Mechatronic system to classify plastic and metal bottles using capacitive and inductive sensors

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ABSTRACT

The problem addressed in this article focuses on the management of plastic waste, which has experienced a significant increase in recent years, posing challenges in its management and recycling. In addition, the concentration of microplastics in water and their impact on health and the food chain is highlighted. The proposed solution consists of developing a mechatronic system for sorting plastic and metal bottles using capacitive and inductive sensors, respectively. The system demonstrated efficiency in tests, achieving 100% sorting for plastic and metal bottles. The need for bottles to be properly positioned for optimal performance was identified. This work highlights the importance of automation in mechatronic systems and the effectiveness of capacitive and inductive sensors in sorting materials.

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1. INTRODUCTION

Plastics have had a remarkable effect on contemporary life during the last 60 years providing significant possibilities to improve the conservation of food resources [1]. However, during the last ten years the production of plastics has increased significantly, accounting for up to half of the environmental impacts in the food chain, producing challenges for its management [2], [3]. Moreover, lakes and canals witness high concentrations of microplastics posing risks to the health of the population and the food chain [4]–[7]. Similarly, aluminum containers that reach lakes and canals generate toxic effects on embryonic development and the production of malformations when combined with drugs [8]. Therefore, it is essential to implement proactive measures to achieve a more sustainable management of plastics and metals worldwide [1]–[8]. One solution to combat plastic waste pollution is recycling. This process has become increasingly important in recent decades as a low-cost waste reduction strategy that offers advantages in the industrial economy [9]. The main importance of recycling lies in its direct impact on the health of the planet and humanity alike [10]. Recycling of aluminum containers in metal recovery by incineration has environmental benefits as its metal loss is less than 1% [11].

Capacitive sensors find application in a variety of industrial uses. In many cases, high accuracy is required, despite the fact that the distance to be measured is usually very small, generally in the range of 10 mm [12]. On the other hand, inductive sensors detect changes in the permeability of their magnetic tape due to the applied magnetic field, their susceptibility and magnetic saturation under weak magnetic fields, these sensors can only measure a limited range [13].

In the field of plastic bottle classification, near infrared (NIR) spectroscopy has been employed, as mentioned in [14], where machine learning algorithms were used for classification of NIR spectra.

Polyethylene terephthalate (PET) and glass bottle data were incorporated into the training set. Also, plastic bottles were classified while moving on a conveyor belt, using both RGB and multispectral cameras. The bottles were sorted into three categories according to their color and material: transparent PET, blue PET, and transparent polypropylene (PP) [15].

Similarly, Cai *et al.* [16] proposed to identify spectra obtained in different wavelength ranges, including multispectral cameras and mid-wave infrared (MWIR) cameras, and offers a solution to classify black plastics and common recycled plastics. Eleven machine learning classification algorithms were experimented with. In the study [17], laser induced fluorescence (LIF) technique was applied to improve the identification of polymers (Expanded polystyrene (EPS), polystyrene (PS), polypropylene (PP), and high-density polyethylene (HDPE)) by processing LIF spectra with multivariate approaches.

On the other hand, in study [18], captured images were used from which features were extracted using the Kernel principal component analysis (PCA) method. In addition, classification was performed using support vector machines (SVM). Similarly, in study [19], a camera and a deep learning model were used to identify and classify bottles by size and weight. If the inserted object was not a bottle, it will be ejected ending the process. Also, Zia *et al.* [20] focused on the classification of plastic, glass, and cans, making use of sensors with barcodes and NIR technology. In parallel, bottle classification was performed following the Otsu method, which extracted various bottle shape features, such as perimeter, area, eccentricity and major axis length, as described in [21]. On the other hand, in the study [22] a test system was implemented to detect and control the amount of bottles and plastic trays of the same size on a conveyor belt. This system used inductive sensors and was managed by an Allen Bradley programmable logic controller (PLC). In the same context, in study [23], an educational environment was developed that included an S7-1200 PLC and a conveyor belt equipped with capacitive sensors, allowing the detection of cylindrical plastic and metal parts, in addition to actuators for the palletization of the parts. Finally, in study [24], a system for automatic sorting of square parts made of various materials, such as plastic, metal, and wood, was implemented using inductive and capacitive proximity sensors. It can be noted that the classification of bottles based on their characteristics is widely popular nowadays. This is achieved by employing image processing and sophisticated spectroscopy techniques applied to materials such as PET, PP, metal, and their derivatives. In addition, there is a marked trend towards the implementation of educational sensing environments with conveyor belts and capacitive and inductive sensors to identify objects of suitable size for the sensing process, since the measurement range of the sensors is usually limited, as previously mentioned in the state of the art.

However, it is important to note that sorting and detection of bottles based on their material using capacitive and inductive sensors together with mechatronic system has not yet been developed. On the other hand, most automated machines designed to perform this sorting are usually composed of multiple interconnected processes [25]. The relevance of this study lies in the accurate detection and sorting of PET and metal bottles with various shapes and sizes, without relying on a specific size, through the use of capacitive and inductive sensors. In addition, a mechatronic system is integrated that overcomes the limitation of the low sensing range through careful positioning, thus improving the detection and classification efficiency of these objects. One aspect that deserves special attention is automation in the mechatronic system, which is achieved through the programming of controllers. It is relevant to note that, so far, this classification concept has not been addressed in any of the previously analyzed articles.

2. METHOD

2.1. Design of the mechatronic system

Figure 1 shows the 3D model created with Autodesk Inventor, providing a detailed visual representation of the final product. This representation clearly shows the dimensions of the structural part, with a height of 140 cm and a width of 70 cm, incorporating 50 mm thick metal plates to support the weight of the structure and components inside the sorting machine and at the same time give it robustness. This graphic representation was essential not only to understand the structure, but also to plan an efficient layout that would allow for the smooth integration of the electronic module and actuators. Figure 1 shows the proposed exterior and interior machine.

2.2. Sensor configuration

Figure 2 shows the front view of the bottle collecting machine. A black arrow indicates the location of the bottle near the detection zone, while red arrows indicate the position of the inductive sensor (Fotek PL-05N) for detection of the metal body of the bottle and the capacitive sensor (Vidonia LJC30A3-H-Z capacitive) for identification of the plastic bottle. Strategically located at the bottom of the reading platform, specifically at the 270-degree position with respect to the x-axis, these sensors seek to obtain accurate information about the material of each bottle. As can be seen, the bottle is placed as close as possible to the sensing zone to overcome the problems of the sensing range of the sensors, which are 4 and 10 mm, which is too small to detect any bottle effectively.

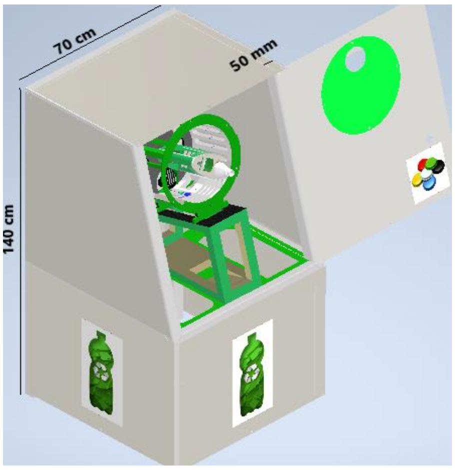


Figure 1. Isometric view of the bottle collecting machine

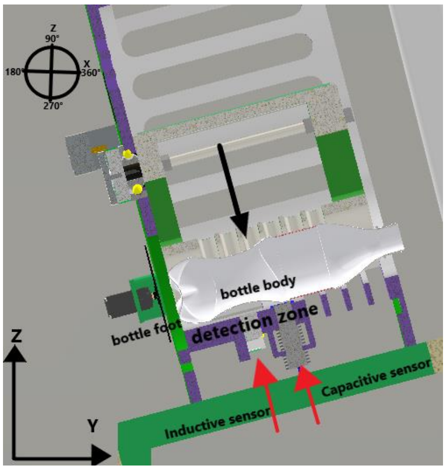


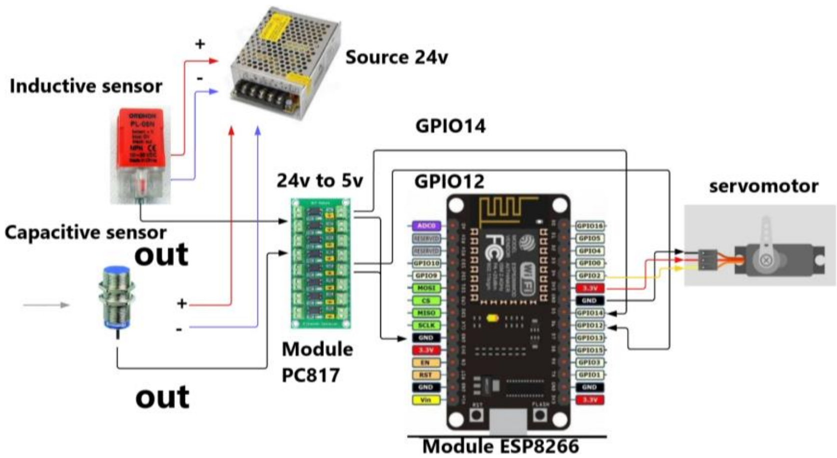
Figure 2. Side view of the bottle collector

2.3. Design of the classification system

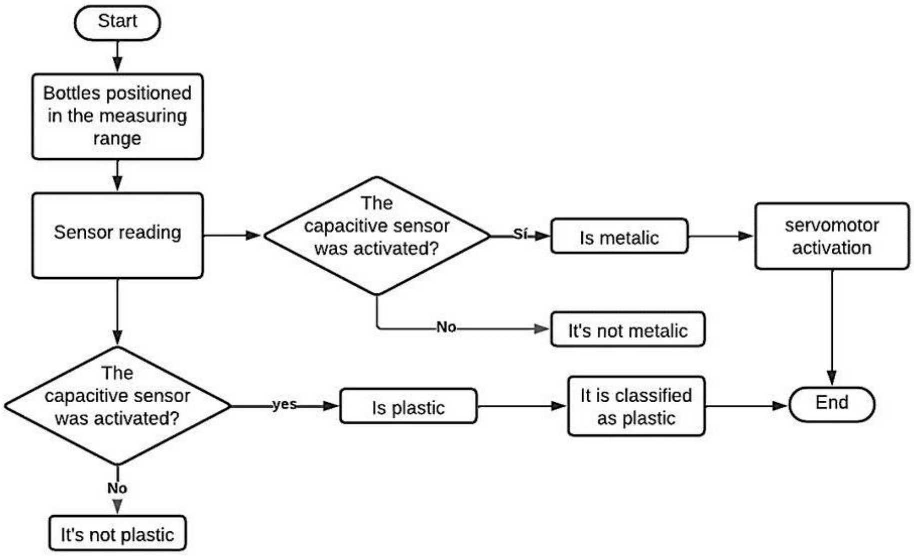
Figure 3 shows the front view of the bottle sorting system and its control circuit, where operation is initiated when a bottle is placed on the bottom. Servomotor control diagram, classification system control logic and positioning mechanism, shown in Figure 3(a)-(c), respectively. As the bottle body approaches the measurement range, the sensors emit 24 or 0 V signals, which are conditioned to 5 and 0 V by a PC817 optical module before being transmitted to the ESP8266. If the system detects a metal bottle or container, the controller activates a servomotor that moves a mechanism located at the rear of the machine where it is marked with a black arrow and red metallic letters, this mechanism works as a gate to select the metal bottle; otherwise, the stepper motor will continue to advance dropping the container or bottle into the opening of the cylindrical structure of plastic section.

2.4. Development of the positioning system

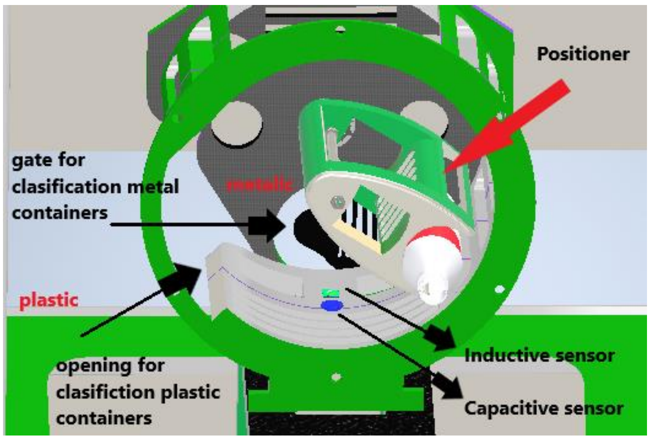
The positioning system is managed by an ESP32 that controls the inversion of the stepper motor rotation, moving the positioner indicated in Figure 3(c) with red arrow. The movement of the stepper motor is performed when the ESP32 module receives a binary signal, this signal is sent to the A4988 driver to finally send control signal to the stepper motor, as shown in Figure 4. When this signal is activated, the motor rotates counterclockwise from 90 degrees to the 270 degrees position, indicating that the positioner is at the bottom, remaining so for 5 seconds to allow the metal sorting system to perform the detection of the type of bottle. It then rotates to 270 degrees and stops for 2 seconds to perform plastic bottle sorting. Finally, it returns counterclockwise to its initial position and waits for the introduction of a new container.



(a)



(b)



(c)

Figure 3. The front view of the bottle sorting system and its control circuit: (a) servomotor control diagram, (b) classification system control logic, and (c) positioning mechanism

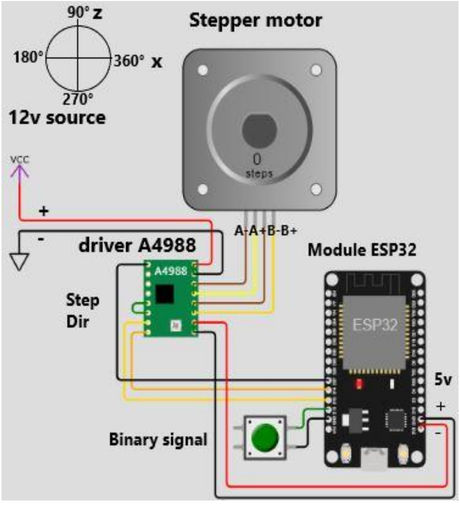


Figure 4. Positioner control circuit

3. RESULTS AND DISCUSSION

3.1. Testing of capacitive and inductive sensors

The results obtained after multiple sensing of the body of various plastic bottles and cans, using the Truper MELA-100 proximity sensor, with a minimum reading distance of 1 mm and a maximum of 1 m to obtain the distance in mm from the body of the bottle to the sensors, are presented in detail in Table 1. For example, values ranging from 2.4 mm minimum with Coca Cola to 3.8 mm maximum with Four Loko are displayed. In Table 2, on the other hand, shows the measurements made from the bottom of the bottles, where values ranging from 1.5 mm with Cifrut to a maximum of 1.88 mm with Coca Cola are observed, these being very small detection ranges.

Table 1. Detection ranges from the body of the bottles

Brand	Capacity (ml)	Distance (mm)
Coca Cola	500	2.40
Inka Cola	500	2.03
Pepsi	500	2.21
Guarana	500	2.17
Four Loko	473	3.80
Cristal	355	3.74
Pilsen	355	3.68
Heineken	330	3.65
Monster	473	3.66
Red Bull	250	3.00

Table 2. Detection ranges from the foot of the bottles

Brand	Capacity (ml)	Distance (mm)
Coca Cola	500	1.88
Inka Cola	500	1.53
Pepsi	500	1.71
Guarana	500	1.79
Fanta	500	1.54
Cifrut	500	1.50

3.2. Mechatronic system efficiency

The results obtained after performing 20 detection and classification tests for each bottle, considering different shapes and sizes, are presented in Table 3. The efficiency of the mechatronic system in the classification of metal bottles of different brands stands out, reaching an efficiency of 100% with the inductive sensors, demonstrating its robustness in the detection of metal containers. In addition, the results of the efficiency of the mechatronic system in the classification of plastic containers using the capacitive sensor are provided in Table 4. In this case, an efficiency ranging from 95% to 100% was achieved.

It is relevant to note that one of the challenges identified during testing was the need for the bottles to be positioned perpendicular to the sensors to ensure optimal performance, and this objective was achieved by adjusting the number of steps of the bottle unscrambler to position it exactly at 270 degrees, which is the position where the sensors are located.

In previous research [9], the Motorola LS 9208 bar sensor was employed in Coca-Cola (PET) bottle detection tests with a measurement range of 10 cm. It was observed that any distance below or above this threshold resulted in detection failures, achieving 97% efficiency. In contrast, in this study, 100% efficiency was achieved using a capacitive sensor and the measurement range problem was overcome using a mechatronic system, highlighting the effectiveness of this new methodology.

Table 3. Plastic bottle classification/detection efficiency

Brand	Tests	Detection efficiency (%)
Coca Cola	20	100
Inka Cola	20	100
Pepsi	20	95
Guarana	20	95
Fanta	20	100
Cifrut	20	100

Table 4. Metal bottle classification/detection efficiency

Brand	Tests	Detection efficiency (%)
Four Loko	20	100
Cristal	20	100
Pilsen	20	100
Heineken	20	100
Monster	20	100
Red Bull	20	100

4. CONCLUSION

The use of capacitive and inductive sensors shows remarkable variations in the detection range between plastic bottles and cans. It is evident that 500 ml plastic bottles have a lower range compared to cans. In addition, the importance of observing the results when sensing from the bottom of the bottles is highlighted, suggesting the need to consider sensing on the entire body of the bottle. The results highlight the efficiency of the mechatronic system in sorting plastic and metal bottles. The previously mentioned problem related to limited sensing ranges has been overcome. The inductive sensors achieve 100% efficiency in sorting metal bottles and, for the most part, 100% efficiency in plastic bottles, with the exception of Pepsi and guarana bottles, which achieved 95% efficiency. It is suggested that future work investigate the implementation of more advanced positioning systems to ensure optimal performance of the mechatronic system. This could include the use of algorithms or machine learning techniques to achieve accurate alignment of the bottles in front of the capacitive and inductive sensors.

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