. This capacitance value is rather different from the parasitic capacitance. As the smartphones of the present era works, in the same fashion, this helmet is going to work. As the sensor placed in the helmet gets activated, it gives its output to the microcontroller placed inside the helmet and this microcontroller will gives its output to the relay present in the ignition system of the two wheeler vehicle. The ignition system is activated only when the condition will be fulfilled that the bike rider wears the helmet or not. The newer concept in this technology is the **call attending facility.** In the helmet there is a Bluetooth module which is directly interfaced with the mobile phone and the microcontroller. The circuit consists of a 16x2 LCD display which shows the initial message as "Wear your helmet to drive your vehicle". As any person tries to call the bike rider, the LCD will display a message which shows the caller identity and his/her mobile number. With just a single tap on the helmet, the rider will be able to attend the call with the use of the Bluetooth module inbuilt in the helmet. This technology ensures the safety of the bike rider and the feasibility of the ride. The circuit will include some cost in the implementation but it ensures the reduction in the road accidents, which is a major problem in the present time.

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