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Color sorting process of materials in a plastics recycling company automated with Arduino

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Abstract*–Plastics recyclers face challenges in efficiently sorting materials due to manual processes that are slow and error-prone. The color sorting process represents a significant bottleneck in terms of time and accuracy. To address this problem, an automation model using an IoT-based system with Arduino microcontroller, color and proximity sensors, and actuators is proposed that optimizes this process by reducing the time required to sort materials. The model was validated by creating a working prototype, which showed a considerable improvement in efficiency: the manual sorting time of 2.75 seconds per material was reduced to 1.95 seconds in automated form, representing a 29% reduction in time per material. This breakthrough demonstrates the potential of automation to increase productivity, reduce errors and improve consistency in the plastics recycling process.

***Keywords*-- Arduino, IoT, industrial automation, plastics industry, plastics recycling**

I. Introduction

The environmental impact generated by the improper disposal of plastic waste has reached critical levels, making recycling an essential activity to address this problem. In Peru, 1.2 million tons of plastic waste is produced each year and only 10% is adequately recycled, considering that an average citizen uses around 30 kilos of plastic, according to the Ministry of the Environment (MINAM, 2024). Despite the importance of recycling, many companies and centers dedicated to recycling, especially those of small and medium scale, face technological and economic limitations that make it difficult to optimize their operations [1]. Manual methods, characterized as slow and error-prone, are still common in many companies, limiting the quality of recycled material and significantly raising operating costs.

In this contextual framework, the problem becomes more relevant when considering that many recycling organizations depend on the accuracy and speed of their processes to ensure the satisfaction of their customers, generally plastic injection companies that require high quality inputs [2]. In addition, the lack of an efficient records management system complicates inventory planning and operational and financial decision making, negatively affecting the competitiveness of these companies. These limitations highlight the need to implement accessible technological solutions to overcome existing economic and technical barriers.

Studying this problem is important because an appropriate solution would not only improve the company's operational efficiency, but also contribute to the sustainability of plastics recycling, helping to mitigate its environmental impact. In addition, effective recycling depends directly on efficient material separation [3]. Therefore, the integration of accessible technological solutions can not only solve the company's current limitations but also serve as a model for other organizations with similar challenges. In terms of efforts, research has shown that technologies such as sensors, artificial intelligence, and automation systems have significantly improved the sorting and management of plastic waste, thereby improving sorting accuracy [4]. For example, solutions based on optical sensors and programmable controllers have achieved sorting accuracy of over 96% [5]. Likewise, tools such as Arduino have been used to implement inexpensive and highly customizable automation systems in small companies, showing promising results in terms of cost and efficiency. Compared to other solutions that tend to be expensive and complex, limiting their adoption in smaller-scale companies [6].

The main motivation lies in the possibility of developing an accessible solution that solves the specific problems of recycling companies with limited resources. Their proposal seeks not only to increase accuracy and speed in sorting processes, but also to improve inventory management and reduce operating costs. In this way, the research is aligned with the objectives of sustainability and efficiency, contributing to the development of a replicable and scalable model for the plastic recycling industry. On the other hand, the objective of the article is to design and implement an automated system based on Arduino and IoT to optimize the sorting of plastic materials and inventory management in recycling companies. The proposal includes the development of a functional prototype that uses color and proximity sensors, actuators and an Arduino microcontroller, connected to the Arduino IoT Cloud platform for real-time monitoring. This solution seeks to offer an efficient, adaptable and low-cost technological tool to respond to the specific needs of the sector.

The proposal to be presented is based on a modular architecture that allows the detection of colors in plastic materials and their automatic classification using sensors. In addition, it includes a registration system that facilitates the traceability of the processed materials by facilitating their control through the use of IoT. This approach stands out for its economic accessibility and its ability to integrate into existing processes, representing an innovative and practical solution to address the main challenges of the plastic recycling industry. Finally, the paper is organized as follows: the first section presents the description of the conceptual framework in the state of the art. Subsequently, the technological proposal is detailed in terms of design and implementation. Then, the validation is developed through the elaboration of a functional prototype of the sorting process to discuss the results obtained, the practical implications and the conclusions of the study.

II. State of the Art

Plastic recycling

Plastics are materials that present a slow degradation, generating a significant impact on the environment. For this reason, the reuse of these wastes has acquired a crucial importance, becoming an essential process. This need has driven numerous researchers to develop innovations in all stages related to recycling, promoting more sustainable and efficient solutions to address this global challenge. Specifically, research focused on the classification of plastic waste exhaustively analyzed the difficulties that recycling plants present in this activity, especially those that use materials containing additives and contaminants; in response, it proposes technological methods such as hyperspectral images and Raman spectroscopy [7]. The use of hyperspectral images is used, in turn, in a study to quickly identify plastic materials for classification, showing a high precision of over 96%. However, there are still difficulties with transparent plastics, due to the light reflection phenomena which cause them not to be classified correctly [5]. Other studies focused on materials composed of polyethylene and polypropylene, which are used in containers that do not biodegrade easily. Based on this, research proposes mechanical classifications for these residues to obtain quality materials by applying electron beam and electrostatic separation, obtaining a purity of the recycled material between 90% and 97% [8].

On the other hand, the recycling of plastic materials is organized according to criteria based on the characteristics of the material. Specifically, a study reveals that the integration of artificial intelligence and Blockchain, complemented by sensors, allows for more efficient classification of plastic waste by analyzing characteristics such as density, color and polymer type [9]. This innovative combination of technologies significantly improves recycling management and encourages the transition towards a sustainable circular economy. Finally, a study applies an energy recycling method to reuse plastic waste as energy sources through different procedures, evaluating its efficiency [10]. However, it states that this method involves a high cost, and the prolonged storage time compromises the quality of the material to undergo the tests.

Industrial Automation

Automation has evolved significantly in recent years, integrating advanced technologies that improve efficiency in various industrial processes and minimize human errors [1]. In relation to the application of industrial automation in recycling, it was found the integration of Arduino microcontroller for waste separation with the support of infrared sensors [11]. In turn, a prototype of automated sorting plastic waste is developed using a programmable logic controller (PLC), sensors, conveyor belts and human-machine interfaces to sort plastics according to characteristics such as weight, color and size obtaining outstanding results, with an accuracy of 98.5%, demonstrating the potential of these technologies to transform recycling processes [4]. However, the study also highlights the associated challenges, such as the significant initial investment and technical training required to operate the system. This automated approach to plastics recycling not only improves sorting efficiency, but also promotes sustainability by reducing mismanaged waste and promoting reuse [3] .

On the other hand, an automation design with the integration of a conveyor belt, Arduino microprocessor and the use of the optical sensor improved the classification by color of recycled caps; in addition, it is evident that the integration components for automation have high costs compared to the designed platform that does not exceed $ 500, demonstrating the economic viability of the proposed automation model [6]. These analyzed studies that integrate Arduino for an industrial automation model show its effectiveness for the recycling of plastics such as the classification of materials by color, as well as its feasibility in costs due to the low budget.

Arduino

Arduino has established itself as an accessible and customizable option to automate processes, especially in companies with technological and economic limitations. As in the study of for the classification of solid waste such as plastic, paper and glass, through a device that uses Arduino UNO, optical sensors and Raspberry Pi. This device also tracks the materials supported by a database, supporting small recycling companies [12]. Another case study in the plastics sector highlights the use of Arduino and DETR model as an effective and low-cost solution for industrial waste management [13]. A similar proposal is the use of Arduino with sensor integration and neural networks for the detection of plastic material types. The types of plastics identified by the device were PE, PS, PP and PET. This research was able to achieve a high level of accuracy and identification, reducing the costs of the case study recycling plant [14].

Other research in relation to machine learning models proposes the use of machine learning and Arduino, using spectra with wavelengths in the infrared range of plastics. These are very effective for the identification of black and recycled plastics, such as PP, PS and PVC [15]. For other authors, these devices are not only effective for the sorting of plastics, but also for the sorting of bio composites, in the study they show how the Arduino was implemented for the selection of banana fibers for future conversion into bottle caps. Thus, highlighting its versatility in different contexts. [16].

IoT

Analyzing the different articles about IoT, it was found that this technology is one of the foundations of Industry 4.0 used for different organizations, including recycling. For example, for waste management in public areas, sensors connected to LoRaWAN and Wi-Fi are used to achieve better waste collection in garbage cans. The use of IoT is also proposed not only for urban areas but also for educational environments, in a university in Indonesia, where the environments are improved by centralizing waste management [17]. The use of IoT is also proposed not only for urban areas but also for educational environments, in a university in Indonesia, where the environments are improved by centralizing waste management [18]. Similarly, in the plastic injection molding industry, different authors propose IoT approaches with Arduino microcontrollers for continuous monitoring of injection parameters that affect mold temperatures to preserve the lifetime of the assets [19], [20]. In turn, that reduces the amount of defective production [21]. Also, based on the IOT approach, other researchers use more powerful microcontrollers such as Raspberry Pi or PLC systems for the introduction of temperature, pressure and vibration sensors inside the injection molds to later analyze the data and propose fault detection models with machine learning tolos [22]. These IOT approaches in the maintenance area can reduce costs by 63.43%. Likewise, it is also used for real-time waste classification and management, this being complemented with deep learning and computation, to improve accuracy in waste categorization [23].

Finally, in the industrial sector, the IOT approach was used in solving supply chain problems through blockchain technologies and fog computing, has made it to be considered as a productivity revolution [24]. It is also used in smart factories where it excels in production monitoring or inventory management applications. However, there are also challenges such as implementation costs, cybersecurity, as well as the need for a reliable infrastructure [25].

III. Contribution

The proposal aims to optimize the color identification time of plastic materials and significantly reduce human failures in the sorting process, proposing an automated system based on an Arduino microprocessor, equipped with color and proximity sensors that improve the accuracy and speed in the classification of materials. The project includes the connection of these sensors to the central system, with the integration of IoT communication modules that enable real-time control and monitoring of the process. This facilitates the automatic recording of the quantity of materials processed and their classification, ensuring accurate traceability and minimizing the risk of manual errors.

To strengthen automation, key process variables are identified and analyzed, such as material color, quantity control, sorting organization and material weight (Table 1). Based on this, the components required for the integration of the automation model are proposed.

TABLE I
PROCESS VARIABLES

Variables	Function
Material color	Properly identify the color for your selection.
Quantity Control	It allows for precise control of inventory and production, ensuring delivery goals are met and avoiding losses.
Organization of separation	There must be an organization to group the identified colors.
Material Weight	It is a critical measure that ensures uniformity, quality and efficiency in the production of caps, ensuring that they meet technical and cost specifications.

Likewise, once the essential variables have been identified, the integration of the components that will allow real-time control of the sorting process and of the separation organization is proposed.

TABLE II
PROCESS VARIABLES

Components	N°	Variable	Function
Color sensor	1	Material color	Detect and differentiate the colors of the caps to ensure that they meet quality specifications.
Infrared Sensor	3	Quantity Control	Accurately count the number of caps that pass through a specific point to keep track of inventory and production.
Servo motor	2	Organization of separation	Move and position separation mechanisms to classify and organize lids according to predefined criteria, such as color or type of material.
Servo Controller Module	1	Organization of separation	Module in charge of powering the servos and communicating directly with the Arduino board to mobilize them.

To implement the automation model in the material color sorting process, an Arduino microprocessor will be used in conjunction with the Arduino IoT Cloud platform. This solution will allow to efficiently program and integrate all the necessary components to ensure optimal operation of the automated system. The platform will provide a centralized environment for real-time management and monitoring, ensuring the interoperability of sensors, actuators and other connected devices.

TABLE III
SOFTWARE COMPONENTS

Arduino UNO R4 WIFI	The Arduino acts as the "brain" of the project, managing communication between sensors, actuators, and other components through programming. With its built-in WiFi module, it connects to the internet and supports the Arduino IoT Cloud platform, enabling real-time monitoring, remote control, and data analysis.
Arduino IOT Cloud	Arduino IoT Cloud is a cloud-based platform that allows you to connect, manage, and control Arduino devices remotely. Using sensors, actuators, and Arduino boards, users can collect and analyze data in real-time, automate processes, and control devices from anywhere via the internet. In addition, it facilitates the creation of IoT applications by easily integrating devices through its intuitive interface and API.

The proposal describes the analytical architecture of the automated system, which integrates sensors and servomotors connected to an Arduino microcontroller. The programming and configuration of the system is done through the Arduino IDE software, while its operation is monitored through a dashboard accessible from mobile devices. This system is designed to detect and classify materials according to their color, manage the movement of the mechanical parts involved in the process and report in real time the quantities processed, thus optimizing the efficiency and traceability of the process.

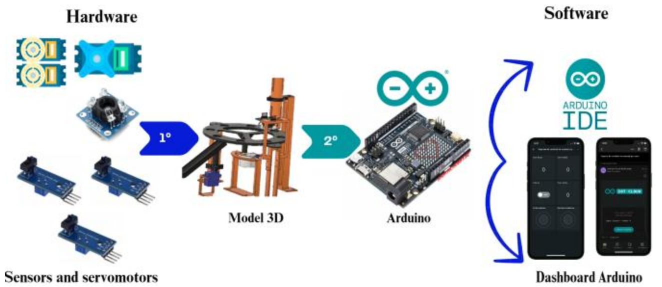

Fig. 1. Analytical infrastructure of the prototype

In terms of hardware components, the system has dedicated sensors and servomotors. A TCS3200 color sensor is used to identify the color of materials and a TCRT5000 infrared sensor is used to detect the proximity of objects at specific positions. The SG5010 and SG90 servo motors enable the controlled and precise movement of mechanical parts in the system. In addition, the PCA9685 servo controller module facilitates the management of several servos at once, contributing to more efficient and coordinated operation.

The system also includes elements for easy connection and power supply. The Arduino UNO R4 WIFI is used as the brain of the system, receiving and processing the data coming from the sensors. For the connections, jumper cables of different types (male-male, female-male and female-female) and a breadboard are used, allowing the circuit to be configured flexibly and without soldering. The power supply of the system is provided by a 5V female jack and a 5V and 3A charger, which provide the necessary power for continuous and stable operation of the hardware.

The process flow starts with data acquisition. Sensors capture relevant information from the environment, such as the color of materials and the proximity of objects and send this data to a selection stage. Next, the Arduino UNO R4 WIFI receives this information and processes it according to program instructions, storing the data to make decisions and control the servos.

Finally, the system is monitored and controlled through a dashboard in the Arduino IDE application, which allows observing in real time the status of the system. In this interface, the user can see the amount of material sorted by color, start the system through a start button, reset the counters with a reset button and send reports of the quantities processed. This dashboard facilitates the management and supervision of the system, offering intuitive control and the possibility of obtaining detailed reports for process analysis.

Overall, the system allows the collection, processing and visualization of data, providing an automated and efficient solution for the classification and control of materials according to their color.

IV. Validation

The proposal is validated by creating a prototype of the automation system, simulating the complete material sorting process. As a key performance indicator (KPI), the average time per unit in the material sorting process is measured. This allows to evaluate the efficiency of the system and its ability to optimize the operation compared to current methods. The prototype will focus on determining whether the automation system is feasible and meets the stated objectives.

The operation of the system depends on the integration of various components that need specific connections to build and operate the model effectively. These connections must ensure communication and synchronization between the various elements of the system, allowing a continuous and accurate data flow. In addition, it is crucial that the configuration of the connections be robust and adaptable to support testing and adjustments during prototype development and validation. The components to be used for this proposal are the following:

TABLE IV
Components of the Color Classification Prototype

Component	Model
Arduino	Arduino UNO R4 WIFI
Jumper cables	Male-male, female-male, and female-female
Breadboard	Breadboard
Color sensor	TCS3200
Infrared sensor	TCRT5000
Servo	SG5010
Servo	SG90
Servo Controller Module	PCA9685
DC Jack Adapter	5V Supply
Loader	Power supply 5V 3A

The parts designed for the system are manufactured by 3D printing, using PLA filament as the base material. This method allows to obtain components with high precision and customization, ensuring both functionality and sustainability, thanks to the ecological properties of PLA. The printed components are assembled by joining. First, the columns and supports for the servomotors are assembled, ensuring a stable structure.

Fig. 2. 3D modeled prototype

Subsequently, the electrical connections are made, integrating the servomotors and sensors with the driver and the Arduino microcontroller. These connections are established using jumper wires connected to a breadboard, which facilitates the assembly and organization of the circuit for functional testing.

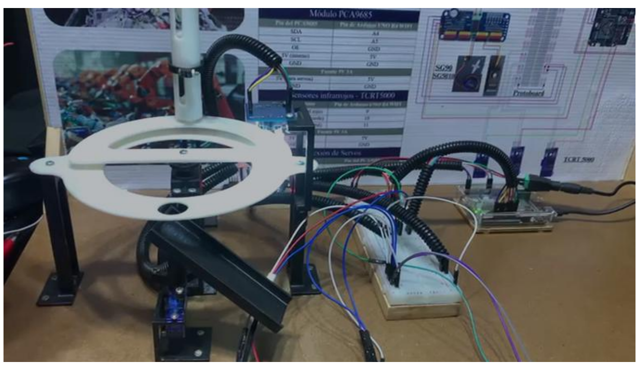

Fig. 3. Final prototype of the model

Components connections

The connections required for system integration are detailed, including the linking of the servomotors to the controller module and their connection to the breadboard and the Arduino microcontroller. This procedure ensures that all elements work in a coordinated and efficient manner. The accuracy and stability of the connections are critical to ensure optimal performance, allowing smooth communication between the hardware and software.

TABLE V
INTERRELATION OF CONNECTIONS

Pin of TCS3200	**Pin of Arduino UNO R4 WIFI**
VDC	5V
GND	GND
S0	4
S1	5
S2	6
S3	7
OUT	8

Pin of PCA9685	**Pin of Arduino UNO R4 WIFI**
SDA	A4
SCL	A5
HEY	GND
5V (internal)	5V
GND	GND
Power supply 5V 3A	
5V (for servos)	5V
GND	GND

Pin of TCRT5000	**Pin of Arduino UNO R4 WIFI**
D0 (1st sensor for red)	9
D0 (1st sensor for green)	10
D0 (1st sensor for blue)	11
Power supply 5V 3A	
5V	5V
GND	GND
Servo	**Pin of PCA9685**
SG90	8
SG5010	11

Based on the connection tables of all the components, a circuit connection diagram is prepared, clearly detailing the pin connections and the interconnection of all the elements. This diagram provides a complete and accurate visual representation of the system, ensuring that connections are made correctly and facilitating the identification of possible errors or improvements in the configuration. In addition, the diagram helps to understand the signal flow and power distribution, ensuring an efficient and orderly integration of the components in the prototype.

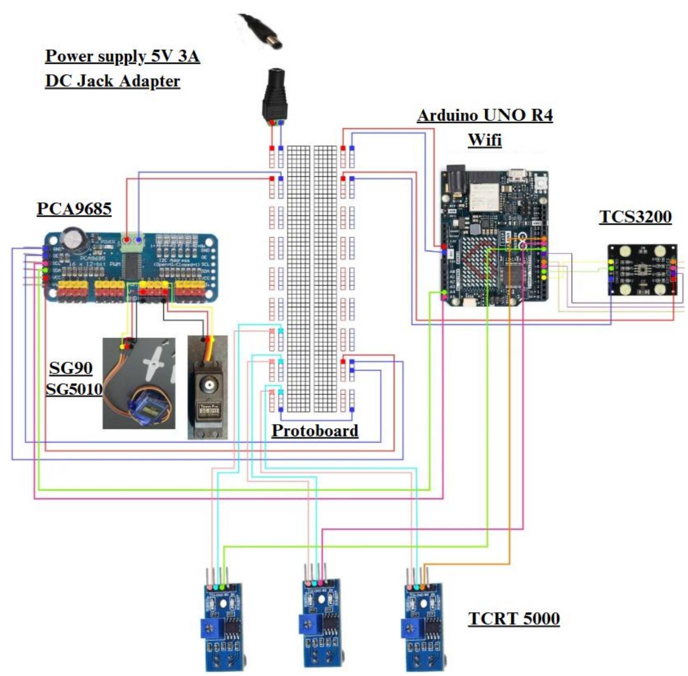

Fig. 4. Connection diagram

With all connections made and parts assembled, the prototype is ready for presentation. The programming of the Arduino Iot Cloud has been implemented so that it manages the coordinated operation of sensors, actuators and other components. It started with the creation of the dashboard variables. For this, the start-end button, counters for each color to display the quantities, the button to report the quantities to the assigned user and the button to reset the counters are considered. The programming code in Arduino Cloud creates the library "thingproperties.h" in which the code for the operation of the project will be stored.

```
// Code generated by Arduino IoT Cloud, DO NOT EDIT.

#include <ArduinoIoTCloud.h>
#include <Arduino_ConnectionHandler.h>

const char SSID[]     = SECRET_SSID;    // Network SSID (name)
const char PASS[]     = SECRET_OPTIONAL_PASS;    // Network password
(use for WPA, or use as key for WEP)

void onMensajeChange();
void onBotonReiniciarChange();
void onBotonReporteChange();
void onSwitchEstadoChange();

String mensaje;
int contador_azul;
int contador_rojo;
int contador_verde;
bool boton_reiniciar;
bool boton_reporte;
bool switchEstado;

void initProperties() {

  ArduinoCloud.addProperty (mensaje, READWRITE, ON_CHANGE,
onMensajeChange);
  ArduinoCloud.addProperty (contador_azul, READ, ON_CHANGE,
NULL);
  ArduinoCloud.addProperty (contador_rojo, READ, ON_CHANGE,
NULL);
  ArduinoCloud.addProperty (contador_verde, READ, ON_CHANGE,
NULL);
  ArduinoCloud.addProperty (boton_reiniciar, READWRITE, ON_CHANGE,
onBotonReiniciarChange);
  ArduinoCloud.addProperty(boton_reporte, READWRITE, ON_CHANGE,
onBotonReporteChange);
  ArduinoCloud.addProperty(switchEstado, READWRITE, ON_CHANGE,
onSwitchEstadoChange);

WiFiConnectionHandler ArduinoIoTPreferredConnection(SSID, PASS); }
```

Proyecto

```
#include <Adafruit_PWMServoDriver.h>
#include <Adafruit_BusIO_Register.h>
#include <Adafruit_I2CDevice.h>
#include <Adafruit_I2CRegister.h>
#include <Adafruit_SPIDevice.h>
#include <Wire.h>
#include "thingProperties.h"

// Code

#define S0 4
#define S1 5
#define S2 6
#define S3 7
#define salidaTCS 8

int ss_infrarojo = 9;
int senalsensorinfrarojo = 0;
int ss_infraverde = 10;
int senalsensorinfraverde = 0;
int ss_infrazul = 11;
int senalsensorinfrazul = 0;
int salva = 0;
Adafruit_PWMServoDriver servos = Adafruit_PWMServoDriver(0x40);
#define ServoMin 100
#define ServoMax 500

void setup() {

  Serial.begin(9600);
  // This delay gives the chance to wait for a Serial Monitor without blocking if
none is found
  delay(1500);

  // Defined in thingProperties.h
  initProperties();

  // Connect to Arduino IoT Cloud
  ArduinoCloud.begin(ArduinoIoTPreferredConnection);

  setDebugMessageLevel(2);
  ArduinoCloud.printDebugInfo();


  pinMode(S0, OUTPUT);
  pinMode(S1, OUTPUT);
  pinMode(S2, OUTPUT);
  pinMode(S3, OUTPUT);
  pinMode(salidaTCS, INPUT);

  pinMode(ss_infrarojo, INPUT);
  pinMode(ss_infraverde, INPUT);
  pinMode(ss_infrazul, INPUT);

  digitalWrite(S0,HIGH);
  digitalWrite(S1,LOW);

  servos.begin();
  servos.setPWMFreq(50);
  switchEstado = 1; }

void loop()
{ ArduinoCloud.update();

  // Your code here
  mensaje = "";
  if (switchEstado == 1)
   {
  setservo(11, 180);
  delay(2000);
  setservo(11, 90);
  delay(500);
  digitalWrite(S2,LOW);
  digitalWrite(S3,LOW);
  int rojo = pulseIn(salidaTCS, LOW);
  delay(500);

  digitalWrite(S2,HIGH);
  digitalWrite(S3,HIGH);
  int verde = pulseIn(salidaTCS, LOW);
  delay(500);
```

```
digitalWrite(S2,LOW);
digitalWrite(S3,HIGH);
int azul = pulseIn(salidaTCS, LOW);
delay(500);

Serial.print("R:");
Serial.print(rojo);

Serial.print("\t");

Serial.print("V:");
Serial.print(verde);

Serial.print("\t");

Serial.print("A:");
Serial.println(azul);

if (rojo <= 114 && verde <= 128 && azul <=121)
{ Serial.println("ROJO DETECTADO");

  setservo(8, 145);
  delay(2000);
  setservo(11, 0);
  salva = 0;
  delay(750);

  do
  { senalsensorinfrarojo = digitalRead(ss_infrarojo);

      if (senalsensorinfrarojo == LOW)
      { salva = 1;
      }
  } while(salva != 1);
    if (salva == 1)
  {contador_rojo=contador_rojo+1;
    salva = 0;}}
else if (rojo <= 130 && verde <= 116 && azul <= 112)

{ Serial.println("VERDE DETECTADO");
  setservo(8, 60);
  delay(2000);
  setservo(11, 0);
  salva = 0;
  delay(750);

  do
  { senalsensorinfraverde = digitalRead(ss_infraverde);
    // Serial.println("esperando señal para sensor verde");
      if (senalsensorinfraverde == LOW)
      {
        salva = 1; }
    // Serial.println(salva);
  } while(salva != 1);

  if (salva == 1)
  { contador_verde=contador_verde+1;
    salva = 0;} }
// else if (rojo <=130 && verde <= 127 && azul <= 119)

else if (rojo <= 136 && verde <= 129 && azul <= 120)

{ Serial.println("AZUL DETECTADO");
  setservo(8, 100);
  delay(2000);
  setservo(11, 0);
  salva = 0;
  delay(750);

  do
  { senalsensorinfrazul = digitalRead(ss_infrazul);
    // Serial.println
      if (senalsensorinfrazul == LOW)
      { salva = 1;
      }
    // Serial.println(salva);
  } while(salva != 1);

  if (salva == 1)
  {
    contador_azul=contador_azul+1;
    salva = 0;}}}
 else
 { Serial.println("Sistema apagado");
   delay(5000);}}

void setservo(uint8_t n_servo, int angulo)
{
 int duty=map(angulo,0,180,ServoMin,ServoMax);
 servos.setPWM(n_servo,0,duty);}

void onSwitchEstadoChange()
{

 if (switchEstado == 0)
  {setservo(8,99);
   setservo(11,90); }}

void onBotonReporteChange()
{
 if (boton_reporte == 1)
 {
 mensaje = "Rojos = " + String(contador_rojo) + "\n";
 mensaje += "Azules = " + String(contador_azul) + "\n";
 mensaje += "Verdes = " + String(contador_verde);}}

void onBotonReiniciarChange()
{ contador_azul = 0;
 contador_verde = 0;
 contador_rojo = 0; }
void onMensajeChange()  {
  //vacio}
```

The prototype incorporates an Arduino board equipped with a WiFi module, which allows it to connect to the Arduino IoT Cloud platform for remote monitoring and control through a customized dashboard. This dashboard offers users an intuitive interface where counters that record the amount of material classified by color are displayed. It also includes a virtual switch to start the prototype remotely. As a complement, it integrates a button to generate and send automated reports to previously configured e-mails, facilitating the management and analysis of data in real time.

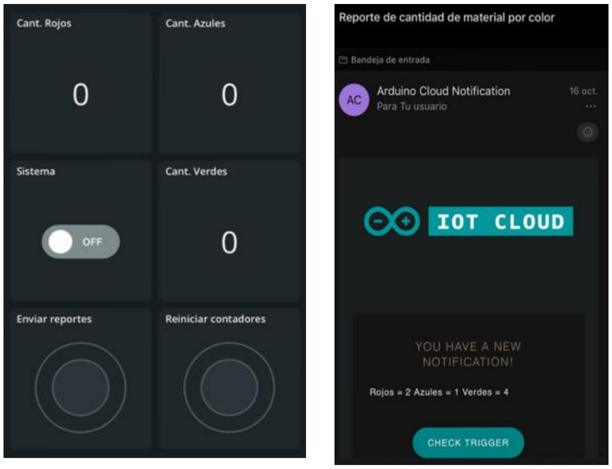

Fig. 5. Dashboard Arduino Cloud

The final prototype (Fig. 6) fully assembled, with all its connections established and ready for operation highlights the connection paths between the Arduino microcontroller and the different modules, as well as the integration of the programming developed in the Arduino IDE environment. This programming allows for efficient coordination of sensors, servo motors and communication with the Arduino IoT Cloud platform. The system structure and code work together to ensure seamless interaction between the hardware and the cloud, optimizing the process of identifying and sorting materials. In addition, centralized control and an intuitive user experience is provided through the dashboard. Everything explained about the sorting process with the application of the automation model is visible in Fig. 7.

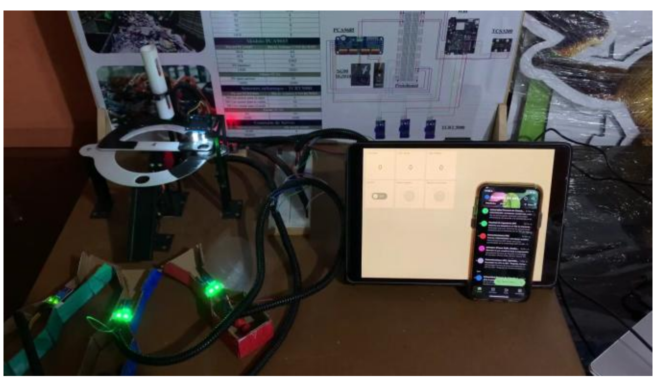

Fig. 6. Final prototype - color classification system

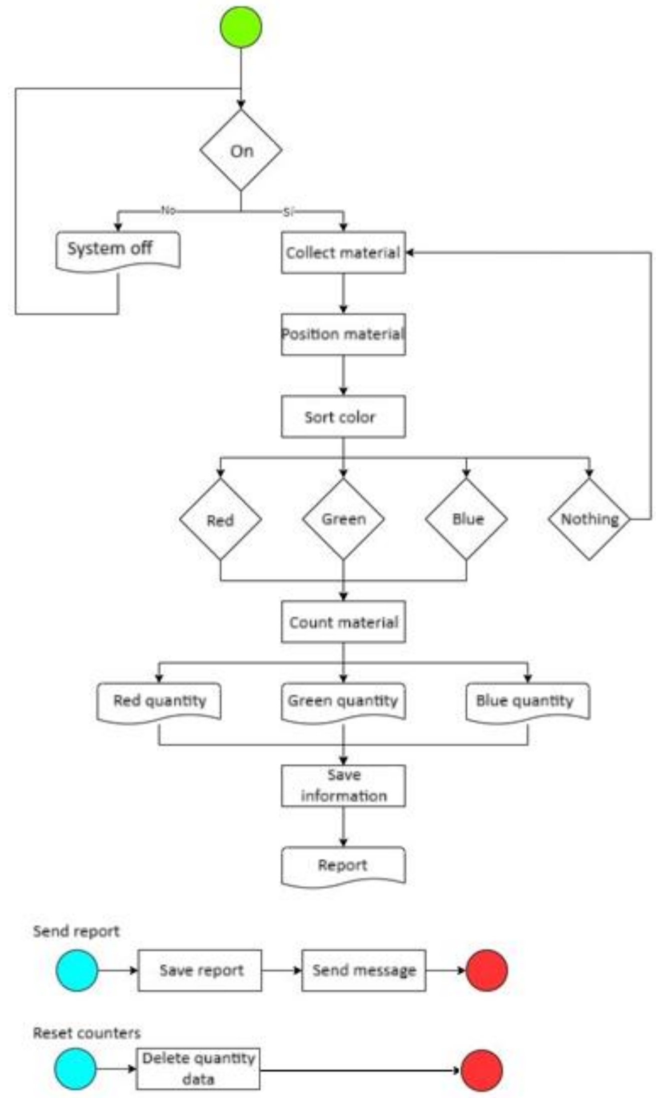

Fig. 7. Classification process diagram

The results obtained in the color sorting process show a notable improvement in efficiency when comparing the manual processing time with the automated one. Manually, the time required to sort each material is 2.75 seconds, whereas, by implementing the automated system, this time is reduced to 1.95 seconds per material with an accuracy of 95%. This time reduction reflects a significant optimization in the speed and accuracy of the sorting process, which implies a considerable improvement in productivity and the reduction of possible human errors in color selection.

V. Discussion

The Arduino-based automated color sorting system for plastic materials is suggested as a cost-effective and affordable option to improve this process. The proposed innovation consists of an automated plastic material sorting system based on an Arduino microcontroller, equipped with color and proximity sensors, and integrated with IoT through the Arduino IoT Cloud platform. This development optimizes the identification and selection of materials by color, achieving an accuracy of 95% and reducing the sorting time per unit from 2.75 to 1.95 seconds, which represents a 29% improvement in terms of operational efficiency. Furthermore, the implementation of this automated system not only improves process efficiency, but also opens the door to future optimizations. The use of Arduino IoT Cloud allows the integration of additional functions such as real-time monitoring of operations, collection of historical data for performance analysis, and the ability to adjust system parameters remotely. In addition, the modular design of the prototype allows for easy adaptation to new needs or the addition of more sensors and actuators, which facilitates the scalability of the system.

In contrast to other technologies, such as hyperspectral imaging systems or artificial intelligence-based classification, the Arduino-based prototype uses color and proximity sensors to achieve simple but effective categorization that is affordable for entities with restricted budgets. [6]. This type of technology generates a significant reduction in the waste of non-conforming products by avoiding misclassification errors and, therefore, production failures in injection molding companies [26]. The effectiveness of this type of prototype has been evidenced by a 30% increase in production, leading to a 15% reduction in the cost of materials. [27]. A case study using sensors, in the industrial field, has been the development of a pneumatic robot capable of detecting up to 62 different colors with 100% accuracy, achieving a fast and accurate classification of any product. [28]. While other techniques, such as the implementation of Blockchain and IoT, can provide transparency and traceability to the collection and sales process, their implementation demands a more robust infrastructure and is more difficult to incorporate in smaller organizations [28]. The proposal is a more affordable option and offers a considerable advancement to the system without requiring sophisticated infrastructure or specialized technical skills as other approaches. This is evidenced by comparing different technologies used for waste classification. For example, one study uses Faster R-CNN algorithms that excel in detection and categorization in controlled environments, achieving an accuracy of 98.106%. [29]. In addition, convolutional neural networks (CNN) achieve a fast detection and classification of any object according to different characters with an accuracy of 95%. [27]. Another study uses deep learning applying the RWC-Net model to classify different types of waste, obtaining an overall accuracy of 95.01%. [30].

In relation to models using Arduino, a study incorporates IoT, Machine Learning, Deep Learning and AI for classification reaching an accuracy of 93.3%. [31]. Similarly, another author develops a low-cost model of material type detection with an Arduino UNO microcontroller with 94% accuracy [26]. The development of the prototype achieved a yield of 95% under normal conditions, which is evidence of outstanding performance. However, the system has some limitations, such as difficulties in classifying more complex colors and transparent materials, which could require improvements in the sensors used. In addition, the dependence on connectivity to operate with Arduino IoT Cloud could be a challenge in environments with limited network infrastructure, and the need for periodic calibrations could slightly increase maintenance times. In relation to models using Arduino, a study incorporates IoT, Machine Learning, Deep Learning, and AI for classification reaching an accuracy of 93.3%. [31]. Similarly, another author develops a low-cost model of material type detection with an Arduino UNO microcontroller with 94% accuracy. The development of the prototype achieved a yield of 95% under normal conditions, which is evidence of outstanding performance. However, the system has some limitations, such as difficulties in classifying more complex colors and transparent materials, which could require improvements in the sensors used. In addition, the reliance on connectivity to operate with Arduino IoT Cloud could be a challenge in environments with limited network infrastructure, and the need for periodic calibrations could slightly increase maintenance times.

Despite these limitations, the potential impact of this innovation is significant, as it opens new opportunities to democratize access to automation technologies in plastics recycling. Its implementation can foster sustainability and strengthen the circular economy while driving future research to integrate new parameters and extend its application to other industrial sectors. Ultimately, the automated system increases operational efficiency and sets a precedent for the development of affordable and effective technological solutions in resource-constrained environments.

VI. CONCLUSION

The implementation of the color sorting prototype based on low-cost technologies, such as the Arduino UNO R4 microcontroller with WiFi connectivity, TCS3200 optical sensor, infrared sensors and servomotors, constitutes a technical and efficient solution to optimize sorting processes in plastic recycling companies. This automated system, designed under a modular approach, achieved a 29% reduction in processing time per unit, going from 2.75 seconds of average sorting per unit to 1.95 seconds with an accuracy of 95% with an automated system, representing a significant improvement in productivity and evidence of the accuracy of the sorting process. Integration with the Arduino IoT Cloud platform enables real-time monitoring and control, historical data collection for analysis and operational adjustments, and automatic report generation, ensuring complete traceability of the process and minimizing the chances of human error. The system architecture, which includes sensors, actuators and control modules, was designed to ensure robust and scalable operation, facilitating its implementation in resource-constrained scenarios.

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