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V-Shopper: A Virtual Automatic Shopping System Based on 5 DOF Robotic Arm with Real-Time Visualization and Billing

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Abstract*— In an era where e-commerce demands are soaring, the quest for an immersive and efficient shopping experience is more relevant than ever. This paper introduces a cutting-edge virtual reality based automatic online shopping system that offers real-life shopping experience in a virtual platform via real-time product visualization and robot-based automated product collection. Central to our system is a low-cost, 5-degree-of-freedom (DOF) robotic arm mounted on a line-following robot, equipped with basic Wi-Fi connection and an online user-friendly shopping platform. Customers can browse a fully designed e-commerce website where products are listed and view a live video feed via an ESP32 camera, allowing them to virtually inspect and select products with precision. Unlike current solutions, our platform incorporates a robust closed loop feedback system utilizing force-measuring sensors to ensure secure and precise material gripping, proper weight lifting, and handling of products, addressing issues related to varying weights, shapes, and sizes. The system's open-source software, requiring no paid licenses, enhances its accessibility and cost-effectiveness. Rigorous testing across diverse environments and product types demonstrated the system's ability to deliver accurate, reliable performance, even under challenging conditions. By bridging the gap between digital and physical shopping experiences, our solution not only streamlines the process but also elevates it with superior virtual reality integration, add secured communication, and seamless billing satisfaction, low cost operation, setting a new benchmark in the realm of online retail.

Keywords—online shopping, virtual shoppers, automation, closed-loop feedback, real-time video streaming, open source software, robotic arm.

I. Introduction

After Covid-19 pandemic, use of computing technology with smart applications has gained great attention. The global pandemic of Covid-19 makes a paradigm shift in people's tendency towards online shopping [1]. Online shopping has attracted the citizens to be a solution for physical shopping hassles worldwide. Customers often rely on their five senses (smell, sight, touch, hearing, and taste) to feel confident in their purchase decisions. This paper aims to bridge the gap between the online shopping experience and traditional grocery shopping, combining the advantages of both to enhance the overall shopping experience.

A number of online shopping systems have been established to ease the customer activities. In [2], a line following robot based automatic trolley system is introduced where the robot, as per customers choosing the product, reaches the desired product and picks it with a robotic arm attached to it. The product is returned to the customer after collection. However, the customer needs to go to the mall themselves. Different types of shopping trolleys are introduced in [3] and [4] that utilize RFID readers and reads the RFID tag placed on the product and performs measurement of weight and billing. Not only the customer needs to go to the mall but also have to walk through the aisle of the shop and pick the product themselves. In [5], a robotic arm was built to pick fruits of different sizes and shapes precisely without deformation. However, the arm is manually controlled. A similar logistic handling robot is designed in [6] that can pick products with its robotic arm with great accuracy using image processing. A robotic arm with five degrees of freedom is designed in [7] which is Internet of Technology (IoT) enabled. Both robots can very well be combined with an online shopping system.

It is clearly visible in the aforementioned work [2] - [7] that neither work has integrated automatic product picking along with real-time visualization from customers' end in an online shopping system. The main impediment to the online shopping platforms like Amazon or Instacart is that only the pre-captured images of the products are available rather than the actual current scenario. So a dubiousness persists in the customers' mind about the certainty of the quality of the product, particularly for perishable and size-sensitive products. Although Amazon Dash Cart and Instacart's Caper AI automate billing and navigation but still requires presence and manual picking by the customer rather than online shopping. Moreover, the robotic arms available are not configured to adapt to the contradictory size and shape of products, not to mention the complexity revolving around the system.

The proposed smart shopping system addresses these critical gaps with an affordable, open-source solution by suggesting a vision driven online shopping system. With the presented prototype, the customer can place their order from an e-commerce site where the products available in the physical store are displayed. The order is received by the cart placed in the store, and it moves through the shop following lines along the aisles. As it reaches a particular product that was ordered, real-time visualization is available for the customer via live video feed in the shopping site. If the customer is happy with the quality of the product, then the robot automatically picks it up with the help of a mechanical arm with five degrees of freedom (DOF) and secure online billing and moves on to the next product. The use of force sensors in the robotic arm ensures proper gripping of products of different size and shape, minimizing the risk of damage. The use of open-source software and affordable hardware components appends scalability for a wide range of enterprises with varying size. A fully automated retail system is no longer a dream with the implementation of this prototype. This approach eliminates the need for customers to visit stores physically while magnifying their ability to inspect and approve products before purchase, thereby bridging the gap between online and physical shopping.

II. METHODOLOGY

The proposed system includes a database containing all items in the store, along with their quantities and unit prices. This database is accessible to store employees, allowing them to add new items, remove old items, and update item quantities as they restock.

A. User Interface

First, a website is designed for the product available to the shopping mart. It integrates all other features and serves as the starting point for the entire system. Given its importance, the website must be highly user-friendly to ensure that customers can easily navigate and utilize the features, thereby enhancing their shopping efficiency [8]. The website provides the customer with a list of products along with their images in the homepage. The customer can choose their favorite groceries with desired quantity. They can then increase the quantity of the products and also delete any item selected prior. They are then redirected to the confirmation page where they can send the order to the shop and see the live stream of the robot and then can order or delete the product from the cart. The website hosting and site to robot communication is done using the ESP32 (ESP WROOM 32) Wi-Fi & Bluetooth Dual-Core MCU Module. The customer will be able to access the site of the shopping cart using any LAN connected mobile or computer devices [8].

B. Line Follower Robot

The line follower robot can detect and move according to the lines. Generally, the path is predefined based on the products placed in the racks throughout the shopping mall.The robot's lane can be either observable, such as a black line on floor, or discreet, like a magnetic field. The robot uses infrared (IR) sensors installed underneath to detect the line [9]. The sensor reading is then transmitted to the processor via communication protocol. The processor interprets the data and issues appropriate commands to the driver, enabling the line follower robot to follow the designated path [10]. The total system can be categorized into following sections.

1) Sensor section: It contains IR diodes, a potentiometer, comparators (Op-Amps), and LEDs. Potentiometer sets the base voltage at one side of the comparator, while the IR sensors detect the line and cause a voltage variation at the opposite side. Based on the difference of the voltages the comparator produces a binary signal at the output. In this line follower circuit, two comparators serve as the sensors. The LM358, which contains two low-noise Op-Amps, is used as the comparator.

2) Control section: Arduino Pro Mini is employed to control the entire process. The outputs of the comparators are connected to digital pins 2 and 3 of the Arduino. The Arduino sends command to the controller which operates the line follower.

3) Driver section: This segment contains two motor drivers and four DC motors. Motor drivers are essential as Arduino alone cannot supply sufficient voltage and current to operate the motors. The motor driver circuit is integrated to ensure adequate power delivery to the motors when ordered by the Arduino. The process is summarized as follows.

Stage 1 – The IR sensors detect the line by sensing the contrast between the line and the surrounding surface.

Stage 2 – The IR sensors send the detected line information as a signal to the Arduino.

Stage 3 – The Arduino processes the signal to determine the necessary movement adjustments for the robot.

Stage 4 – Based on the processed signal, the Arduino sends commands to the motors, directing the robot to follow the line accordingly.

The data from the website as per the choice of products of the customers are transmitted through LAN and received by the ESP32 Wi-Fi & Bluetooth Dual-Core MCU Module. Serial communication is maintained in between the ESP32 module and the Arduino Pro Mini. So the data from the website sets the appropriate path and direction of the line follower robot to reach the desired destination, that is, the product as per the customer's wish.

C. Robotic Arm

Robotic arms are designed to perform specific tasks or jobs quickly and efficiently, without the need for wiring, with high accuracy [11]. Typically powered by motors, these arms are commonly employed for the fast and consistent execution of heavy or highly repetitive tasks over long durations. They mimic the structure of a human arm, with components similar to a wrist, forearm, elbow, and shoulder. The various joints provide the necessary degrees of freedom for movement.

The designed robotic arm has several sophisticated parts to properly function, such as:

1) Robot arm tool: A robotic arm, known as a manipulator, extends the reach of a robot through cylindrical or spherical parts, links, and joints. The design and length of the arm are significantly influenced by the type and function of the end effector tool it supports.

2) End effector: The end effector, located at the end of the robotic arm, performs specific tasks such as gripping objects [12]. The gripper has enough friction so that the product does not slip away while picking and dropping to the cart accurately or in the midway. Furthermore, we added a force sensor along the inside portion of the gripper which can sense the presence of the product based on the variation of the force measured by the sensor. The gripper will stop closing when the force sensor reading crosses a threshold limit. It will ensure that the product is not too highly gripped that may lead to smashing the product [13].

3) Actuators: Actuators generate motion in both the robotic arm and its end effectors. The arm used here has a stepper motor to rotate the whole body of the arm to pick product from both sides of the path and five servo motors dedicated to picking and placing the product accurately.

Different parts of the robotic arm are separately shown in Fig. 1.

Fig. 1. Parts of robotic arm – 1: claw segments; 2: segments for elbow, wrist and shoulder; 3: base of robotic arm; 4: assembled claw; 5: assembled wrist, elbow and shoulder; 6: final assembled robotic arm with base.

D. Video Processing

The camera to be used along with the robotic arm in order to visualize the product to be picked will continuously capture the product [14]. Based on the video received, video processing improves the movement of the arm to near perfection in regards to picking the product. The product will not be tilted or slips while picking by the virtue of accuracy provided by video processing.

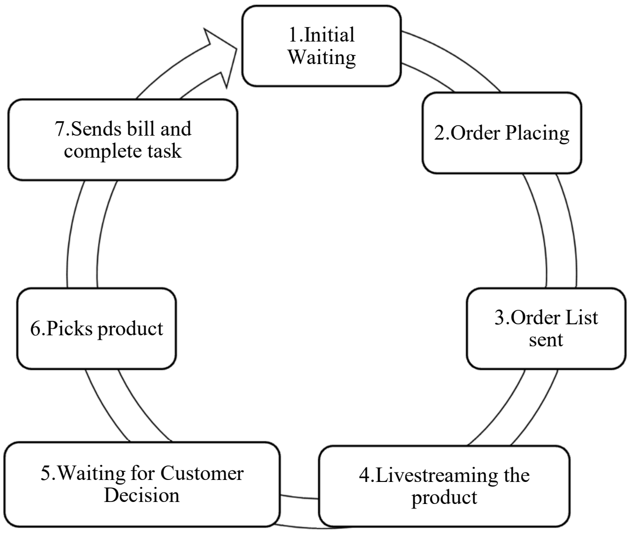
The ESP32 CAM Wi-Fi module with OV2640 2MP camera module is designed for product visualization as shown in Fig. 2., offering a compact and competitive small camera module capable of independent operation as a minimal system. It features a very low deep sleep current that peaks up to 6mA, making it highly efficient.

Fig. 2. ESP32 CAM for product visualization through the website.

Ideal for smart home devices, industrial wireless control, and monitoring applications, the ESP32 CAM integrates Wi-Fi, Bluetooth, and BLE beacons. It features two powerful 32-bit LX6 CPUs and a 7-stage pipeline architecture, with frequency ranging from 80MHz to 240MHz. The module has on-chip sensors, Hall sensors, a temperature sensor, and more. When powering the ESP32-CAM via the 5V power pin, ensure the FTDI adapter is set to output 5V VCC. Using a 5V setup is recommended for extended range without needing an external antenna. During programming, GPIO 0 must be connected to Ground.

III. Implementation of the Design

The cart is designed to carry items weighing up to 5 kg at an average speed of 1 meters per second. A flow chart is provided below to launch the total system.



A. Website and Product's Video Streaming

HTML, CSS and JavaScript was used to design the website for online shopping. For communication between the robot and the website we used the WebSocket protocol. HTML was used to provide the site structure, CSS was used to stylize the site. The interactive features of the website were designed using JavaScript.

We developed a Wi-Fi remote-controlled car robot utilizing the ESP32-CAM. This setup allows us to control the robot via a web server that streams live video from the robot's perspective. Programming for the ESP32-CAM is done using the Arduino IDE. The user end view is shown in Fig. 3.

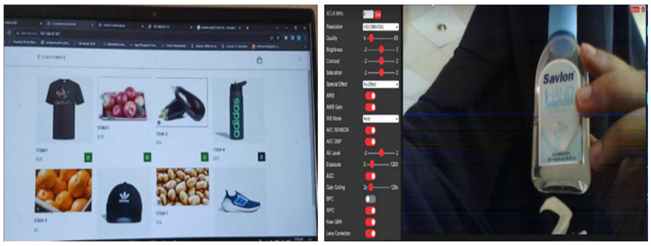


Fig. 3. Website for user interface and real-time streamed video.

The website can easily be accessed from computer or mobile phone providing a roaming facility to the user [15].

B. Line Follower Configuration

IR transmitters and IR receivers were utilized here. In this system, for a black line, the Arduino input is 0 otherwise the input is 1 [16]. The proposed line following structure is shown in Fig. 4.

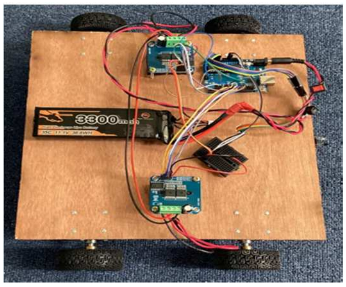


Fig. 4. Line follower base with wheels.

Based on the High or Low inputs, the Arduino Uno generates appropriate outputs to control the robot [17].

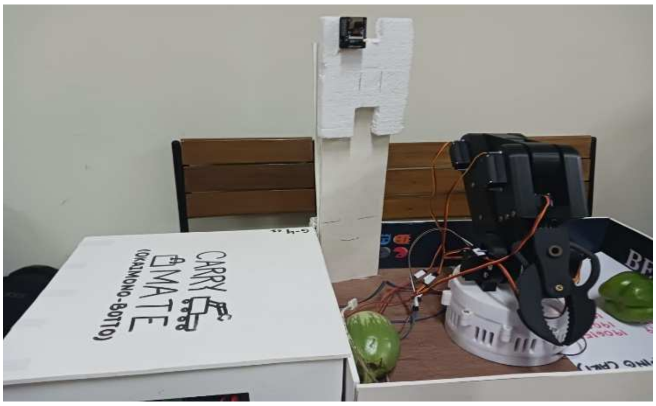


Fig. 5. Assembled structure of the full product.

C. The Robotic Arm

The hardware used to curb the motions of the robotic arm includes a Robotic Arm, IR Receiver, Arduino Uno board, and Shield board. The Arduino IDE (Integrated Development Environment) serves as the software platform for uploading the robotic arm program [18]. We designed a robotic arm that has five degrees of freedom [19] - [21] and can pick a weight up to 600 g of products as per the customer's desire. The arm can move up and down, left, right, and rotate 360°. The total integrated setup is provided in Fig. 5.

The fundamental principle underlying most robotic arm designs is similar across various sources [17], [19], [22], [23]. The movements of the robotic arm at the different stages of picking a product are separately shown in Fig. 6.

Fig. 6. Robotic arm movement – 1: initial rest position; 2: wrist moves to the initial position; 3: claw extends; 4: elbow moves to the initial position; 5: arm set to product height by the movement of shoulder; 6: claw retreats for product gripping; 7: elbow moves back; 8: product is brought within the range of cart; 9: claw releases the product and arm moves to initial rest position.

IV. Result and Analysis

Each user needs a laptop or mobile phone to access the shopping website. For the livestream segment of the experiment, five users were recruited to evaluate the video streaming capabilities of the cart system. Each user accessed the system via a designated website and selected their preferred video resolution from available options. After placing their order, the time taken for the video stream to initiate was recorded as latency, measuring the delay from order placement to video visibility. Additionally, users provided feedback on connection stability throughout their streaming experience, which was quantified as a percentage to reflect the reliability of the video stream. In the line follower robot segment, the robot was tested across three trials with varying loads, specifically set at 2.5 kg, 3 kg, 4 kg, 5 kg, and 6 kg. For each load, the average speed of the robot was measured while following a predetermined path, and this speed was recorded in meters per second (m/s). The battery life of the robot was also assessed, noting the duration of operation until the battery was depleted, recorded in minutes. This segment aimed to analyze the robot's performance under different weight conditions. The robotic arm was tested with five different types of products: carrot, tomato, onion, chili pepper, and water bottle. Each product was handled ten times to ensure consistency in measurements. Gripping accuracy was calculated by determining the percentage of successful picks without dropping or damaging the product. The average gripping force applied during handling was measured using a force sensor and recorded in Newtons (N). Additionally, the product handling time was measured, noting the duration from the initial rest position to the return of the arm to the rest position after placing the product.

TABLE I. User Trial and Review

Parts of the Setup	**Criteria of Review**			
	User No	***Resolution***	***Latency(s)***	***Connection Stability (%)***
Livestream	1	1280 ×1024	9 s	75
	2	320×240	2 s	100
	3	352×288	2 s	100
	4	1024×768	7 s	80
	5	640×480	3.5 s	95
	Trial No	***Load (kg)***	***Average Speed (m/s)***	***Battery Life (min)***
Line Follower Robot	1	2.5 kg	1.48	30 min
	2	3 kg	1.42	28 min
	3	4kg	1.23	20 min
	4	5kg	1.05	18 min
	5	6kg	0.3	7 min
	Product Type	***Gripping accuracy (%)***	***Average Gripping Force in Newton (N)***	***Average Product Handling time (s)***
Robotic Arm	Carrot	100	6.65 N	26.3 s
	Tomato	100	2.12 N	21 s
	Onion	100	4.53 N	24 s
	Pepper	100	1.36 N	19.6 s
	Water Bottle	100	3.56 N	23 s

The analysis reveals that lower video resolutions in the livestream resulted in more reliable communication and reduced latency, while higher resolutions increased delays due to internet speed limitations. For the line follower robot, carrying loads over 5 kg significantly decreased speed and battery life, indicating that lighter weights optimize performance. In the robotic arm section, all products were successfully picked, but larger items required greater gripping force, leading to longer handling times due to the balance needed between secure gripping and preventing damage.

V. CONCLUSION

In this paper, a novel approach to virtual reality-based autonomous shopping is presented, integrating robotic automation and real-time product visualization. The proposed system demonstrates significant improvements in precise product picking, proper gripping, and low-cost implementation, capable of lifting products up to 600 g, with the cart able to carry items weighing up to 5 kg at an average speed of 1 m/s. However, the integration of the ESP32-CAM for real-time product visualization presents several challenges. Low picture quality, limited bandwidth, and short transmission range lead to disruptions in server connectivity, reducing system reliability. The device's reliance on Wi-Fi further restricts its operation to short-range environments.

To overcome these issues, using more advanced platforms such as Raspberry Pi, NVIDIA Jetson, or PexiCam could provide better image quality, more stable long-range communication, and enhanced processing power. Moreover, incorporating lifting mechanisms in the arm architecture could improve elevation and facilitate product picking from various shelf heights. Additionally, improving battery life through more efficient solutions and modifying the robotic arm architecture to elevate items exceeding 600 g would enhance performance. Implementing higher resolution cameras could innovate features such as object detection, enabling precise picking based on detected items. Overall, this research contributes not only in the advancement of the field of robotics and automation but also sets a strong toe-hold for future developments in fully automated retail systems, offering transformative potential for e-commerce and consumer interaction.

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