Evaluation of Proximity Sensors: Their Suitability for Sensing Objects in Dynamic Motion

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تقييم أجهزة استشعار التقارب: مدى ملاءمتها لاستشعار الأجسام المتحركة

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Abstract:

Proximity sensors are widely used in industrial and commercial fields. There are various types and forms of these sensors, with significant differences in their sensitivity and measurement ranges. Proximity sensors in our current era are a subject of study and research for the systematic development of new and innovative applications. This research paper examines the performance of proximity sensors for measuring the speed of moving objects and as product counters. The study includes an analysis of various types of industrial proximity sensors, which are capacitive, inductive, and photoelectric (infrared and red light), by conducting experiments to measure their performance in determining object speed. The results demonstrated that all the sensors studied could sense and measure speed. Speeds measured by proximity sensors were compared with those measured by the optical digital tachometer. The error rate for capacitive and inductive sensors was between 3% and 5%, and for photoelectric sensors, it was between 1% and 7% at rotation speeds less than or equal to 832.7 RPM. At rotation speeds greater than this value, the error rate increased to over 10%. The study concluded by providing an understanding of the capabilities and limitations of proximity sensors, which helps in making decisions about their applications and selecting the appropriate sensor based on specific application requirements for the set sensors of experiments.

Keywords: Industrial proximity sensors, Capacitive sensors, Inductive sensors, Photoelectric sensors.

الملخص:

تُستخدم مستشعرات التقارب على نطاق واسع في المجالات الصناعية والتجارية. وتتنوع أنواعها وأشكالها، مع وجود اختلافات كبيرة في حساسيتها ونطاقات قياسها. تُعدّ مستشعرات التقارب في عصرنا الحالي موضوعًا للدراسة والبحث بهدف التطوير المنهجي لتطبيقات جديدة ومبتكرة. تتناول هذه الورقة البحثية أداء مستشعرات التقارب في قياس سرعة الأجسام المتحركة وكعدادات للمنتجات. تشمل الدراسة تحليل أنواع مختلفة من مستشعرات التقارب الصناعية، وهي السعوية والحثية والكهروضوئية (الأشعة تحت الحمراء والضوء الأحمر)، وذلك من خلال إجراء تجارب لقياس أدائها في تحديد سرعة الأجسام. أظهرت النتائج أن جميع المستشعرات المدروسة قادرة على استشعار وقياس السرعة. تمت مقارنة السرعات المقاسة بواسطة مستشعرات التقارب بتلك المقاسة بواسطة مقياس سرعة الدوران الرقمي البصري. تراوح معدل الخطأ للمستشعرات السعوية والحثية بين 3% و5%، بينما تراوح للمستشعرات الكهروضوئية بين 1% و7% عند سرعات دوران أقل من أو تساوي 832.7 دورة في الدقيقة. عند سرعات دوران تتجاوز هذه القيمة، ارتفع معدل الخطأ إلى أكثر

من 10%. وخلصت الدراسة إلى توفير فهم لقدرات وقيود مستشعرات التقارب، مما يساعد في اتخاذ القرارات بشأن تطبيقاتها واختيار المستشعر المناسب بناءً على متطلبات التطبيق المحددة لمجموعة المستشعرات المستخدمة في التجارب.

الكلمات المفتاحية: أجهزة استشعار التقارب الصناعية، الحساسات السعوية، الحساسات الحثية، الحساسات الكهروضوئية.

Introduction:

Sensors that detect objects without requiring physical contact are called proximity sensors, making them ideal for applications unsuitable for direct contact. Proximity sensors are considered important technologies in the modern era, used in numerous industrial, medical, and commercial applications. Common industrial applications include measuring centering and alignment, measuring diameter, thickness, or displacement, and controlling dimensions in industrial processes [1]. These sensors depend on various physical principles to sense the presence of nearby objects. With technological advancements, these devices have become more accurate and efficient, enabling broader and more complex applications, such as improving the performance and accuracy of mechatronics systems. For example, they are used in industrial robots to sense and locate objects [2], and in automobiles, many proximity sensors are used in systems such as braking, safety, and control systems [3, 4]. The study [5] also discussed the characteristics and applications of what is known as proximity-sensing electronic skin. This research presented the latest findings on flexible proximity sensors, focusing on understanding the operating principles of capacitive and triboelectric proximity sensors. It also summarized the importance of flexible proximity sensors in applications such as human-robot collaboration, human-machine interfaces, and remote monitoring.

Proximity sensors differ from mechanical sensors in that they detect objects and operate without contact. Their main advantages are long life, silent operation, and low power supply. However, the sensing distance of proximity sensors can be influenced by ambient conditions such as temperature and humidity. Additionally, switching distance can depend on object characteristics, such as surface features, color, and material. Furthermore, contamination can also cause changes in the switching distance of optical sensors [3, 6].

This paper evaluates industrial proximity sensors using capacitive, inductive, and photoelectric (red light and infrared) sensors to determine their performance, responsiveness, accuracy, and reliability in measuring object speed. Object speed measurement is crucial in numerous practical applications, such as monitoring vehicle movement in intelligent traffic systems or measuring object speed on production lines to ensure quality and efficiency. However, the challenges associated with using proximity sensors cannot be overlooked. While these devices offer significant benefits, their use faces some limitations, such as the impact of environmental factors on sensing accuracy, and how to overcome these factors to ensure reliable and efficient performance [7]. Finally, the paper provides a conclusion of proximity sensors, in terms of their suitability and velocity measurement capabilities, to offer a deeper understanding of this technology and how to use it effectively in several applications.

Types of Proximity Sensors:

These devices vary based on the technology used in their design; the types of sensors that are experimented with in this study are shown in Table 1.

Table 1: Technical data for sensors [8]

Proximity sensor	Scanning range (mm)	Wavelength (nm)	Nominal switching distance (mm)	Operating temperature(°C)
Capacitive	0.5 - 10	-	5	-25 to 70
Inductive	0.5- 10	-	5	-25 to 70
Photoelectric (infrared)	20 -150	880 nm	-	-25 to 55
Photoelectric (red light)	5.-200	660 nm	-	-25 to 65

Capacitive Sensors: Capacitive sensors react when an object approaches the active surfaces. The capacitance increases, changing the sensor's switching state. A built-in potentiometer can be used to adjust the switching distance. A capacitive proximity switch responds to all solid and liquid media. Since air is also an insulator, changes in humidity cause a change in the sensing distance [9].

Inductive Sensors: In the case of inductive sensors, if an electrically conductive material moves into the field, an induced eddy current is created in the material. These current draws energy from the resonant circuit, and thus, the decrease is converted into an electrical signal [10].

Red Light and Infrared Photoelectric Sensors:

Compared to inductive or capacitive sensors, photoelectric sensors have a bigger range. The sender light is reflected by the object to be detected to the receiver and is then electronically evaluated. The scanning range of a photoelectric proximity sensor depends largely on the object's reflectivity. The

scanning range of smooth, white objects is much greater than that of matte, black objects. For example, an infrared transmitter transmits a signal within a limited range. When infrared light strikes an object's surface, some of the light is reflected depending on the surface's colour. The brighter the colour, the more infrared light is reflected; similarly, the darker the surface, the more infrared light is absorbed and the less is reflected [10].

Laboratory Experiments:

Preparing the Experiments: The experiments were conducted in the mechanical engineering laboratories at the University of Tripoli, as shown in Figure 1. The figure shows the components of the experiment, as the four sensors were installed in their designated inlets, as shown in Figure 2. The sensor response is indicated by the lighting of an LED indicator, and the switching distance can be read using a meter or micrometre.
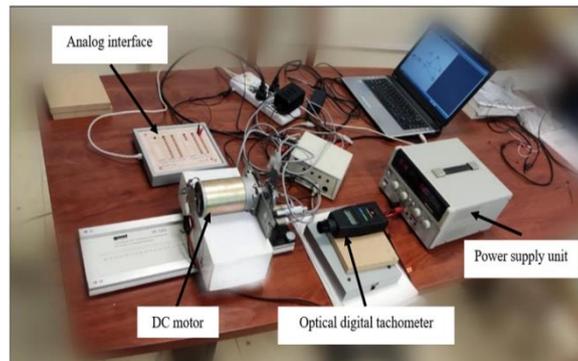

Figure (1): Picture showing the equipment used in laboratory experiments to measure the response speed of the sensors.

Figure (2): Picture of the types of sensors, micrometer and DC motor and the rectangular piece of iron used in laboratory experiments.

Table (2): Specification of the optical digital tachometer.

Technical data	
Accuracy	0.05 %
Sampling time	1 sec. (over 60 RPM)
Test range select	Automatic.
Operating temperature	0 to 50 °C

Laboratory Experiments to Study the Performance of Sensors in Detecting Moving Objects:

The use of proximity sensors in applications such as measuring motor rotational speed and in mass production requires knowledge of the response speed of the sensors to select the appropriate sensor [1]. Therefore, experiments were conducted to achieve this objective, as shown in Figure 2. The DC motor was prepared by fixing a rectangular piece of iron (20 cm x 4 cm, thickness 2 mm) to it, perpendicular to its axis, so that it rotated with the motor in the same plane, then placed directly in front of the sensors to give a signal during the motor's rotation. By measuring the frequency of the motor rotation signal, two signals were produced; it was assumed that each frequency represented a complete cycle. The sensors were connected to a computer using an analogue interface (USB port connection) and the Visual Designer software to allow for real-time recording and storage of results on the computer. After connecting all the components, the system was switched on so that the frequency speed that was generated by each sensor could be measured. Concurrently, a digital optical tachometer, shown in Figure 1, was used to compare its results with those obtained from the proximity sensors.

The DC motor was started in steps (starting at low speeds and gradually increasing the speed by increasing the input voltage). The recorded results on the computer are displayed in Figures 3, 4, 5, and 6, which lay out samples of the results. They illustrate the variation in the behavior of the sensors (capacitive, inductive, photoelectric red light, and infrared) under the influence of different speeds when the DC motor was supplied with voltages of 5, 10, 15, 20, and 25 V. The horizontal plane represents the sampling time Ts, which is 0.001 seconds, while the vertical plane represents the amplitude of the output signal pulse in volts (V). In Figures 3, 4, 5, and 6, an irregularity in the frequency at 25V input voltage is observed, which affects the accuracy of the results at high speeds.

Regarding the determination of the rotational speed, synchronous sampling of the analog signal to the digital range was performed, and thus the signal frequency f_O can be calculated by dividing the sampling frequency f_s by an integer N_0 [11].

For example, in Figure 3, the difference between the beginning of the two peaks of the capacitive sensor is $T_s=4$ at the first peak and $T_s=286$ at the second peak when the input is 5 volts. Thus, $dT=$ 284 ms (284 x 1 ms). Since in this case, the values of $N_0 = 1$ and $N_s = 1$. Then, the rotational speed of each sensor can be calculated using equations (1, 2, 3), as shown in Table 3.

$$f_s = \frac{N_S}{dT} \qquad (1)$$

$$f_O = \frac{f_s}{N_O} \qquad (2)$$

$$\frac{1}{f_o} = \frac{60}{\omega} \qquad (3)$$

Where the signal frequency is f_O per cycle, the total sampling frequency during dT is f_s, N_0 is the number of frequencies per cycle of the motor, N_s is the number of frequencies during dT, and ω is the rotational speed.
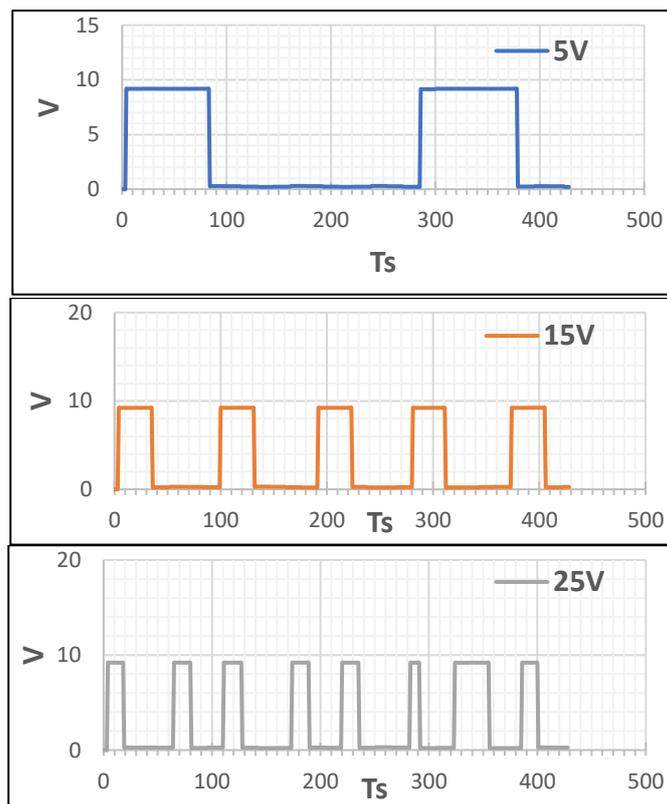

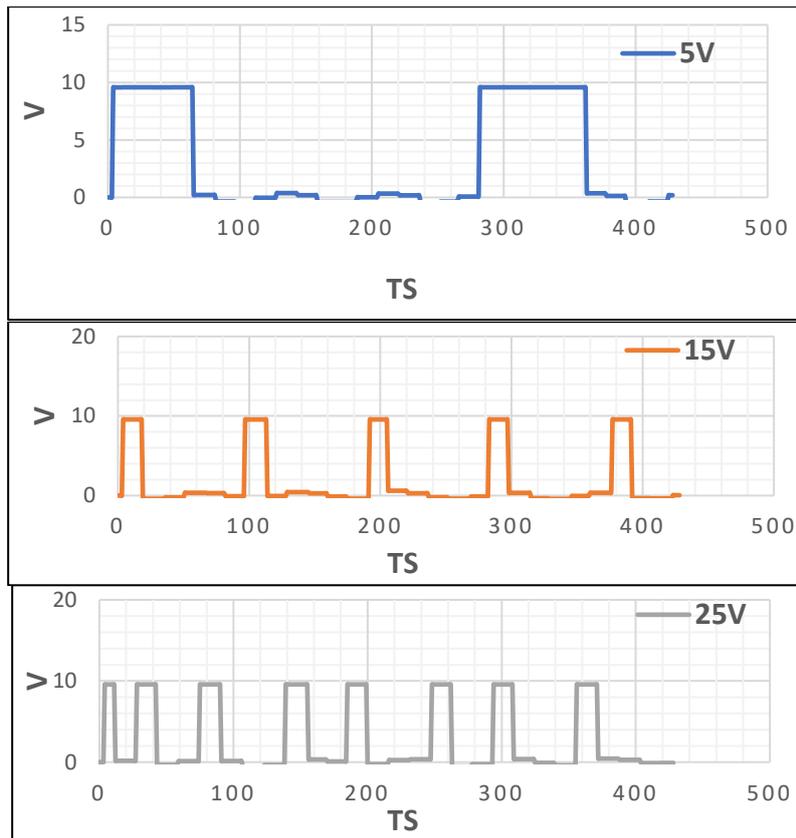**Figure (3):** The behavior of the capacitive proximity sensor.

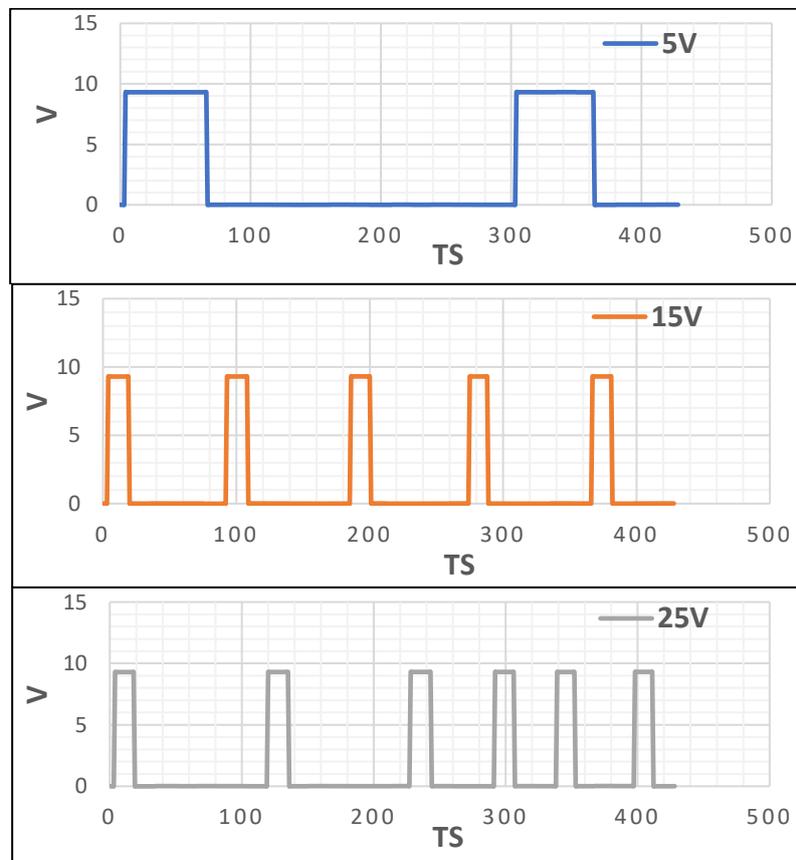**Figure (4):** The behavior of the inductive proximity sensor.

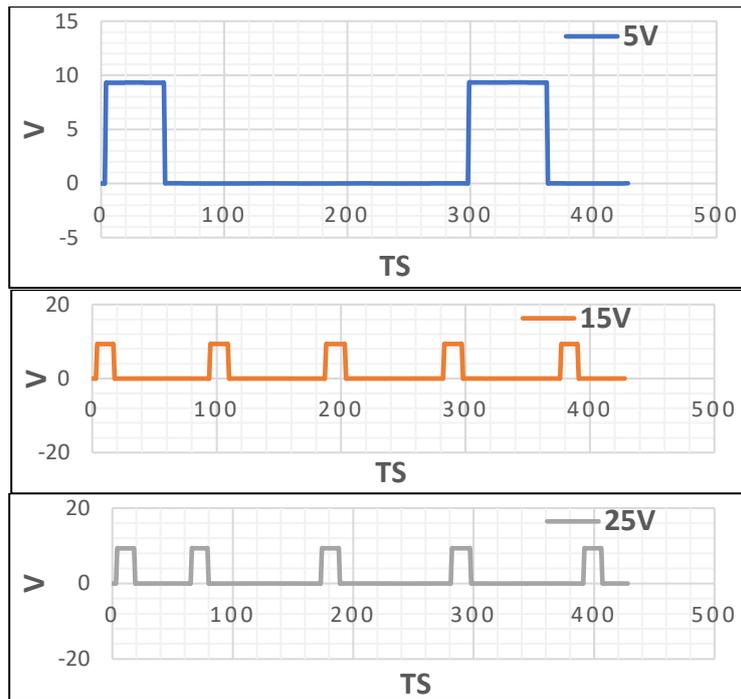**Figure 5:** The behavior of the infrared proximity sensor.

Figure (6): The behavior of the red light proximity sensor.

Table (3): Experimental results for the calculation of rotational speed for each sensor.

Sensor	Input voltage (v)	N_s	dT (ms)	f_0 (Hz)	ω (RPM)
Capacitive	5	1.0	282.0	3.5	212.8
	10	6.0	838.0	7.2	429.6
	15	4.0	370.0	10.8	648.6
	20	1.0	80.0	12.5	858.0
	25	7.0	364.0	19.2	1153.8
Inductive	5	1.0	278.0	3.6	215.8
	10	3.0	417.0	7.2	431.7
	15	4.0	373.0	10.7	643.4
	20	8.0	558.0	14.3	860.2
	25	7.0	352.0	19.9	1193.2
Infrared	5	1.0	300.0	3.3	200.0
	10	3.0	424.0	7.1	424.5
	15	4.0	363.0	11.0	661.2
	20	4.0	283.0	14.1	848.1
	25	5.0	394.0	12.7	761.4
Red light photoelectric	5	1.0	295.0	3.4	203.4
	10	4.0	565.0	7.1	424.8
	15	4.0	373.0	10.7	643.4
	20	4.0	269.0	14.9	892.2
	25	4.0	388.0	10.3	618.6

After measuring the response of the sensors at different speeds, the results were confirmed by comparing the sensor readings with those taken from a digital optical tachometer, as shown in Table 4. The error was determined as in the following equation:

$$|error| = \frac{sensor\ measure - tachometer\ measure}{tachometer\ measure} \text{x}100$$

Table (4): Comparison of the error of experimental results with those obtained from a digital optical tachometer.

Digital optical tachometer (RPM)	Capacitive %	Inductive%	Infrared%	Red light photoelectric%
206.0	3	5	3	1
412.2	4	5	3	3
624.4	4	3	6	3
832.7	3	3	2	7
1050.0	10	14	27	41

Discussion of the Results:

The results of the experiments to evaluate the ability of proximity sensors to measure the speed of moving objects showed that all the sensors studied demonstrated their measurement capabilities. Table 4 and Figures 7, 8 illustrate a comparison between the speed measured by the capacitive and inductive sensors and the speed measured by the digital optical tachometer, showing an increased error rate after rotational speeds exceed 832.7 RPM (the error rate became nonlinear). Compared to the readings taken from the digital optical tachometer. The error rate for capacitive and inductive sensors was between 3% and 5%, and for photoelectric sensors, it was between 1% and 7% at rotation speeds less than or equal to 832.7 RPM.
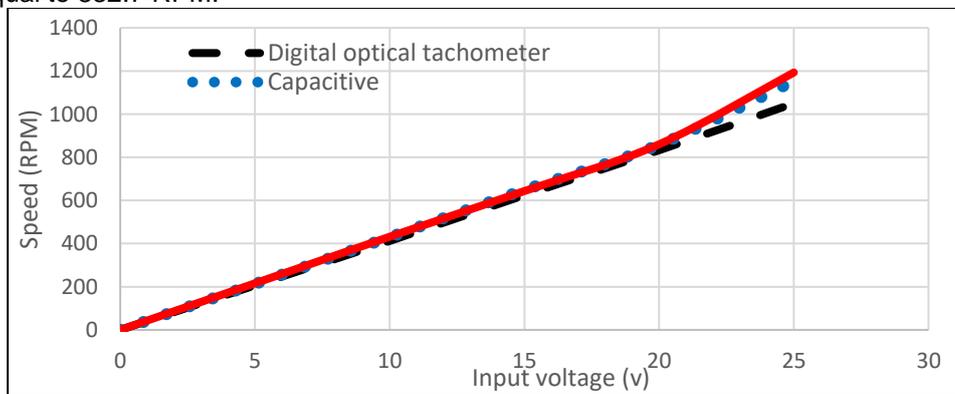

Figure (7): Shows a comparison of the experimental results from the capacitive and inductive sensors with the readings recorded from the digital optical tachometer measuring device.
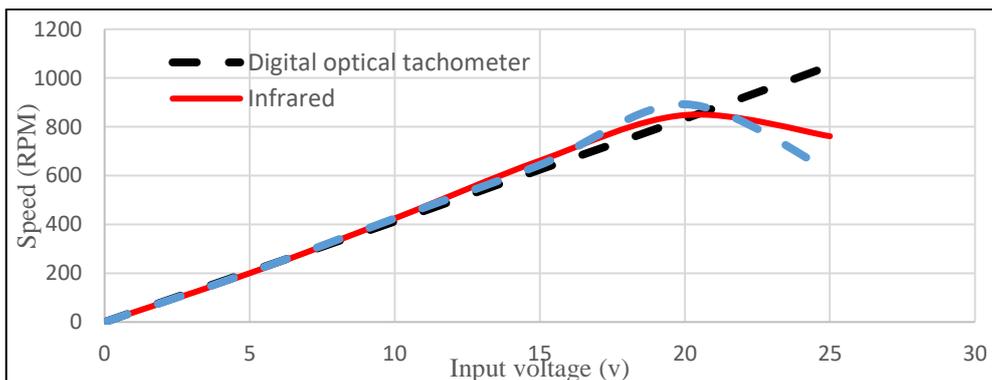

Figure (8): Shows a comparison of the experimental results from the photoelectric sensors with the readings recorded from the digital optical tachometer measuring device.

Conclusion:

An understanding of the capabilities and limitations of proximity sensors helps in making decisions about their applications and selecting the appropriate sensor based on specific application requirements. The study concluded with several findings that enable users to choose the most suitable sensor. Inductive proximity sensors only detect metallic objects; however, there is a variation in the maximum sensing distance for different types of metals. Capacitive proximity sensors, on the other hand, are distinguished by their ability to sense all materials, including metals and non-metals. This is what distinguishes these sensors from inductive sensors, as the maximum measured distance for a capacitive sensor depends on the dielectric constant of the material. Both sensors are characterised by

low power consumption, but their measuring range is small (not exceeding a few millimetres). Photoelectric sensors have a much larger measuring range than both inductive and capacitive types. It has also been shown that the sensing distance of photoelectric sensors is affected by the intensity of light in the location and by atmospheric pollution or dust in the sensor's spatial area, which affects the accuracy of the measurement. Also, one of the factors that affects the accuracy of the measurement is the presence of an external electromagnetic or electric field in the measuring range of the inductive or capacitive sensor. In this phase of the study, the ability of proximity sensors to measure the speed of moving objects in front of them was tested. By comparing the data recorded by the sensors with the digital optical tachometer, the error rate for capacitive and inductive sensors was between 3% and 5%, and for photoelectric sensors, it was between 1% and 7% at rotation speeds less than or equal to 832.7 RPM. At rotation speeds greater than this value, the error rate turned nonlinear and increased to over 10%. Table 3 shows that when these sensors are used as a counter for products, the maximum quantity that can be counted per second is 15 pieces with an error rate not exceeding 7%.

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