Length and Speed Detection Using Microwave Motion Sensor

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***Abstract*—This paper introduces a new approach to design a vehicle detection module using a microwave motion sensor in order to obtain vehicle length and vehicle speed. The design of this module aims to apply for Intelligent Transport System (ITS) in which it plays a role as a unit of Traffic Detectors with Inductive Loops, Video, Infrared Sensors, etc. The module has advantages of using low power, costing low price and especially providing reliable results for measuring vehicles. The output signal of the microwave motion sensor is a low-level voltage whose frequency (Doppler) represents the speed at which a vehicle is moving towards or away from the sensor. We process this signal to get information about length and speed of the vehicle. We implemented the method in a microwave motion sensor named HB100 to measure the movement in radius of 8[m] in line-of-sight, vehicle speed range from 5[km/h] to 40[km/h]. We achieved the accuracy of more than 80% in 100 times observing a specific vehicle in a specific speed range.**

Keywords*—Doppler Effect, Intelligent Transportation System, Traffic Detectors, Microwave Motion Sensor, HB100.

I. Introduction

Traffic vehicles play an indispensable role in the transportation of people and goods. However, the constant increase in the number of vehicles has caused a variety of problems such as traffic accidents, traffic congestion, etc. To solve that pressing problems, ITS is introduced to bring significant improvement in transportation system performance, including reduced congestion and increased safety and traveller convenience [1]. The system applies modern technologies of electronics, communications, to control and manage all kinds of vehicles through transmitting real-time information [1] [2]. In ITS, traffic detectors are the devices that are used for detecting vehicles, bicycles, and pedestrians.

Vehicle detection technology has developed dramatically in the couple decades ago. Most popular detection methods focused on getting vehicle presence information [3]. However, today we need much more information about speed, movement direction and size of vehicles to control traffic efficiently. For this purpose, a wide range of methods has been applied to measure characteristics of this motion objects. The following provides general information about several solutions applied for measuring length and speed of vehicles.

Measuring vehicle length and vehicle speed with Inductive loop detector: Loop detector is the most popular installation in the vehicle detection technology, because loops have been commodity-priced while the alternative detectors have not due to the short history of these detectors [3] [4]. The use of inductive loop based on the decrease inductance of loops when a metal object passes through it. The object will be detected by this decrease. To get information about length and speed of vehicles, two loops are arranged in a row in a specified distance. We observe amount of time between two consecutive changes of inductances of loops and correlate with the distance between two loops to calculate length and speed of vehicle passing through the system. However, the difference in size, model between vehicles makes this method more difficult, so the major use of inductive loop detector is to detect rather than to measure [5] [6] [7].

Vehicle speed measurement using an imaging method: The imaging method is researched and applied widely in traffic system over the world. In the imaging method, the axis of the camera was perpendicular to the road and a single interlaced frame was captured by a frame store. Speed is measured based on comparing two consecutive half frames by using matching technique to determine the displacement of the vehicle between consecutive half frames [8]. This method needs very expensive high resolution cameras, highly complex image processing.

Vehicle speed measurement using laser speed gun: Laser speed gun is a device mostly used by police. A laser speed gun measures the time for infrared laser light to reach a vehicle and reflect. The light is much focused and faster than sound. The gun estimates the distance to vehicle by multiplying round-trip time to velocity of the light and then dividing by 2. Because light from the gun moves very quickly, the gun can take a large number of samples per second. The laser gun compares the change in distance between samples and calculates the speed of the vehicle [3]. The disadvantage is that laser speed gun can only be used at a large distance of a thousand feet, where it is not given much time for aiming or vehicle identification. Sensitivity to environmental conditions is another drawback of the laser gun.

Measuring vehicle speeds with microwave motion detector: Microwave motion detector uses Doppler Effect to detect and measure the movement of an object. The familiar form of applications using microwave motion detectors are in home security system, detecting a person entering or leaving an area, and in traffic system, taking the measurements of vehicles. The microwave motion detector sends a Radio-Frequency (RF) signal at a given frequency to a target, and if this object/person is moving, the reflected signal's frequency will be shifted [9]. By calculating the time required for the reflection and the change in frequency, it computes speed, based on Doppler Effect, of the object observed.

Currently, the market for microwave motion sensors is abundant with various models. Each manufacturer provides a product with differences in power, distance detecting, width

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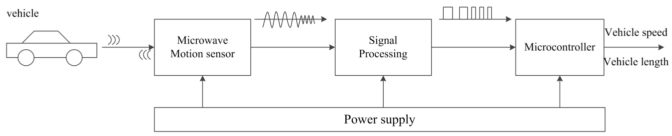

Fig. 1. Overall microwave motion detector structure

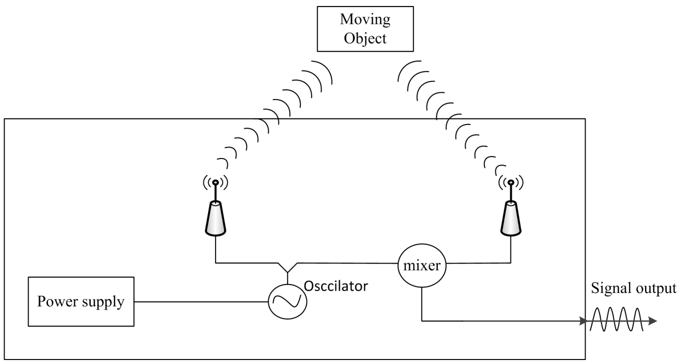

Fig. 2. Block diagram of a microwave motion sensor

of beams, etc. These differences make the implementation of products in a specific system more difficult. This paper presents a mutual approach for the processing output signal of microwave motion sensors to get information about length and speed of vehicles. The detector using that method has provided the result with the accuracy of more than 80%.

This paper is organized as follows. Section II presents the general description of a microwave motion detector structure. Section III describes a method to process the output signal of microwave motion sensor. Section IV presents an algorithm to calculate vehicle length and vehicle speed. In section V this method is implemented in a real module and the experimental results are presented. Section VI concludes the paper.

II. Microwave motion detector structure

In this section, we describe general structure of microwave motion detector, which consists of four main blocks (Fig. 1)

A. Microwave motion sensor

An overall structure of a microwave motion sensor consists of an Oscillator, path antennas and a mixer. Oscillator produces wave in X-band, path antennas aim at the object and the mixer compares created wave and reflected wave to make a wave whose frequency resulted from subtraction of two frequencies above. The general description of a microwave motion sensor is described in Fig. 2.

Depending on each manufacturer, the sensor can have different characteristics, designers should notice before applying.

- Power supply: a microwave motion sensor uses low power, the power supply ranges from $3.3(V)$ to $5(V)$ based on factory. Some types of sensors can be powered by low duty cycle pulsed trains in order to reduce its power consumption.
- Transmit frequency: the transmit frequency is in X-band and set by factory, There is no user adjustable part in this device. Table I presents the allocated frequency in some countries [10].
- Radiation Pattern: The sensor is mounted with the antenna patches facing to the desired detection zone. The user may vary the orientation of the sensor to get the best coverage.
- Output signal: the output signal frequency is Doppler frequency. Based on each specific application, ranges of Doppler frequency are various, which cause the difference in the signal-processing blocks (Fig. 1). The figure of output signal may be sin-wave in sensor HB100 [10] or square-wave in sensor 32213-X-Band Motion Detector [11], etc. depending on factories. Another key note of the output signal is the Received Signal Strength (RSS). The signal is attenuated by two ways free-space loss, reflection loss, absorption loss of the target and other losses. Circuit designer must take note the maximum and minimum RSS specified in technical data sheet, when designing the amplifier.

TABLE I. Allocated frequency for movement detection

Frequency (GHz)	Country	Remark
9.35	Germany	
9.9	France, Italy	
10.525	USA, Belgium, Netherlands	
10.587	UK	Outdoor applications
10.687	UK	Indoor applications

B. Signal Processing

The function of the signal-processing block is to amplify the output signal of the microwave motion sensor and then transform it into a square wave to be fed into microcontroller. With this aim, a signal-processing block contains two parts: an amplifier and a comparator made based on Doppler frequency ranges and RSS. Designers can choose Inverting Amp Band Pass Filter or Non-Inverting Amp Band Pass Filter [12] as Fig. 3.

C. Microcontroller

A microcontroller can be described as a small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals. There are different kinds of microcontroller like PIC, AVR, and ARM etc. In this work, we use PIC microcontroller which is popular with both industrial developers and hobbyists alike due to their low cost, wide availability, large user base, extensive collection of application notes, availability of low cost or free development tools, and serial programming (and re-programming with flash memory) capability [13]. The output of the signal-processing block is a square wave fed to the microcontroller counter. The microcontroller performs the tasks of calculation of frequency, calculation of length and calculation of speed of the vehicle.

III. Output signal processing

The goal of this section is to build a method to process the output signal of a microwave motion sensor in order to design the signal-processing block mentioned in section II. As we said above, the output of the sensor is a low-level voltage whose frequency (Doppler) represents the speed at which an

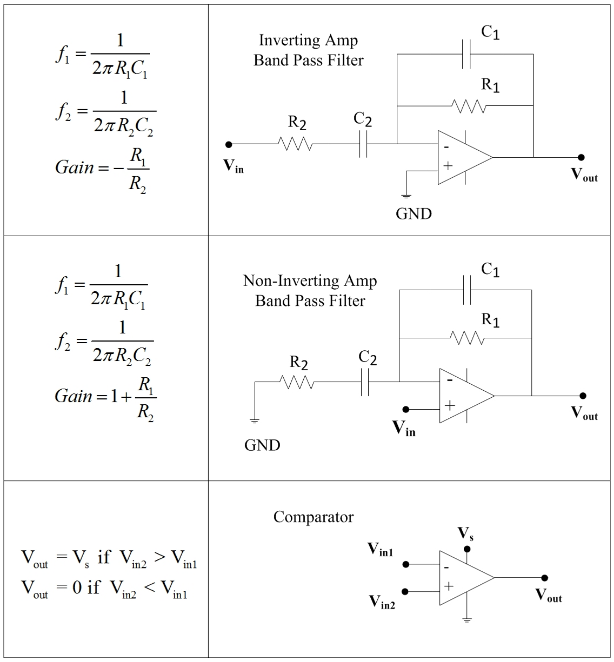

Fig. 3. Amplifiers Band Pass Filter and Comparator

object is moving towards or away from the sensor. The signal-processing circuit has to meet the following constraints.

1) The circuit can measure the movement when moving objects are in a certain distance of d_0 in the detection zone of the sensor.
2) The circuit should only amplify the signal whose frequency is in a specified bandwidth. This bandwidth is relied on the velocity of objects and selected in advance.

To solve the first problem, the designer has to choose an appropriate $Gain$ for amplifiers. If $Gain$ is too large, the signal is distorted and noises are multiplied. In reverse, if the $Gain$ is small and the distance between the sensor and moving objects is large, the signal cannot be fed into microcontroller. To solve the latter, the designer needs to survey the speed range and directions of objects and afterwards transforms to frequency range or bandwidth.

A. Gain selection

We assume the transmitted signal strength is E_{tx}. During propagation in free space and reflection of objects, the signal is weakened by two ways free-space loss, reflection loss, absorption loss of the target and other losses. The Received Signal Strength is E_{rx} computed by below equation:

$$E_{rx} = E_{tx} - 2 \times L_{free\ space} - L_{re} - L_{ab} - L_{others}[dB] \quad (1)$$

Where $2 \times L_{free\ space}$, L_{re}, L_{ab} and L_{others} are two ways free-space loss, reflection loss, absorption loss of the target and other losses, respectively.

While we can calculate free-space loss, it is difficult to estimate losses related to reflection, absorption, etc. due to the differences in figure, material, etc. of objects. Equation (1) can be rewritten:

$$E_{rx} = E_{tx} - 2 \times L_{free\ space} - \sum loss[dB] \quad (2)$$

Free-space loss is proportional to the square of the distance between the transmitter and receiver, and proportional to the square of the frequency of the radio signal. Free-space loss is given:

$$L_{free\ space} = (\frac{4\pi d}{\lambda})^2 = (\frac{4\pi df}{c})^2 \quad (3)$$

Where:

λ is the wavelength of the transmit wave $[m]$

f is the frequency of the transmit wave $[Hz]$

d is the distance from the transmitter $[Hz]$

c is the speed of light in a vacuum $[m/sec]$

In decibels:

$$L_{free\ space} = 20\log_{10} d + 20\log_{10} f - 147.55[dB] \quad (4)$$

From (2) and (4) we have the Received Signal Strength computed:

$$E_{rx} = E_{tx} - 40\log_{10} d + 40\log_{10} f - 295.1 - \sum loss \quad (5)$$

Because the frequency of transmit wave is constant, we can set:

$$\sum Loss = -40\log_{10} f + 295.1 + \sum loss[dB]$$

Therefore, Equation (5) is rewritten:

$$E_{rx} = E_{tx} - 40\log_{10} d - \sum Loss[dB] \quad (6)$$

After passing through amplifier with $Gain = G$, to be fed into microcontroller, the signal strength should be E_0. Therefore:

$$\begin{aligned} E_0 &= E_{rx} + 10\log_{10} G \\ &= E_{tx} - 40\log_{10} d - \sum Loss + 10\log_{10} G \\ &= E_{tx} + 10\log_{10}\frac{G}{d^4} - \sum Loss \end{aligned} \quad (7)$$

From (7) we can design an algorithm to choose an appropriate $Gain$. Following steps are used to select $Gain$ for amplifier when objects move in a distance of d_0 from the sensor. ε is an acceptable deviation of detecting distance.

Step 1) Initialization: $G = G_0$, $d = d_0$, $\varepsilon = \varepsilon_0$

Step 2) Gain establishment:
Set: $Gain = G$

Step 3) Experiment:
Calculate the max distance (d_{max}) between the sensor and objects that the sensor is able to detect.
Set: $d = d_{max}$

Step 4) Reference:
If $|d_0 - d| < \varepsilon \rightarrow$ end.

Else $\rightarrow$ Set: $G = Gain \times (d_0/d)^4 \Rightarrow$ Go to Step 2.

By using that method, we achieved a detection of moving objects at a distance of about $8[m]$ in light-of-sight with $Gain = 12000$.

B. Bandwidth selection

The goal of this subsection is to select the best bandwidth for filters of the signal-processing circuit. We have Doppler equation [10]:

$$F_d = 2v(\frac{F_t}{c})\cos\theta \tag{8}$$

Where:

F_d is Doppler frequency $[Hz]$

v is speed of the object $[m/sec]$

F_t is transmit frequency $[Hz]$

c is speed of light $[m/sec]$

θ is the angle between the object moving direction and the axis of the sensor

Table. II shows bandwidths correlated with a speed range of $5[km/h] - 40[km/h]$ and $\theta = 0\,°$.
The design of filters with precise bandwidth helps avoid noises from the surrounding environment. Designers should take notes about the transmit frequency of the sensor, speed range of objects and the direction of objects in order to make perfect filters.

TABLE II. BANDWIDTH WITH DIFFERENT TRANSMIT FREQUENCIES

Transmit Frequency $[GHz]$	Bandwidth $[Hz]$
9.35	87 - 692
9.9	92 - 733
10.525	97 - 780
10.587	98 - 784
10.687	99 - 792
24.125	223 - 1787

IV. ALGORITHMS FOR LENGTH AND SPEED MEASUREMENT

The aim of this section is to introduce an algorithm to calculate length and speed of vehicles. The output signal from the sensor is converted to a square wave after passing the signal-processing circuit and this square wave is fed into microcontroller. From this wave, the microcontroller gets information about length and average speed of vehicles.

The square wave fed to microcontroller has a form as Fig. 4. The time (t_1) when a vehicle begins moving to the detection zone of the sensor is demonstrated as time the output signal (after passing the signal-processing block) is set to high level. The Doppler frequency information is expressed in the square wave during the period that the vehicle still be in the detection zone and can be calculated as times the output signal is set from low level to high level in a specific amount of time. If the amount of time (Δt) the output signal is set to low level from the time t_n is greater than $\Delta t_{time-out}$, the vehicle is considered moving out the detection zone.

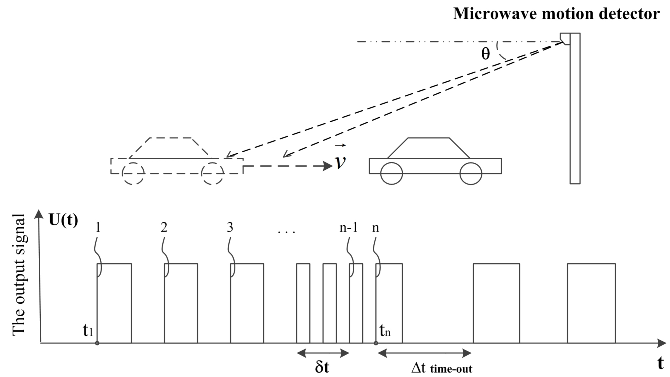

Fig. 4. The square wave at input of microcontroller

We consider in the differential time δt, vehicle speed is constant. Therefore, the Doppler frequency is:

$$F_d = \frac{x}{\delta t} \tag{9}$$

Where x is the number of times, the output signal is set from low level to high level during the period of δt.

The sensor is installed in the center on the road lane. The antennas of the sensor is oriented to the lane and the transmit wave from the antennas make an angle of θ with the lane. Because the direction of vehicles is parallel with the lane when they move in the detection zone of the sensor, the angle between the velocity of vehicles and the transmit wave is equal to θ and constant. By using Doppler Equation (8) we have the vehicle speed in δt is:

$$v = \frac{F_d \times c}{2cos\theta F_t} = \frac{F_d}{k}$$

With scale factor k formulated:

$$k = \frac{2F_t}{c}\cos\theta$$

Therefore, in this δt-period the sensor gave the length information:

$$\delta s = v\delta t = \frac{F_d}{k}\delta t \tag{10}$$

From (9) and (10), we have:

$$\delta s = \frac{x}{k} \tag{11}$$

Vehicle length (S) is the integral calculus of δs in the period between times the vehicle moves in and moves out the detection zone.

$$S = \int_{t_1}^{t_n} \delta s = \int_{t_1}^{t_n} \frac{x}{k} = \frac{n}{k} \tag{12}$$

With n is the gross number of times, the output signal is set from low level to high level over the period from t_1 to t_n.

From (12), we have "*vehicle length is formulated as a ratio of times the output signal is set from low level to high level and the scale factor k*".

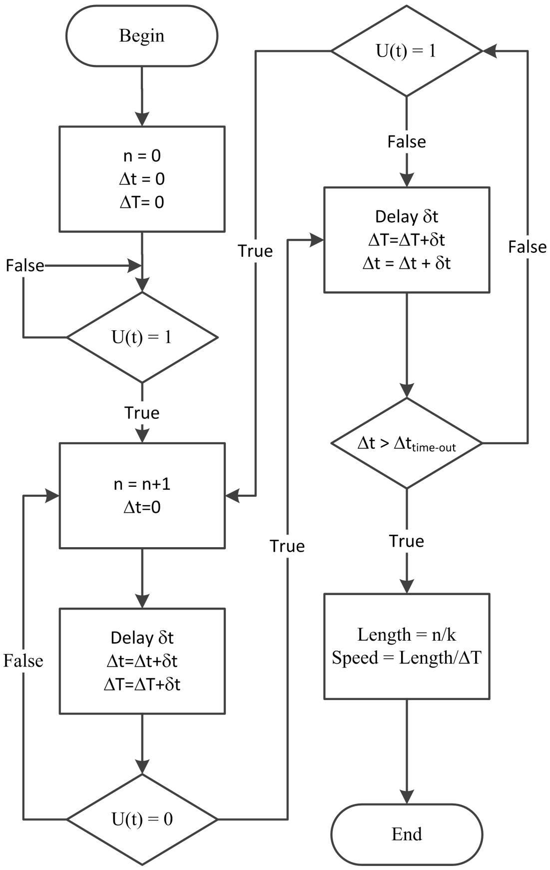

Fig. 5. Flowchart for speed and length calculation

The average speed of vehicle is:

$$V = \frac{S}{t_n - t_1} = \frac{S}{\Delta T} \tag{13}$$

Where ΔT is the amount of time vehicle moves in and move out the detection zone.

From (12) and (13) we design a flowchart as Fig. 5 to calculate vehicle length and speed.

The scale factor k depends on transmit frequency and position of the sensor with the vehicle. The value $\Delta t_{time-out}$ depends on the minimum of the vehicle speed and it is computed:

$$\Delta t_{time-out} = \frac{1}{F_{dmin}} = \frac{1}{kV_{min}} = \frac{c}{2V_{min}F_t\cos\theta} \tag{14}$$

For example, using Transmit frequency $F_t = 9.9[GHz]$, speed ranges from $5[km/h] - 40[km/h]$, $\theta = 30\,°$.

$$\Delta t_{time-out} = \frac{3 \times 10^8}{2 \times (5 \times 10^3/3600) \times 9.9 \times 10^9 \times \cos 30\,°}$$
$$= 12.6 \times 10^{-3}[s]$$

Using this algorithm, length and speed of vehicle is calculated in real time by using a microwave motion sensor.

TABLE III. RESULTS OF OBSERVATION OF VEHICLE LENGTH AND SPEED

Type	Real length	Range of speed (km/h)	Accurate percentage (%)
Car	3.60	0-10	85
		10-20	90
		20-30	87
		30-40	80
Bus	5.6	0-10	81
		10-20	92
		20-30	90
		30-40	85
Truck	7.3	0-10	88
		10-20	96
		20-30	94
		30-40	89

V. REAL SYSTEM IMPLEMENTATION AND RESULTS

The real system was implemented using methods, algorithms mentioned. The following hardware was used:

a) Microwave motion sensor: HB100, $F_t = 10.525$ $[GHz]$, $\theta = 30\,°$.
b) Amplifier circuit: LM324.
c) Microcontroller: PIC 16F886.
d) Power Supple: 5[V] DC.

The system was used to calculate length and speed of vehicles in radius of $8[m]$ in line-of-sight, vehicle speed range from $5[km/h]$ to $40[km/h]$.

These parameters was determined by algorithms

- $Gain = 12000$
- $Bandwidth = 80[Hz] - 800[Hz]$
- $k = 61$
- $\Delta t_{time-out} = 11.8 \times 10^{-3}[s]$

We observed three types of vehicles: Car, Bus, Truck, each type in four different ranges of speed. After each time, if the observed length ($L_{observed}$) of the vehicle has:

$$\frac{|L_{obsevered} - L_{real}|}{L_{real}} \leq 10\%$$

, we mark with a tick as a correct time of the measure. With each range of speed in each type of vehicle, we observed $100\ times$ and worked out the accurate percentage. Table III presents results observed by the system.

VI. CONCLUSION

A real-time microwave motion detector with the aim of length and speed calculation of vehicles has been implemented. This detector was experimented many times and received feedback in order to have a good detection. The use of gain selection, bandwidth selection methods helps to save time for experiment and the integration of the length-speed calculation algorithm in a single detector reduces cost and makes the product become compact and portable.

However, this detector have still had its limitations. It gives wrong results when more vehicles move consecutively in a short amount of time and the speed range measured is limited in some real system. More works will be done in the future in order to implement the detector in Intelligent Transport System.

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