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A Low-Cost Computer Vision Approach to Robotic Weight Sorting in Pharmaceutical Manufacturing

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Abstract

Precise dosage delivery is an obligatory requirement in pharmaceutical manufacturing. Minor deviation in the weight of a tablet can impede treatment effectiveness and even endanger a patient's life. This study showcases a potential alternative to the conventional high-cost checkweighers to support small manufacturers. The proposed system integrates a 3-D printed robotic arm that has 6 degrees of freedom (6-DOF) with a commercial digital weighing scale and an Optical Character Recognition (OCR) system. The robotic arm is actuated by servo motors that are controlled by Arduino Uno and coordinated using Python scripts that utilize PaddleOCR for real time weight extraction. The system reads the displayed load from the digital screen of scale, compares it with the previously set tolerance values and takes sorting decisions automatically - either allowing the product to move to the next stage or rejecting it. Multiple trials indicate the processing time of each item is on average 8 seconds with precision up to 1 mg. This current prototype system demonstrates the possibility of replacing expensive milligram-level sensors with a vision-based solution. The outcome of this investigation indicates the potential of this system as a low-cost, reliable automation system that would be applicable in a controlled manufacturing environment that also highlights the pathways for improvements to enhance speed and accuracy.

Keywords
Pharmaceutical Manufacturing, Vision-based Inspection, Optical Character Recognition (OCR), Low-cost Automation, Arduino.

1. Introduction
Strict quality control measures are imposed on the pharmaceutical industry in order to maintain the safety, effectiveness, and uniformity of drug products. The weight of tablets and capsules is one of the dominant pillars to ensure accurate dosage (Minichmayr et al., 2024; Fritsch, 2021). Change of mass occurred due to process variability, fluctuation in material or medicine breakage during the production may result in an inaccurate amount of active pharmaceutical ingredient (API) than prescribed. Both offer dose, and underdose can adversely affect human health (Piercefield et al., 2010; Tariq et al., 2024; Mulac et al., 2020). Accurate weight sorting of drugs ensures that only the

correct amount of product is accepted to move forward to packaging and distribution. Checkweighers that are usually used in the commercial industry depend on high-precision electromagnetic force restoration (EMFR) sensors, which are often costly and sometimes inaccessible to small manufacturers. In addition, these machines require rigorous maintenance. In recent years, researchers have shown interest in the microcontroller-based automated weighing systems and vision-assisted inspections (Rehman et al., 2015). In this project, our aim is to address this challenge and develop a more accessible solution. It uses image processing and OCR technology to read weight values directly from a digital scale. This study demonstrates a cost-effective, reliable solution that ensures accuracy.

1.1 Objectives

- Developing an affordable vision-based system for sorting by weight within a specified tolerance (1140–1260 mg) that provides an alternative to expensive milligram-level weighing sensors in the pharmaceutical manufacturing sector.
- Integrating real-time OCR (Optical Character Recognition) with robotic actuation to allow automatic weight-based sorting using a commercial digital scale and webcam interface.
- Designing a software-hardware architecture combining Python and Arduino that can be tailored to other quality management processes in small-scale manufacturing environments.

2. Literature Review

High precision load cells and conveyor integrated checkweighers have long been considered the foundation of accuracy in automated verification of weight in pharmaceutical manufacturing processes to aid in Good Manufacturing Practice (GMP) compliance (Principles of Checkweighing, 1997). Even though such commercial systems provide a high accuracy, the need of high capital and maintenance costs only limits them to large scale productions and research laboratories leading to an exploration of low-cost alternatives. In pharmaceutical practice, the acceptable variation of weight for medicines weighing more than 250 mg is ±5% (Ghimire et al., 2020). For our experiments, the selected medicine weighed approximately 1200 mg. Therefore, the acceptable tolerance band was 1140–1260 mg.

Islam et al. (2009) explored image processing inspection of gelatin capsules which concentrates on defects associated with the visual aspects rather than the weight. Similarly, Holtkötter et al. (2022) created the self-monitoring pill detection tools, which prove the feasibility of camera-based examination in medical cases. However, such systems usually concentrate on presence, absence or color checks instead of accurate weight checking. Other similar works in machine vision and robotics are already in the development phase where in most inspection processes camera-based inspection and vision-guided sorting can be considered viable options. Various comparable studies that have focused on the field of machine vision have proved that the appearance and geometry can successfully be decoupled to identify surface defects in tablets and capsules (Podrekar et al., 2017). Each of these primitive techniques was developed to create end to end imaging systems for the continuous production lines that enable the inspection of the shape defects, coating and color defects throughout the production process (Barimani et al., 2022).

The latest developments in the field of computer vision have offered general-purpose object detectors which can be implemented in this field. Faster R-CNN (Ren et al., 2015) and YOLO (Redmon et al., 2016) among other architectures employ a region-proposal and single-shot detection functionality that can provide accurate and near-real-time localization of small objects and digital displays on a congested scene. Moreover, open-source Optical Character Recognition (OCR) frameworks also have developed greatly. The PaddleOCR and PP-OCR families established ultra-light, angle-sensitive deep models with the ability of multilingual text recognition capability (Du et al., 2020; Du et al., 2021). The toolkits allow strong digit recognition with low-cost commodity GPUs or single-board computers, rendering text extraction computationally efficient and affordable.

Robotic sorting based on physical properties is also effectively documented on the actuation side. Weight-based sorting with 5-DOF was demonstrated by Abdullah et al. (2024) and Hariharan et al. (2022) though such systems normally needed direct connections with load cells that added signal noise and calibration complications. Sawaithul et al. (2024) applied robotic arms for object segregation, but did not reach the accuracy of milligrams of pharmaceuticals.

In order to bridge the divide between heavy vision processing and real-time control, detached system architectures are becoming increasingly popular. These types of designs use a PC to execute a vision/OCR stack and transmit deterministic commands over UART/USB to a microcontroller (e.g., Arduino) to control the servos (Bui et al., 2020). This separation makes actuation loops more reliable and reduces the latency. Although the pharmaceutical uses generally require direct digital instrument interfaces to be regulated (Barimani et al., 2022), OCR-based display readings are a convenient and required approach when the older devices are not programmatically available.
The literature shows that display-based OCR algorithms are the more effective small object detectors and repeatable Arduino-controlled manipulators, which together with the lower cost weight-sorting design, could be considered a combination of the approaches which could be effective. Nevertheless, no comprehensive end-to-end system that employs computer vision to scan commercial scale displays other than using precision load cells, and also deals with throughput, accuracy and fault-tolerance in pharmaceutical laboratory settings has been firmly investigated. The gap that is to be considered by the present project is incorporation of display reading preprocessing and OCR with robotic sorting in a cost effective prototype that is able to meet the needs of a small pharmaceutical manufacturing facility.

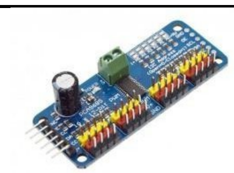
3. System Design and Architecture

3.1 Hardware Components

Required hardware components for the robot:

Table 1. Hardware Components

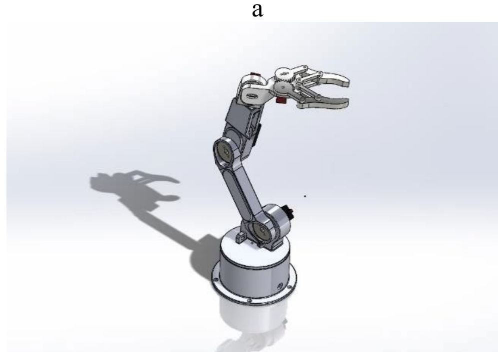
Components	Figures
Webcam Model: ROG Eye S 1080p resolution and 60 fps output	 Figure 1. ROG Webcam
Robotic arm	
i. 3D Printed Parts	 Figure 2. Printed Parts
ii. Servo Motors a. 3 x SG-90: b. 3 x MG-995	 a b Figure 3. a. SG-90 Servo Motors b. MG-995 Servo Motors
iii. Metal Servo Horn	 Figure 4. Servo Horn

iv. Jumper Wires	 Figure 5. Jumper Wires
Microcontroller Arduino Uno R3	 Figure 6. Arduino Uno
Battery Wild Scronpion Li-Po 7.4V 1100mAH battery	 Figure 7. Li-Po Battery
Voltage Regulator LM2596 with Digital Voltage Display	 Figure 8. LM2596
Servo Driver 16-channel 12-bit Servo motor Driver PCA 9685	 Figure 9. Servo Driver
Weight Machine AND GULF precision Weighing scale 1 mg to 20 gm	 Figure 10. Precision Weighing Scale

3.2 Software Components

- **SolidWorks 2020:** To design and model our 6-DOF robotic arm.

a



b

Figure 11. a. Parts of the Robotic Arm
b. Fully Assembled Arm

- **Visual Studio Code (VS Code):** A source-code editor used to write and run the Python script for image processing and OCR.

- **Arduino IDE:** Open source microcontroller editor used to move the arm on the Windows 10 operating system

3.3 Final Model

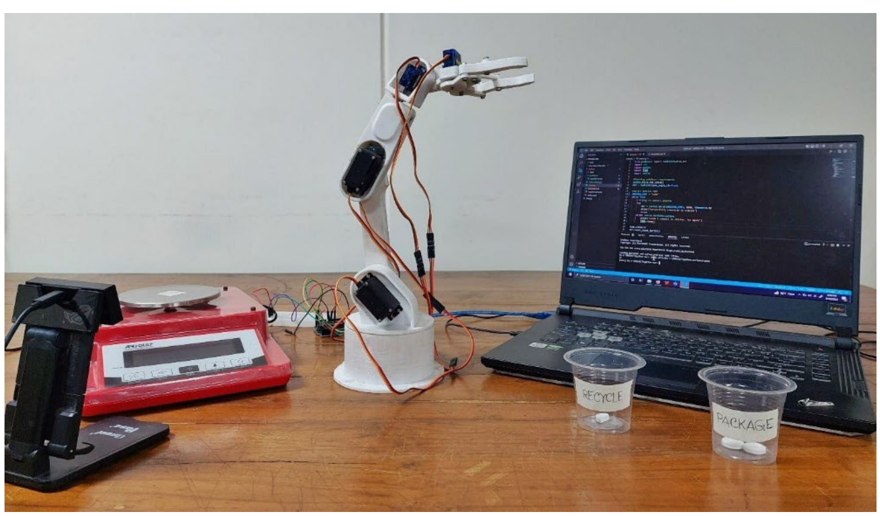


Figure 12. Picture of the final model

Figure 12. presents the fully assembled configuration of the final system, showing the placement of the weighing scale, the webcam, and the robotic arm within the working setup. It highlights how the sensing and actuation components are physically arranged to support the automated sorting workflow. This serves as the visual reference for understanding the integrated operation.

The suggested weight-sorting system is developed on the basis of a Python-Arduino hybrid control architecture that is an integration of computer vision, OCR-based measurement extraction and robotic actuation. The processing unit is a personal computer with Python script which is in charge of the image acquisition, the extraction of weights, and decision-making. The main sensing device is a commercial digital weighing scale and a webcam above the scale constantly records the image of the weight display on the scale.

When the medicine arrives at a previously fixed spot, the weight machine screen shows the numerical value and the webcam captures the image. The system identifies the seven-segment digits and transforms them into a number using an OCR model. When extracted, this value will be obtained against the pre-determined acceptance range of pharmaceutical capsules. Python sends messages via serial communication to an Arduino Uno, which acts as the embedded motion controller of the 6-DOF robotic arm. The arm includes both MG-995 and SG-90 servo motors. It uses MG-995 servo motors for the high-torque joints and SG-90 servo motors for lighter gripper and wrist movements. Depending on the received classification signal (Accept or Reject), the Arduino will run a programmed motion pattern under PWM control. These codes identify the arm and move towards the scale to grab the tablet and place it into the correct bin.

The general picture of the system integration is shown in Figure 13. illustrates how the webcam, the OCR module, the Arduino controller and the actuators communicate and respond to one another during the operation. The entire cycle starts with the placement of a tablet on the scale. The system reads the displayed weight and processes it using OCR and instantly determines whether the capsule is within the required tolerance band. The sorting is then carried out automatically by the robotic arm. After a complete cycle is made, the system reinitiates and waits for the next capsule. This design of a modular pipeline would guarantee that every subsystem such as vision, decision logic, and actuation works autonomously although it works in concert during execution, and this renders the system scalable and adaptable to prolonged pharmaceutical use.

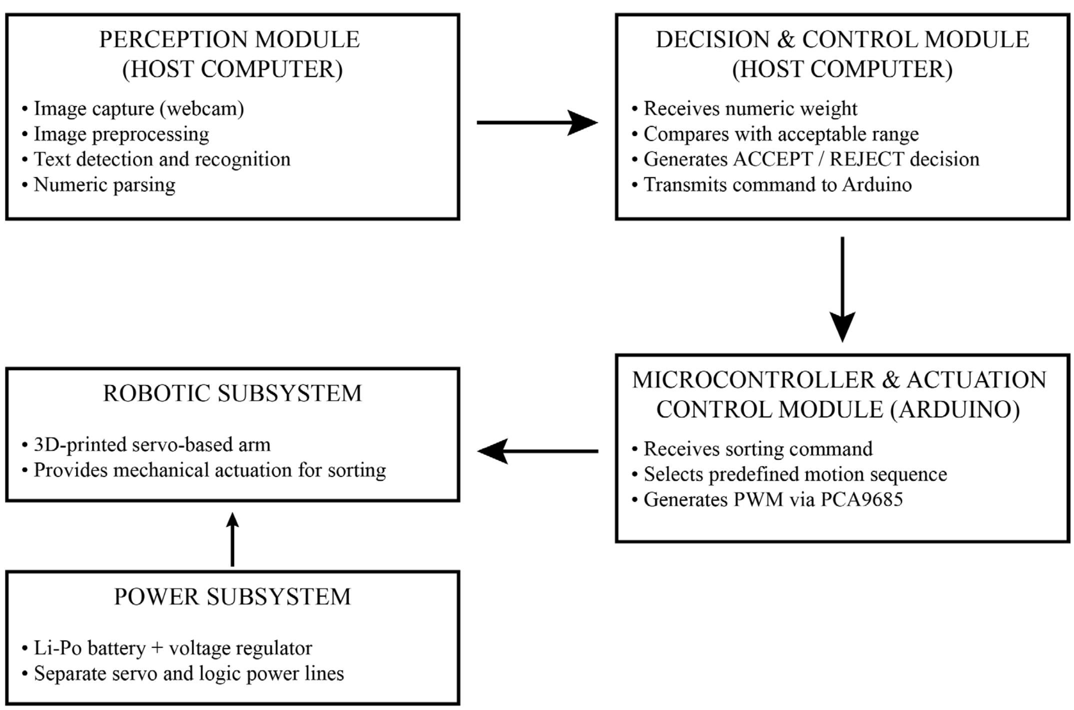


Figure 13. System Architecture

4. Methods

4.1 Python Based Algorithm

The Python program serves as the brain of the weight-sorting system. When the program starts, it initializes the OCR engine, then opens the web-camera and after that, establishes the serial connection with the Arduino microcontroller. After a short warm up, the program reads frames continuously from the camera. The frames are cropped to the previously calibrated area with the scale display in it and then converted into a fixed image format for recognition and finally processed to increase the clarity of the digits. To enable homogeneous processing of the image, the captured image is initially converted to RGB then a preprocessing stage is done so as to increase the readability of the scale numbers. This comprises grayscale conversion to make the picture easy to understand, thresholding to isolate the lit areas and noise removal to eliminate background interference. After enhancing the area of interest, the frame is passed to the OCR engine which reads the numeric weight on the scale. The continuous process of acquisition and preprocessing is used to make sure that the system is aware of the changes in lighting, scale behavior, and display clarity during the usage.

For each capture, the program selects the most likely numeric string from the OCR output, retains only the numeric characters and single decimal point, and decodes the resulting string as a floating-point number. The program will only record a value as stable when multiple successive values are within a close band of each other; as the consistent value is observed, the program will compare the value to the tolerance band that had been previously set at 1.140 g to 1.260 g. When the weight is within this band the program prepares the accept token and when it is outside the band it prepares the reject token. The token is sent over the serial connection to the microcontroller. This classification step is a real-time one, which allows the system to get the decision in a short time without stopping the visual processing chain or the camera feed.

The program then waits for the microcontroller to respond with an acknowledgment message to which it then logs to a file in a timestamped format that contains the raw OCR text, the processed weight, the decision token and the acknowledgment status. If no appropriate acknowledgement is received within the set timeout the program repeats transmission a few times before going back to the capture loop. This form of feedback mechanism ensures that vision and actuation are synchronized so that mis-sorting is not produced by delays in communications or temporary OCR mismatches. The continuous flow of image acquisition, decision-making and communication facilitated by the loop enables the program to be run consistently over the long testing periods or batch processing cycles.

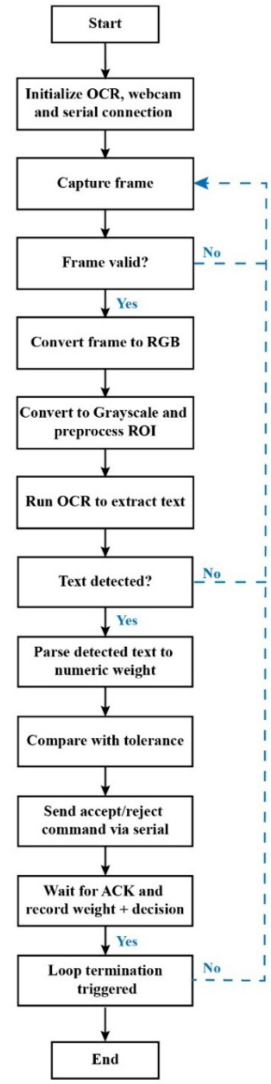


Figure 14. Flowchart for Python code

4.2 Arduino Based Algorithm

Arduino takes care of the actuation part of the system. On power-up the communication link is configured and the servo driver is initialized. The robotic arm moves to home configuration during initialization so that the arm is ready for movements on command. The controller monitors the serial stream of input for a short token which is terminated by a newline and is sent by the vision module. When an incoming token arrives it is trimmed and validated either as an accept or reject command. Any invalid incoming token is ignored and the controller resumes listening.

Whenever a valid accept or reject token is received the controller carries out the most appropriate predefined motion sequence. The sequence starts with positioning the manipulator over the scale, descending the end effector into a grasping position, actuating the gripper to pick the tablet, lifting the tablet away from the scale, moving the end effector to the selected bin position (accept or reject) based on the instruction, releasing the medicine, and returning the end effector to the standby position over the scale. Each joint motion is achieved by using the pulse commands of the servo driver at the set frequency and conservative timing to make the movement repeatable.

On completion of the sequence of motions the controller sends a short message back to the vision module over the serial link in the form of an acknowledgement message and then returns to monitoring for the next token. In case a motion is not completed or an unexpected condition takes place during the sequence the controller dispatches an error response and goes back into the listening state after bringing the arm to a safe hold posture. This cycle of communication-and-action occurs throughout the entire course of the operation and enables the controller to interact with the Python module without interruption to ensure that all the sorting commands are addressed by the reliable mechanism.

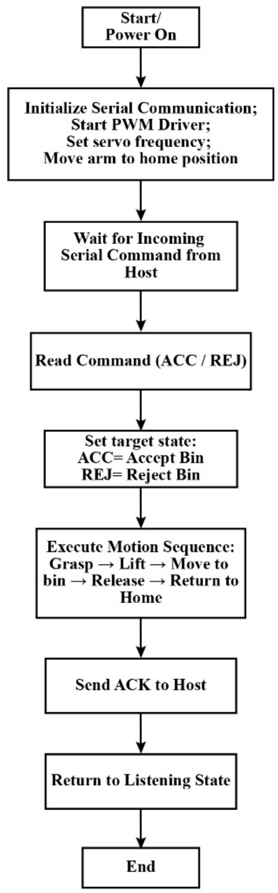


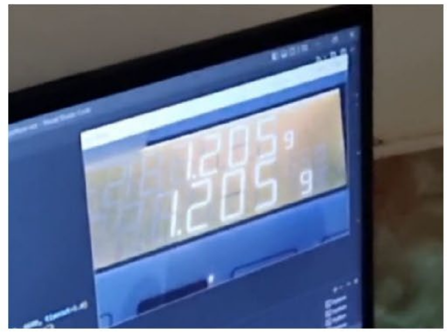
Figure 15. Flowchart for Arduino code

5. Results and Discussion

For testing, a batch of 50 pharmaceutical tablets was used. Each ones were manually placed on the weighing scale. The webcam captured an image from the scale. Then, the system extracted the weight using OCR and passed the result to the Arduino. The given acceptance range was from 1.140 g to 1.260 g. The robotic arm sorted each capsule into the appropriate category.

A medicine is placed at the marked spot on the scale. In Figure 16(a), we can see that the tablet weight falls within the tolerance limit. Figure 16(b) illustrates that the OCR module accurately detected and parsed the numerical value from the scale display.

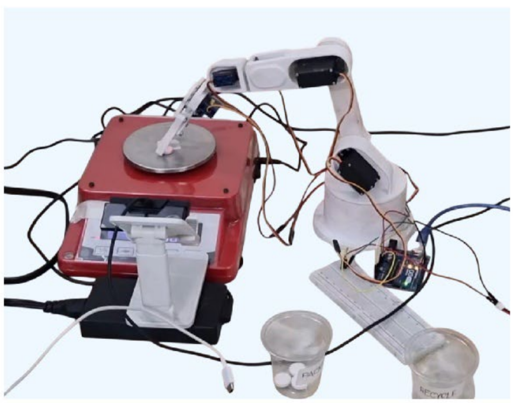
(a)



(b)

Figure 16(a). Weight display showing acceptable tolerance band
(b). OCR extraction of the displayed weight

Then, the robotic arm was commanded to pick and place it in the correct container, in this case that would be the packaging bin, as we can see that in Figures 17(a) and 17(b). On the contrary, when the weight is outside of the acceptance window, as shown in Figure 18, the system classified it as a reject and commanded the arm to place it in the recycle bin (Figure 19*/).



(a)

(b)

Figure 17(a). Robotic arm positioned to pick up
(b). Accepted capsule being placed in package bin

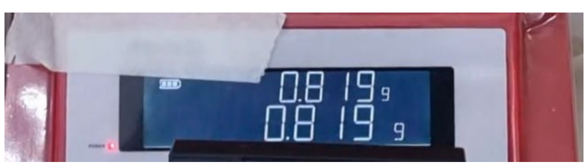


Figure 18. Scale reading outside tolerance

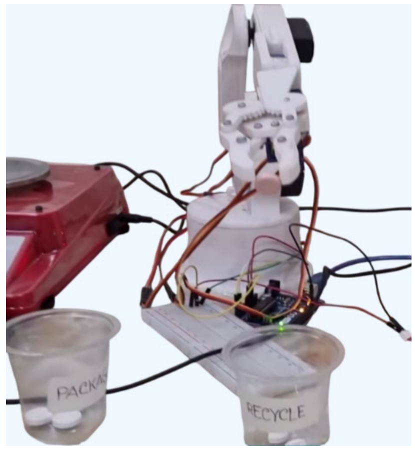


Figure 19. Arm placing rejected capsule in recycle bin

Across all the trials, the system achieved an accuracy of 86%. The average processing time per capsule was approximately 8 seconds. The system maintained stable performance across multiple runs. Even the system identified small weight variations and responded accordingly. We have also included a cost analysis of the entire experimental setup in Table 2, which demonstrates that the proposed system can be implemented using affordable, commercially available components.

These results demonstrate the feasibility and effectiveness of integrating OCR-based vision systems with low-cost hardware for real-time, automated sorting tasks in controlled environments.

Table 2. Cost Analysis

Components		**Quantity**	**Price**
Web Camera		1	$80
Robotic Arm	3-D printed parts	As needed	$21
	SG-90 servo motor	3	$3.85
	MG-995 servo motor	3	$8.97
	Li-Po Battery	1	$7.44
	Voltage Regulator	1	$2
	Servo Motor driver	1	$3
	Jumper wires & Screws	As needed	$1.88
Arduino Uno		1	$8.55
Weight Machine		1	$27
Miscellaneous		As needed	$12
Total			**$175.69**

5. Conclusion

The present paper describes a low-cost vision-based robotic sorting system capable of being utilized to automatically examine pharmaceutical medicines, based on their weight. It employs a webcam, extracts measurements through OCR, decision logic written in Python, and an Arduino-controlled robotic arm, allowing high quality end-to-end automation without having to use specialized industrial hardware. The testing results using a batch of capsules demonstrated an overall accuracy of 86%, with an average processing time of approximately 8 seconds per item. Separation of perception, decision-making and actuation was also efficient in preserving the flexibility and stability of the system across repeated trials. Moreover, the system was deployed based on low-cost, easily available components, which makes it also economically feasible as an alternative to traditional industrial checkweighing systems in small-scale environments. The results suggest that OCR-based interpretation of measurements and low-cost robotic components can be an effective and viable tool to use in automated manufacturing processes in controlled environments.

Additional improvements to the system could involve the implementation of remote monitoring and control. The disturbances to the environment might be reduced by placing the weighing unit in a vacuum or a controlled environment. To remove the manual placement and provide constant operation, the feeding mechanism of a conveyor can be added. Another enhancement is to upgrade Arduino based architecture to a Raspberry Pi or other edge processor with the ability to execute the Python OCR module on-board, eliminating the requirement to connect to an external laptop as well as enhancing the overall compactness of the system.

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