Vehicle identification by capacitance and infrared sensors

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Abstract. Currently, large inductance coils buried underground are commonly used to detect passing vehicles at road toll stations. The inductance-based systems are vulnerable to environmental magnetic interference and hence are inaccurate in counting passing vehicles. Also they cannot categorise the vehicles. This paper presents a capacitance sensor array, which has been developed not only for detection of passing vehicles but also for identification of types of the vehicles. Together with infrared sensors, the new system can be used to control a road barrier and to keep a record of passed vehicles through a driveway accurately. Tests have demonstrated that it is more reliable than the inductance-based systems.

1. Introduction

Currently, inductance-based systems are commonly used at road toll stations to detect passing vehicles and to control road barriers [1]. A key element of such systems is an inductance coil, which are buried underground as a sensor. The coils are usually large, about 2×2 m. A main problem with the inductance-based systems is that the inductance coils used are vulnerable to environmental magnetic interference, e.g. vehicle ignition, thunder and lightning. Because it counts not only for vehicles, but also other metal objects, the recorded traffic flow is often over-counted. On the other hand, if two close vehicles are on the coil, which is large, at the same time, the system may just count as one, resulting in under-counting the traffic flow. Furthermore, they are unable to categorise passing vehicles automatically while the highway authority needs such information [2].

At some road toll stations, image recognition systems are used to categorise passing vehicles [3-6]. However, the cost of such systems is so high (about 100 times of that of inductance-based systems), that small and medium road toll stations cannot afford deploying them.

To solve the above problems, a new vehicle detection and identification system with a capacitance sensor array and infrared sensors has been developed. This paper presents the sensor design, discusses some key issues on vehicle detection and identification and gives some test results.
2. Sensors and operational principle

2.1 Capacitance sensor structure

Fig.1 shows the designed capacitance sensor array with 11 excitation electrodes and 30 detection electrodes. It can be used on a driveway up to 3 m wide. In Fig.1, all excitation electrodes (i.e. Plate A) are connected together, and measurements are taken from detection electrodes B_1~B_{30}, from the left to the right in turn. The middle is equipped with Plates A, and B_0, a multiplexer and a capacitance measuring circuit. The multiplexer is connected to Plate B_i in turn, and the capacitance between Plate A and Plate B_i is converted into voltage by the capacitance measuring circuit.

![Figure 1. Capacitance sensor array of 3 m wide (1 – excitation electrode, 2 – detection electrode)](image)

To force passing vehicles to slow down, road ra mps are commonly used at highway toll stations. The capacitance sensor array shown in Fig.1 is encapsulated in a road ramp. Fig.2 shows the cross-sectional view of a road ramp with capacitance electrodes in it. A capacitance sensor array is actually encapsulated in multiple road ramps, with 1 excitation electrode (Plate A) and 3 detection electrodes (Plates B_{i-1}, B_i and B_{i+1}) in each road ramp. When no wheel is on the capacitance electrodes, the capacitance between electrodes A and B_i is rather small. When a wheel is on the electrodes the capacitance is increased.

![Figure 2. Cross-sectional view of road ramp with capacitance electrodes in it (1 – Plate A, 2 – Plate B_i, 3 – screened plate, 4 – insulation material)](image)

2.2 Design issues

The following issues need to be considered when designing the capacitance sensor array.

(a) Size of electrodes: The length of detection electrodes, q (see Fig.1), is an important parameter. If q is too large, it is difficult to measure the tyre touchdown breadth b and the tyre thread e accurately (see Fig.1). If q is too small, there are three difficulties: (1) too many detection electrodes are needed, (2) the capacitance to be measured is too small, and (3) a large number of multiplexing channels and a complicated measuring circuit are needed. To determine the second dimension of detection electrodes, p (see Fig.2), the tyre touchdown length needs to be considered. If p is too large, it would be difficult to encapsulate the electrodes in the ramp, but the sensitivity may not be improved.
(b) Spacing between electrodes $B$; If the spacing $s$ (see Fig.1) is too large, it is difficult to measure the tyre touchdown breadth $b$ and the tyre thread $e$ accurately (see Fig.1). If $s$ is too small, the coupling capacitance between adjacent detection electrodes would be too large, resulting in low sensitivity.

(c) Distance between electrodes and earthed screen: If the distance between the electrodes and the earthed screen, $h$ (see Fig.2), is too large, it would be difficult to make the ramp robust. If $h$ is too small, the electrodes would be too far away from wheels, resulting in low sensitivity.

(d) Construction of road ramps: If a road ramp is not properly constructed, it would be grinded by vehicle wheels and would not last long. Compound butadiene acrylonitrile rubber may be used, which can be grinded more than 5 million times.

2.3 Capacitance measuring circuit

Given the size of electrodes shown in Fig.1 and 2, when a vehicle wheel rolls on the capacitance sensor array, the capacitance $C_{AB}$ between an excitation electrode $A$ and a detection electrode $B$ is only a few pF at maximum, while the stray capacitance between the detection electrode and the screen and the stray capacitance of the screened cable, $C_s$, can be larger than 100 pF. Therefore, the capacitance measuring circuit must be stray-immune to measure $C_{AB}$ accurately. A capacitance measuring circuit of four-phase charge-transfer detection [7] is used to measure capacitance of the capacitance sensor array. The circuit is shown in Fig.3.

In Fig.3, $S_1$–$S_4$ are CMOS switches and are controlled by 4 square-wave signals with $0^\circ$, $90^\circ$, $180^\circ$ and $270^\circ$ phases respectively. $C_i$ is the unknown capacitance of the sensor to be measured, $C_{s1}$ and $C_{s2}$ are the stray capacitance, one connected to the excitation electrode and the other connected to the detection electrode. When $S_1$ and $S_4$ are closed, a charging pulse charges $C_i$, and the charging current is converted to voltage $V_1$ by op-amp 1. When $S_2$ and $S_3$ are closed, $C_i$ discharges, and the discharging current is converted to voltage $V_2$ by op-amp 2. The two voltages from op-amp 1 and op-amp 2 are summed together by op-amp 3, which acts as a differential amplifier. Because $C_{s1}$ is either driven by a voltage source with negligible output impedance or connected to earth and $C_{s2}$ is held to virtual earth either by op-amp 1 or op-amp 2, the stray capacitance has very little effect on the capacitance measurement, i.e. the four-phase detection circuit is stray-immune. This is very important for measuring change in capacitance less than 1 pF. The output of op-amp 3 is

$$V_3 = 2fV_cC_xR_f + e_1 - e_2$$

where $f$ is the switching frequency, $V_c$ is the DC excitation voltage, $C_x$ is the measured capacitance, $R_f$ is the feedback resistance with op-amps 1 and 2, and $e_1$ and $e_2$ are offset voltage of op-amps 1 and 2.

It has been shown experimentally that the resolution of the circuit is 0.001 pF and the sensitivity is higher than 1 V/pF.
2.4 **Infrared sensor**

The infrared sensor consists of emitting diodes and photodiodes, which are fitted on two sides of the driveway, forming detection paths across a road, while each pair is encoded differently with three pairs or more. The height of the emitting diodes and the photodiodes are chosen so that a vehicle passing through the driveway blocks at least one detection path.

When two front wheels of a vehicle entering the toll station roll over the capacitance sensor array with electrodes $A$ and $B_i$ at time $t_1$, the capacitance electrodes under the left and right wheels generate capacitance $C_1$, larger than 1 pF, simultaneously (see Fig.4). A microcomputer receives two capacitance signals and then initiates the infrared measuring circuit.

![Figure 4. Infrared sensor working with capacitance sensor](image)

When the passing vehicle blocks at least one detection path of the infrared diodes, the infrared measuring circuit outputs a high-level signal. When the rear wheels of the vehicle roll over the capacitance sensor array at time $t_2$, capacitance $C_2$, which is larger than 1 pF, is again measured. In the case that the vehicle has two back axles, $C_3$ is produced at time $t_3$. After the whole vehicle has passed, none of the infrared paths is blocked at time $t_4$, the infrared measuring circuit outputs a low-level signal. According to the level of signal output by the infrared sensor, the microcomputer recognises a vehicle and controls a barrier arm to raise up or fall down.

3. **Detailed design**

3.1 **Count traffic flow and number of vehicle axles**

When an infrared detector is giving a high-level signal and if the capacitance electrodes both on the left and right sides simultaneously generate capacitance values larger than 1 pF, $n \geq 2$, one vehicle is counted. The number $n$ here is also the number of axles of the vehicle.

3.2 **Tyre touchdown width and tyre tread**

In Fig.1, the coordinates $x$ spreads across the driveway, where $x_i$ ($i = 1, 2, \ldots, 30$) is the coordinate on the left side of the capacitance electrode $B_i$, and the dark areas indicate vehicle wheels. The tyre touchdown width $b$ of the left tyre and the tyre tread $e$ between the left and right tyres, as shown in Fig.1, can be calculated as follows.

\[
  b = x_5 - x_3 - 66 + \frac{C_{AB_1}}{C_{AB_1}} \times 66 + \frac{C_{AB_2}}{C_{AB_2}} \times 66, \text{mm}
\]

\[e = x_{24} - x_3 - 66 + \frac{C_{AB_1}}{C_{AB_1}} \times 66, \text{mm}\]
3.3 Number of rear wheels

It is common that there are two front wheels, one on each side, and the type and size of the front wheels are usually the same as the rear wheels. If the number of rear wheels is $k$, the capacitance value produced by the rear wheels rolling over the capacitance sensor array is $k$ times that of the front wheels. Therefore, the number of the rear wheels can be identified.

3.4 Effect of tricycles and close vehicles

When a tricycle, which has only one front wheel, is rolling over the capacitance sensor array, it cannot trigger the infrared circuit. When its two rear wheels are rolling over the capacitance sensor array, they can trigger the infrared circuit. After the whole tricycle has passed, however, there is no signal coming from the infrared circuit. Therefore, there is only one capacitance pulse signal while the infrared sensor is giving a high-level signal (see Fig.4). As a result, a tricycle is not counted as a vehicle. Similarly, other metal objects other than vehicles are not counted as passing vehicles.

The capacitance electrodes $A$ and $B_i$ are designed so small that wheels of two different vehicles cannot roll over the capacitance sensor array at the same time. Therefore, two close vehicles, i.e. with a short distance between them, do not cause problems.

3.5 Effect of body frame

Because the distance between the body frame of a vehicle and the capacitance sensor array is much larger than that between its wheels and the capacitance sensor array, the capacitance between the body frame and the capacitance sensing electrodes is much smaller than that between the wheels and the capacitance sensor array. Therefore, the frame of vehicle does not cause problems.

3.6 Effect of rain

Because the dielectric constant of water is large, the capacitance electrodes $A$ and $B_i$ must be higher than the road surface, so that rain water on the road does not affect the capacitance sensor array. However, the gradual increase in depth of accumulated water would lead to a slow increase in capacitance between electrodes, compared with a passing vehicle. Comparing the current capacitance value with that 1s earlier, if the augment $\Delta C > 1 \text{pF}$, it is regarded as a passing vehicle. Otherwise, it is not counted.

3.7 Calibration of capacitance measuring circuit

To eliminate the effect of long-term drift of the capacitance measuring circuit, the capacitance electrode $B_0$ is mounted in the road ramp in the middle part of the capacitance sensor array (see Fig.1). The capacitance electrode $B_0$ and other capacitance electrodes are connected to the multiplexer. The zero point of the capacitance transducer is adjusted according to the capacitance value $C_{AB_0}$ frequently.

4. Tests on road

Tests have been carried out at a road toll station with cars, mini/micro-buses, pick-up trucks and semi-trailers. Fig.5 shows the output of the capacitance transducer when a car and a pick-up truck were passing. The parameters for the both tests are as follows.

- Number of axles: 2
- Number of wheels on each side of the rear axle of the car: 1
- Number of wheels on each side of the rear axle of the pick-up truck: 2
Tyre touchdown width of wheels: 180 mm
Tyre tread: 1.4 m.

The tests lasted for half a year. During this time period, even with thundershower several times, this system kept working. The testing results show that the system can control a barrier reliably, count the traffic flow, and identify the number of axle(s) and the number of rear wheels of a passing vehicle accurately. However, influenced by the wearing and amount of inflation of tyres, it can distinguish the tyre touchdown width and the tyre tread with an accuracy of 85% and 95% respectively.

![Voltage vs Time Graph](image)

(a) Car
(b) Pick-up truck

**Figure 5.** Output of capacitance transducer when a car and a pick-up truck passing

5. **Conclusion**

The capacitance sensor array is working even with strong magnetic interference, while the traditional inductance-based systems are affected by electric sparks and thunderbolt and hence are not reliable. The new vehicle identification system can record the traffic flow through a driveway accurately. With this function, the personnel fraud at road toll stations can be monitored. While the cost of the capacitance-based system is similar to an inductance-coil-based system, it has more functions than an inductance-coil-based system. Based on the above facts, it is foreseen that it can replace the traditional inductance systems and be widely used at small and medium road toll stations.

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