Capacitive Human Presence Sensor for Safety Applications

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Abstract:

Paper presents a novel idea of capacitive sensor for human presence detection. Due to the use of resonant circuit significant increase of sensor's sensitivity was achieved. In the case of human hand, value of output signal changes up to 421%. Moreover, sensor creates possibility of determination of the material of the detected object. As a result developed sensor can be applied for human presence detection sensors utilized in safety systems, which are especially suitable for underground transportation network.

Keywords: *capacitive sensors, people safety, underground transportation network.*

1. Introduction

Daily capacity of Warsaw Underground, according to its technical data, is up to 500,000 passengers [1]. That number of passengers does not provoke risk only under condition, that rush will be similar during whole day. In fact, people mostly use underground during rush hours. The main hazard for passengers in underground is to be run over by train. Except train collision and derailment run over is the main cause of death and injuries of passengers. Majority of accidents can be prevented by Automatic Train Speed Control System (SOP-2) [2]. That system has been already applied in most underground systems, also in Warsaw. That solution helped prevent main cause of most death accidents. Statistical data about accidents in London Underground, presented in Table 1 [3], shows that only five accidents causing passenger deaths have occurred due to train operation in nearly 150 years. In Warsaw Underground being run over by train was the only cause of death since it was opened in 1995. Risk of fall of from the platform on track can be decrease by automatic barriers between train and platform. Synchronization with Automatic Train Speed Con-

trol System (SOP-2) is critical for such solution because doors on platform should be in front of train's doors, to let passenger go out. That brings very serious danger in case of fire and was the main cause of death of 200 passengers in underground in South Korea [4]. This is the reason that on second underground line barriers are not planned.

In conclusion there is no sufficient method to prevent passenger from being run down by train accident. For this paper show an example a human detection system that in cooperation with Automatic Train Speed Control System can increase passenger's safety in underground.

2. Principles of operation

Passenger's safety can be increase by detecting human presence on track and preventing to from entering train to station if such incident occurred. System SOP-2 can stop the train, when track sensors indicate signal that track is occupied by other train. The idea is to communicate with that system to stop the train in the shortest time before train enters the station, when danger situation has been noticed. Three types of sensors are used to detect human presence on track. Motion detectors based on passive infrared detector and image processing method work as human detectors. Single beam optical sensors are used to detect train. Third types of detector are proximity sensors, which are installed on platforms edge to detect human's presence between train and platform.

Proximity sensor is based on permittivity phenomena. Materials, which are found in typical environment, have different permittivity level, as shown in Table 2. There is significant difference between water and other material permittivity. It is more than ten times lower then in metals and higher then in insulators. There is no other material that has the same permittivity level. Sensor uses that difference to recognize objects, which can be found in operation area.

Table 1. Statistic of Accidents in London Underground.

Place	Year	Fatality	Type	Cause
Northwood	1945	3 killed	Collision	Driver failure
Edgware	1946	Minor injures	Hit in the and of tunnel	Death of the driver
Stratford	1953	12 killed	Collision	Signalization failure
Moorgate	1975	43 killed	Hit in the and of tunnel	Unknown
Holborn	1980	Minor injures	Collision	Operator's failure
Camden Town	2003	6 injured	Derailment	Wrong steering system configuration
White City	2004	No injured and killed	Derailment	Wrong steering system configuration

Table 2. Permittivity for different materials.

Material	Permittivity ε_r
Air	1,0005
Polyethylene	2,25
Silicon	11,68
Rubber	7
Paper	3,5
Water	80
Metals	>1000

Capacitance is directly proportional to permittivity, thus it is possible to detect an object by measuring changes of it. Therefore sensor should be a kind of capacitor. Capacitive sensors are very common in industry, and others applications. The novel is the form of capacitor, which is described on figure1 has the ability to recognize material of which the detected object is made.

Mostly capacitive sensors have small detecting area. In this application it would be necessary to use hundreds of those devices in entire hazard area. Most of known sensors are cylindrical, which brings problems with mounting it in the floor, or in the edge of the platform. Only capacitive sensors, developed in GM factory to protect workers from robots, were in the form of wire [5]. Ability to recognize metal from insulators is achieved by some of sensors [6]. There are also systems, which can recognize man from insulators, but only in case, that he is grounded and there are no other grounded objects in operation area [7]. Those conditions cannot be achieved in under-ground. Developed sensor is flat, long and adjustable to curve of the ramp. It minimizes the cost and optimises detecting area. Flat device is easy to install and do not disturb architecture of the station.

The purpose was to maximize the sensitivity to changes of permittivity and minimize thickness. In classical flat capacitor two sheets are in front of each other. That configuration would be not advantageous in this case, because it indicates more than three plies of board, or tape to construct sensor and it reduced electric field outside the capacitor. Changes in capacitance of capacitor are observed only under condition that object will be in electric field produced by capacitor what result of following equation is:

$$C = \frac{Q}{U} \tag{1}$$

where U is given as

$$U = \int_0^d E \cdot dl \tag{2}$$

In equation (2), E is electric potential and dl is differential track.

When $E = 0$ outside of the capacitor, integral given by equation (2) is equal to zero. Therefore electric field should be put outside the capacitor, because object cannot be between capacitors sheets. Technical solution of such specialized capacitor is shown in Figure 1.

In classical flat capacitor major part of electric stream is between sheets. When sheet's area is equal to zero and width is big, most of electric field lines come outside the capacitor. There can be find-detected object (dotted area). To prove that, fundamental Maxwell's equation can be applied:

$$\oint_L E \cdot dl = 0 \tag{3}$$

On closed track integral of electric field is equal to zero (doted line), thus there have to be electric field not only between sheets, but also outside. In other case integral would not be equal to zero.
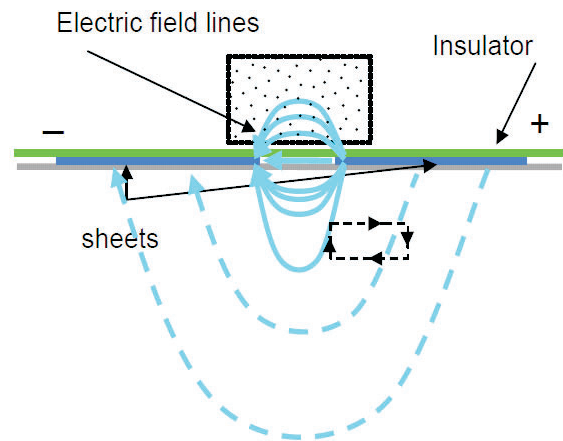

Fig. 1. Principles of operation of sensing capacitor.

Capacitance is proportional to permittivity, but also other factors have influence on it. In detecting area insulated metal can be found, and grounded objects, like train body. Sensor has to be resistant to that disturbance. Case with insulated metal can be transformed as it is shown in Figure 2. In that case two series connected capacitors are created. Resultant capacitance is:

$$C = \frac{C_1 \cdot C_2}{C_1 + C_2} \tag{4}$$

Equation (4) shows that resultant capacitance is smaller then capacitance of each capacitor. In fact those two capacitors can have bigger capacitance than empty sensing capacitor, because of big sheets area. In conclusion small increase of capacitance can be observed.
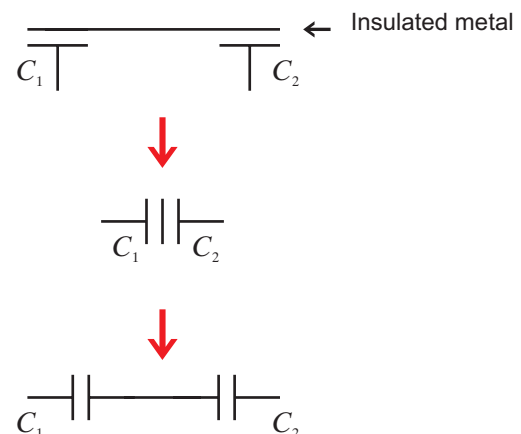

Fig. 2. Analyse of the case, where insulated metal is present nearly the sensor.

Configuration of two capacitors may be considered, when grounded metal is present nearly to capacitive sensor. That case is presented in Figure 3. Most of stream from sensing capacitor sheets will be absorbed by grounded metal. Only minority of stream will be transferred between sensing capacitor sheets, therefore decrease of capacitance of circuit will be observed. Insulator in neighbourhood of capacitor increases capacitance proportionally to the material permittivity, which is much higher for water, then other materials.

Tests with automatic capacitive bridge have proven theoretical conclusions in every case of object. For insulated metal small change of capacitance was observed. In case of grounded metal output signal was lower than for empty capacitor. Insulators were increasing capacitance. Results of these tests are presented in Table 3. Capacitance was measured for 1 kHz and 10 kHz bridge supply frequency.
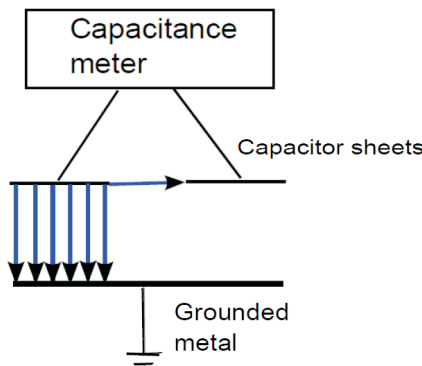

Fig. 3. Analyse of the case where grounded metal is presented nearly the sensor.

Table 3. Capacitance of sensing capacitor for different materials.

Object	C (pF) 1kHz	C (pF) 10kHz
Empty capacitor	15,7-16,2	16,3
Hand	292,0 - 390,0	229 - 237
Insulated metal	33,7 - 34,1	33,9
Grounded metal	15,9 - 16,0	15,3
Wood	26,7 - 26,8	22,1

3. Developed capacitive sensor for safety applications

Change of capacitance is not a typical electric signal, thus it has to be transform to current or electric voltage. To increase signal, electrical resonance is used. Resonance can be achieved when capacitor is empty; it means that there is no object in detection area. When resonance occurres voltage drop on LC elements, according to equation (5), is the lowest (U_{LC}). Even small change of capacitance cause significant decrease of voltage drop, which can be observed in Figure 5. Sensors circuit is shown in Figure 4.

Frequency of supply current, resistance and inductance has to be matched to achieved resonance of capacitance of empty capacitor. Significant is also quality factor of circuit. It can increases sensibility of circuit to changes of capacitance. Too high quality factor can increase noise level, and cause poor resistance to disturbances.

U_{LC} increases when capacitance differs to capacitance of empty capacitor. Higher resistance decreases quality level according to equation:

$$U_{LC} = \frac{U \cdot \sqrt{\left(\omega L - \dfrac{1}{\omega C}\right)^2}}{\sqrt{R^2 + \left(\omega L - \dfrac{1}{\omega C}\right)^2}} \tag{5}$$

where U is supply voltage, L - inductance, R - resistance of circuit and T - current pulsation.

Dependences of U_{LC} calculated for different resistances are presented in Figure 5. Due to use of the resonance circuit, significant changes of the output signal from the sensor are achieved.
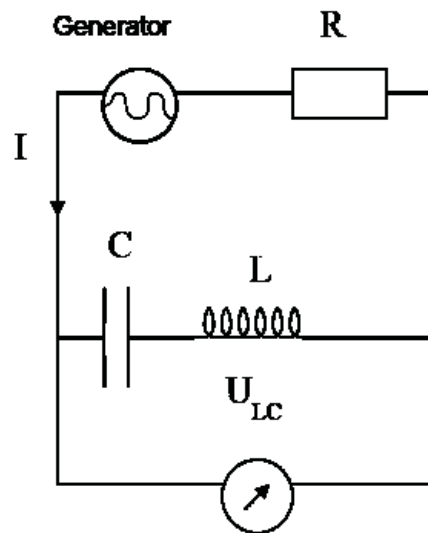

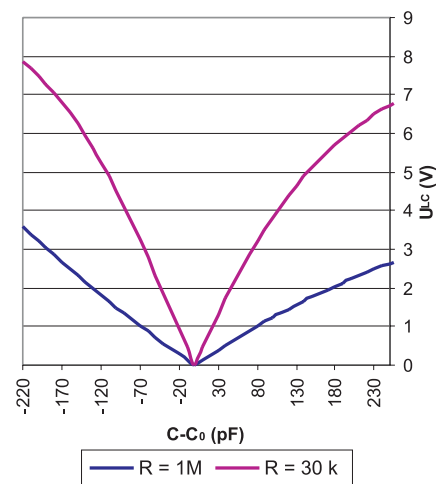Fig. 4. Electrical connections of the sensor (U_{LC} - output signal).

Fig. 5. Dependence of the calculated sensor output signal U_{LC} as a function of changes of its capacitance, calculated for different values of resistance R.

4. Experimental set-up and results

Main part of sensor is consisted of two metal sheets, which are on the same plane. Areas of the sheets and

Table 4. Experimental results.

Object	32 V / 928 Hz U_{LC} [V] range 1 V			100 V / 860 Hz U_{LC} [V] range 10 V		
Empty	0,340			0,95		
Hand	0,404	0,573	1,800	1,11	1,20	2,14
Hand distance	5-10 mm	1-5 mm	0 mm	5-10 mm	1-5 mm	0 mm
Insulated metal	0,301			1,04		
Grounded metal	0,264			0,94		
Wood	0,345			1,05		

ravine between them have to be optimised. Sensor was made on printed board. As a result an influence of differences of shape and ravine during mounting and measuring was decreased. Such differences may occur in the case of metal leaf. Moreover, there was insulation on copper ply to prevent break down.

Model of the sensor shown in Figure 6 has been tested in laboratory, for different types of materials, and configurations. Testing circuit was shown in Figure 7. Accuracy of resistance, inductance and capacitance has not influence on detecting ability, thus current frequency is adjustable and it is only needed to adjust resonance for empty capacitor.
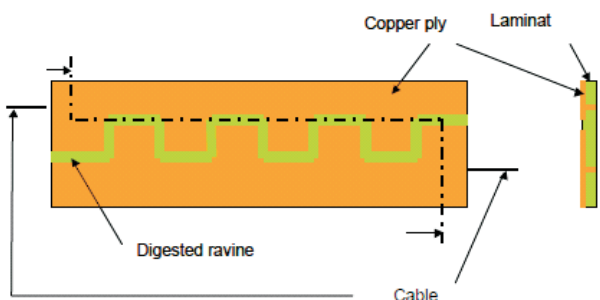

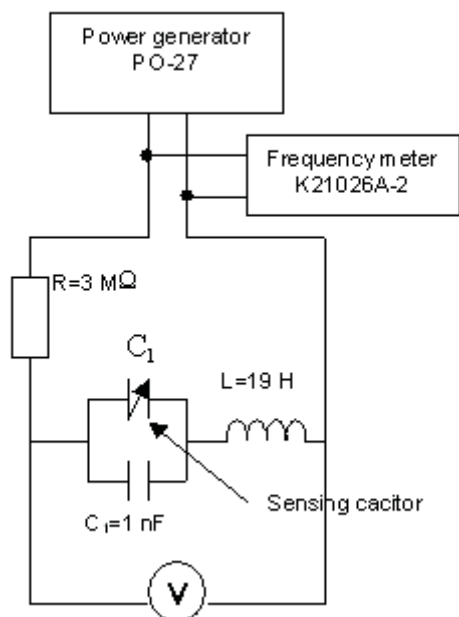*Fig. 6. Model of the sensing capacitor.*

Fig. 7. Schematic diagram of the experimental set-up.

For configuration shown in Figure 7 resonance frequency was 928 Hz for 32 V supply and 860 Hz for 100 V. During experiment the reaction of four different types of object was tested: insulated and grounded metal, for wood and human hand. In case of human hand signals for different distance were measured.

Driving properties and results of the tests were shown in Table 4. Resonance frequency changes due to supply voltage. This is because of internal capacitance and resistance of generator.
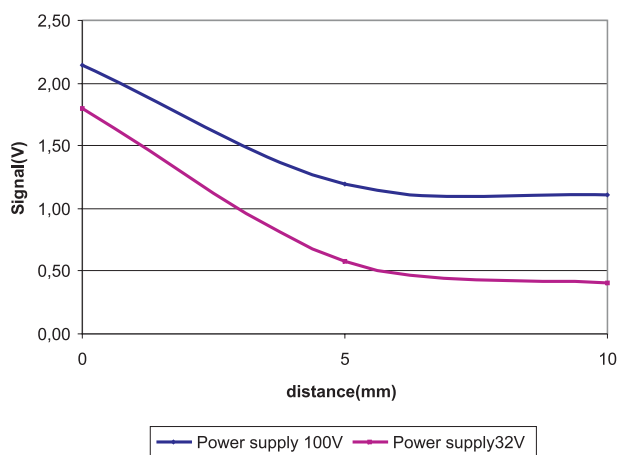

Fig. 8. Output signal as a function of distance of human hand, measured for different power supply voltage.

Changes of output due to object material are very significant. They are 17% higher from wood for hand in distance up to 10 mm and 421% higher for distance 0 mm in case of 32 V supply. Results confirm that sensor is able to detect living tissue. Relation of signal to distance for human hand is shown in Figure 8. Shape of function does not change with supply value, thus smaller supply voltage can be used.

4. Conclusion

Proximity sensor described in this paper is able to achieve the requirements. On the other hand, ability to detect in distance is not sufficient. Probably it can be improved by increasing frequency, which can straighten electric field propagation in detection area. Good feature, which was observed by experiment, is fact, that detecting range is not related to supply voltage. It can decrease probability of break down, and electric shock risk.

Experimental results indicate, that it is possible to develop a simple sensor, which not only detect objects, but also recognizes material. This kind of sensor is a good alternative for sensing mat, which uses stress to detect an object. As compared with safety mats [8], used in industry to detect human presence in danger area, developed sensor is thinner, more adjustable and does not depend on stress, which can provoke uncertainty in operation. To detect presence of man's feet on the floor high detection range is not needed. Therefore described sensor can be used in many cases to detect human presence in hazardous area.

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