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Design and Fabrication of Low-Cost Tennis Ball Collector Robot

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ABSTRACT

Tennis players often practice by hitting many balls from one side of the court to the other when no one else is present, which makes collecting the balls during practice sessions time-consuming. The goal of this research is to design and build a self-driven tennis ball collector that can gather balls from one side of the court, allowing the player to relax instead of physically collecting them. This mechanical tennis ball collector was conceived and developed using a Raspberry Pi controller and Python. Python code was used to locate the tennis balls and measure the distance to obstacles. An Arduino Uno controlled the DC motor's speed and direction. The main structure of this automated tennis ball collector is composed of structural frame materials, facilitating the attachment of all electrical components. Test run results demonstrate that the automatic tennis ball collector, equipped with image detection, can gather a large number of tennis balls on the court within a set time limit.

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I. Introduction

Tennis is a popular and interesting sport nowadays. However, if you run out of balls throughout the game, you must stop and gather them. The time wasted collecting the balls is money wasted, especially when you're working with a coach. In the same way, you have to pick up hundreds of balls from the field at the end of the game. This is especially challenging for players who are exhausted throughout the game. Various tennis ball collection devices have been designed to deal with this problem. Duru Saricalar [1] suggested designing and implementing a robotic assistant capable of independently gathering tennis balls. The ball-gathering area is designed to resemble a small tennis court. For the purpose of localization and planning, a camera is positioned two meters above the ground to capture the necessary image. The machine is controlled using Matlab software once it has been imaged. Tennis balls are automatically directed to the launch mechanism before being collected by a container guides. The robot, which was introduced by Vehbi Umur Cabuk [2], detects the balls using a camera fixed on its head and conducts gathering of the nearest one. The device employs a rotational shaft mechanism, eliminating the requirement for an extra ball collecting actuator. The balls may fit into the system when they are placed in the storage. Hung-Kuang Chen [3] suggested a patented robot designed for picking up tennis balls. The study offers a multichannel collector with expandable configuration and extremely efficient tennis ball collection to increase collecting efficiency and allow for a larger range of tennis balls. A intelligent car with automated navigation is developed using an Arduino microcontroller and an Android-based smartphone to decrease labor and human interaction. The innovative design is more user-friendly and efficient than traditional methods. Elamvazuthi et al. [4] presented a study that intends to create a tennis ball retriever robot that is autonomous for use in the sports sector. Ali et al. [5] explored various path planning methods for an autonomous tennis ball retriever. They compared Coverage Path Planning (CPP) U-Turn, CPP ISS, and Probabilistic Roadmap Method (PRM) algorithms. Their findings indicated that the CPP U-Turn method was the most effective for integration into a tennis ball retriever robot. The robot was made to save tennis players the time and effort of having to pick up tennis balls by hand after practice. The study examines the mechanical and controller subsystems, navigation, and the overall system performance. Ha et al. [6] studied a machine to collect tennis ball. Nurhanum Omar et al. [7] presented the Autonomous Tennis Ball Collector by using Raspberry PI. Shiqian Zhang et al. [8] studied a smart tennis picking robot based on STM32 and Raspberry Pi. John Wang explored A Low-

Cost Robot for Tennis Ball Retrieval, called “Ballbot”. Automated ball retrieving robot for tennis training sessions is researched by Dulanjana et al. [9].

After conducting a literature review as part of this investigation, it was determined that numerous robotic tennis ball retrievers have been created over the years. However, there are several disadvantages. The problems with the current way of gathering tennis balls have wasted time, neglected rest periods, made tennis players more tired, and caused them to perform poorly during practice sessions. Currently, there is no dedicated product in Vietnam that focuses on smart tennis selecting robots, making it a potential market for development.

The paper is outlined as follows: In Section 2, the mechanical and electronic control systems are described. Product Implementation is discussed in Section 3. Results and discussion are detailed in Section 4. Conclusions is presented in Sections 5.

2. Mechanical System And Electronic Control System

The robot contains the subsequent characteristics: The chassis motion control system exhibits remarkable adaptability and precision, utilizing a two-wheel mechanism and a mechanical framework for both movement and turning. The second step is to separate the controllers for the chassis motion and the image recognition processing. The STM32 (used to control two motors) and Raspberry Pi (used to control camera to determine the ball position) will be used as the control centers for these two parts, which will separate decision-making and control, make the system more stable and reliable, and make development easier. Furthermore, the tennis pick-up mechanism is not only highly efficient but also finely constructed, and it is able to fulfill the typical requirements of users.

(a) CAD model (b) Real model

Figure 1. *3D view of tennis ball catcher robot.*

2.1. Mechanical System

Figure 1 illustrates views of the mechanical system of the autonomous tennis ball catcher. The robot can be devided into the drive mechanism, base platform and ball pickup.

Drive mechanism: The driving mechanism shown in Figure 2, is situated near the robot's center of gravity to allow it to turn more readily and move with greater flexibility. The mechanism serves as the active motor for the robot, facilitating the efficient transmission of power from the motor to the wheels. This enables the robot to travel in many directions, including forward, backward, and modify its course successfully.

Ball Container and the Chassis: the physical platform is built on robot chassis illustrated in Figure 3, giving it good stability and handling at high speed. The chassis is ccreated by 20x20 Aluminium Extrusion frames.

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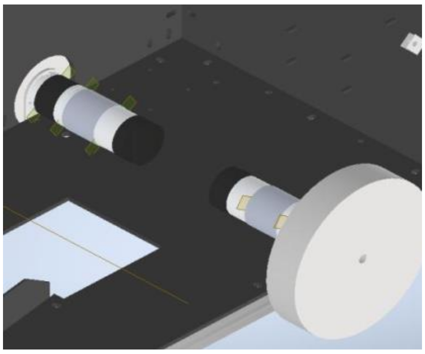
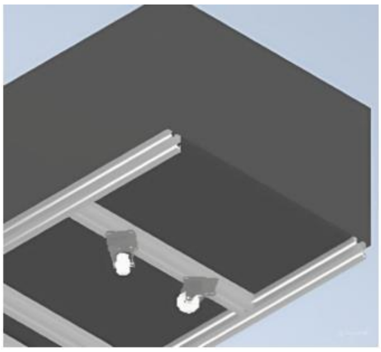


(a) The main driving mechanism



(b) The guide driving mechanism

Figure 2. *Robot chassis with 20x20 Aluminium Extrusion.*

Ball pickup: The ball pickup system depicted in Figure 4 is designed to gather tennis balls from the ground, store them, and return them to players. It operates using two horizontally aligned rollers, each driven independently by DC motors through toothed belts. The rollers are sufficiently wide to accommodate minor misalignments when approaching the ball. By reversing the rotation of one roller, the mechanism can effectively manage the roll-in and roll-out of the balls. This straightforward design has demonstrated a high level of reliability, with an error rate of just 3%. As shown in Figure 5, the camera is mounted just above and in front of the ball pickup mechanism.

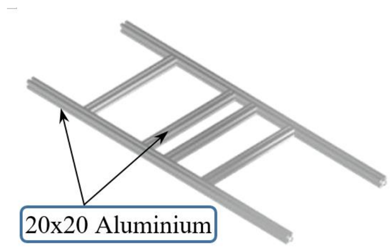


Figure 3. *Robot chassis with 20x20 Aluminium Extrusion.*

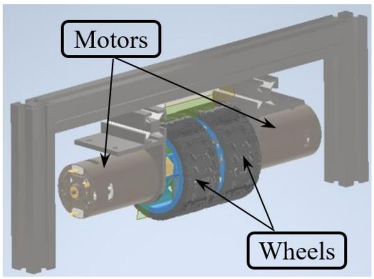


Figure 4. *Ball pickup mechanism.*

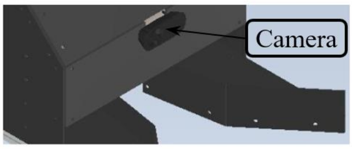


Figure 5. *Camera position.*

2.2. Electronic Control System

The control system software block diagram of the robot, as depicted in Figure 6, is partitioned into three main parts: input signals, processing, and control. The input signal part receives external signals for processing, such as the Control App, tennis ball location data, surrounding obstructions data, and successful ball pickup signals. All input signals get from the camera with position shown in Figure 5.

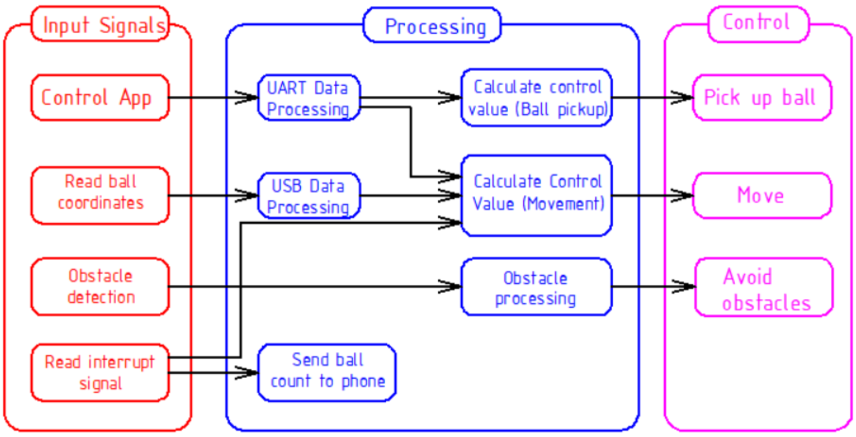


Figure 6. *Flow chart of electrical software control system.*

The processing part serves as the central hub for receiving and processing signals from the input signal part. The system performs a variety of functions, including processing data received from the control application via UART communication, analyzing USB data regarding tennis ball coordinates, transmitting information about the quantity of balls collected to the control application on the mobile device, computing control values for ball retrieval and movement, and handling information about obstacles to prevent collisions. Finally, the control part performs actions based on the control values calculated in the processing part. Specifically, the robot will perform the action of picking up tennis balls, moving to necessary locations, and avoiding obstacles along the way.

2.3. Electronic Control System

The overall system controller is designed as shown in Figure 7. The control system is configured with two proportional-integral (PI) controllers and one proportional (P) controller. The PI controllers are used to maintain and adjust the motor speed, ensuring stable and accurate operation at an appropriate velocity. Meanwhile, the P controller helps the robot adjust its movement direction, allowing it to effectively approach and retrieve the ball.

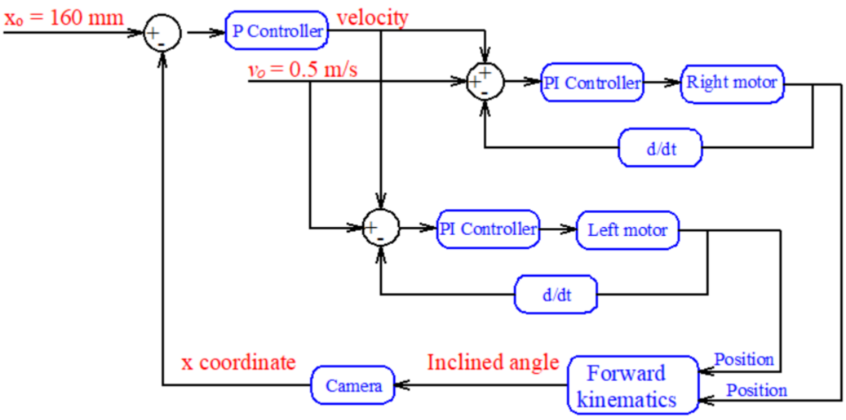


Figure 7. *The overall system controller.*

The value v_0 = 0,5 m/s is the speed that helps the car move straight forward. The control value from the P controller allows the robot to turn its head towards the left side of the ball. To change the direction towards the ball, the robot's two motors will receive control values with opposite signs, causing them to rotate accordingly. The coordinate origin, O, is positioned at the upper left corner of the camera frame. The Ox axis runs from left to right, while the Oy axis runs from top to bottom. When the two wheels rotate through forward kinematics, the robot will turn at a corresponding angle. Since the camera is rigidly attached to the robot, it will also rotate at a similar angle. As the camera rotates, the x coordinate of the ball in the frame will change. This *x* coordinate value is used as feedback for the P controller, with the desired value x_0 =160 mm (the *x* coordinate of the ball in the middle of the frame).

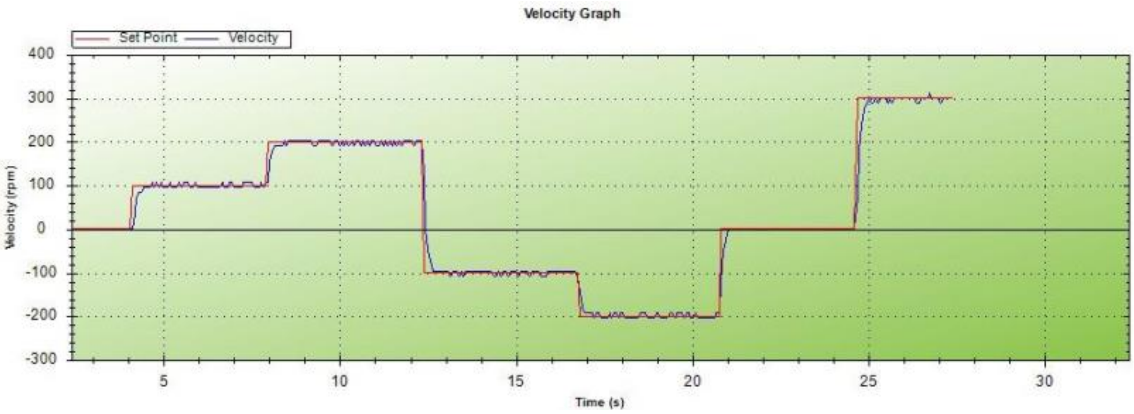


Figure 8. *Graph shows the relationship between velocity and time for the left motor*

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The PI controller is employed to maintain and regulate the motor speeds, ensuring stable and accurate operation at the desired velocity. Meanwhile, the P controller is responsible for adjusting the robot's heading, enabling it to approach and retrieve the ball. The control coefficients for the two drive wheels were tested and calculated using the IMC method. The formula for the PI controller in the form of a transfer function is used for the motor on the left side. The formula for the PI controller in the form of a transfer function is used for the motor on the right side. Additionally, the research team employed a PID control algorithm to compensate for pixel error. Specifically, the pixel deviation was processed through the PID controller to generate output values corresponding to the velocities of the two wheels. Figure 8 presents the velocity response of the left motor after applying PID control.

$$G_{PI}^{L} = K_p\left(1+\frac{1}{\tau_i s}\right) = 2{,}833874094\left(1+\frac{1}{0{,}0555496s}\right) \quad (1)$$

$$G_{PI}^{R} = K_p\left(1+\frac{1}{\tau_i s}\right) = 1{,}63627321\left(1+\frac{1}{0{,}03331125s}\right) \quad (2)$$

Figure 9 presents the velocity response of the right motor after applying PID control to it.

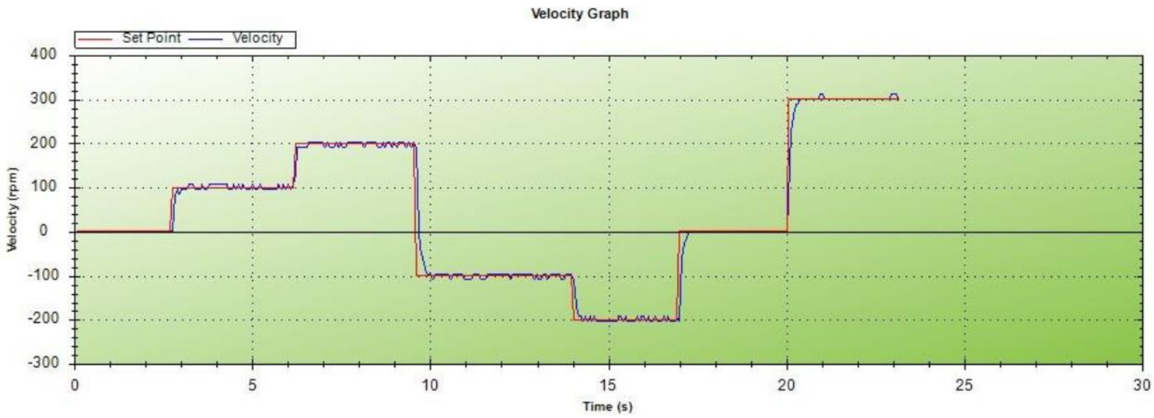
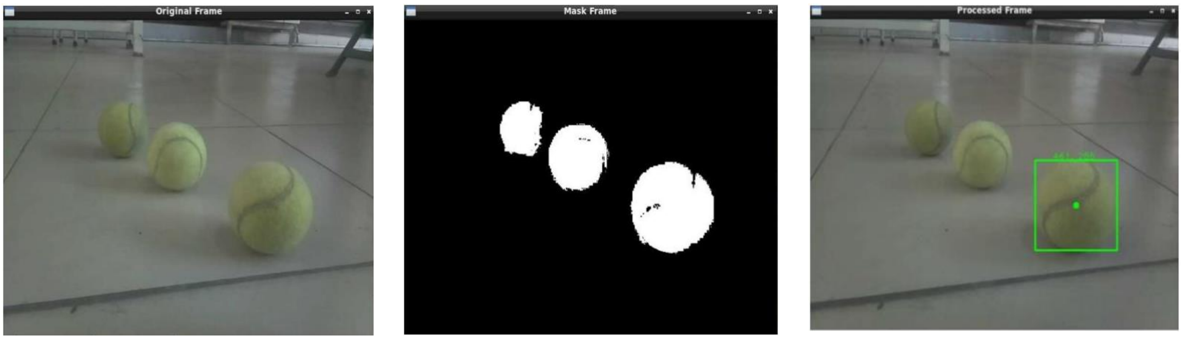


Figure 9. *Graph shows the relationship between velocity and time for the right motor*

2.4. Image Processing and determination the position of the balls

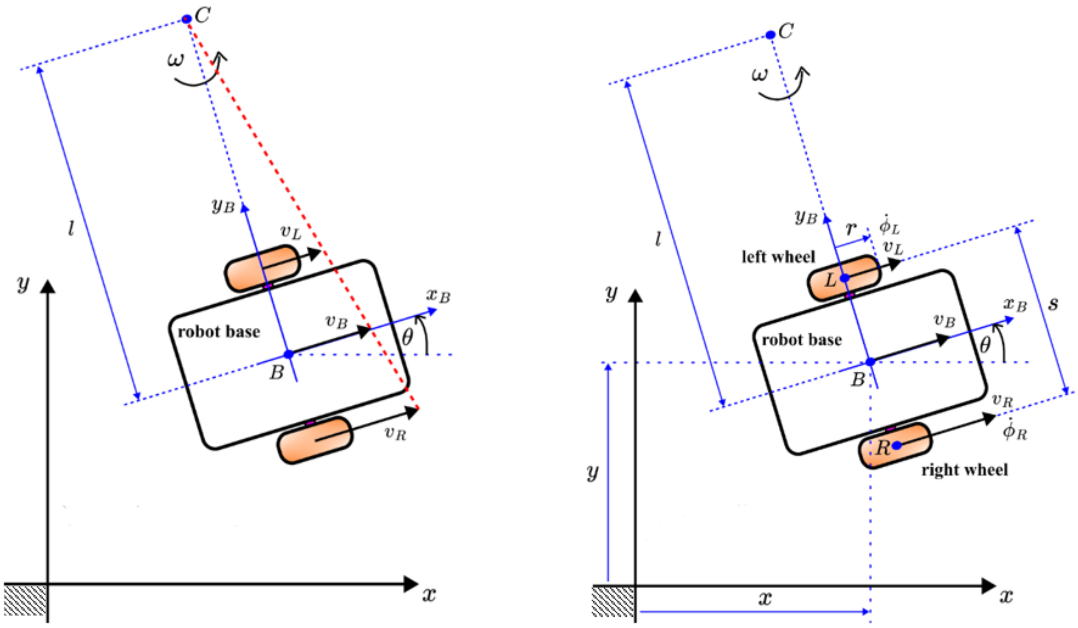
There are many methods to determine the balls such as: AI in combination with CNN method [10], Lidar (Light Detection and Ranging) sensor [11] and Color Image Segmentation (CIS) method [12]. In this study, we use the CIS method to detect the balls. The PID algorithm is employed to adjust the discrepancy in pixels.



(a) Original image
(b) The processed image using HSV color space segmentation
(c) Image after determining the largest contour center

Figure 10. *Detecting and giving locations in case of numerous balls*

More precisely, the PID function uses the pixel error to compute the output value, which in turn determines the velocity of the two wheels. The robot use HSV color space filtering and contour search algorithms to identify the precise center coordinates of the ball. The recognition system has exhibited exceptional precision in detecting and providing the coordinate values of the ball. The ball recognition system demonstrated remarkable accuracy, effectively distinguishing and prioritizing closer balls while disregarding others that were farther away. The color segmentation outcomes are displayed in Figure 10.



(a) (b)

Figure 11. *Kinetic (velocity) diagram of the differential drive robot.*

2.5. Kinematic analysis of differential drive robot

Assume that the left and right wheel rotation angles ϕ_L and ϕ_R, as shown in Figure 11, are functions of time. We assume $\phi_L = \phi_L(t)$ and $\phi_R = \phi_R(t)$. The forward kinematics problem involves determining the time-dependent functions of x, y, and θ. The goal is to find time-dependent functions that characterize the x and y coordinates of the robot point B, as well as the angle rotation of the robot body θ. As a function of time, we may differentiate these quantities to find the angular velocities $\dot{\phi}_L = \dot{\phi}_L(t)$ and $\dot{\phi}_R = \dot{\phi}_R(t)$. The forward kinematics problem can therefore be expressed as a function of angular velocity.

$$\dot{x} = \frac{v_L}{2}\cos\theta + \frac{v_R}{2}\cos\theta \quad (3)$$

$$\dot{y} = \frac{v_L}{2}\sin\theta + \frac{v_R}{2}\sin\theta \quad (4)$$

$$\dot{\theta} = -\frac{1}{s}v_L + \frac{1}{s}v_R \quad (5)$$

where v_L and v_R denote the velocity of the center of the left and right wheels. $\dot{x}, \dot{y}$ are is the projection of the velocity v_B on the x, y axes. $\dot{\theta}$ is the instantaneous angular velocity of the robot body.

$$v_L = \omega\left(l - \frac{s}{2}\right) \quad (6)$$

$$v_R = \omega\left(l + \frac{s}{2}\right) \quad (7)$$

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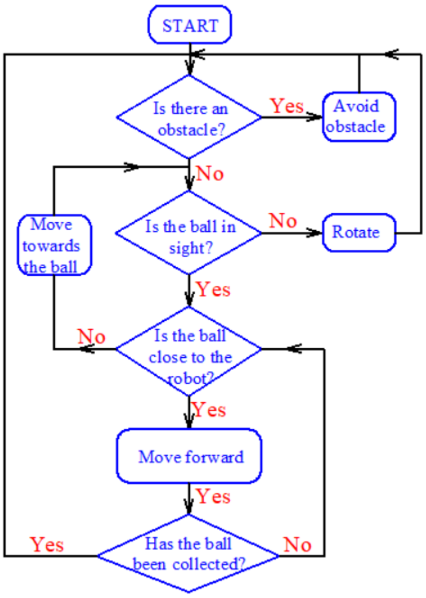


Figure 12. *General flow chart of the operation of the system.*

(a)

(b)

Figure 13. *Successfully developed a tennis ball collector robot.*

The inverse kinematics problem can therefore be expressed as

$$v_R = \sqrt{\dot{x}^2 + \dot{y}^2} + 0.5\omega \times s \tag{8}$$

$$v_L = \sqrt{\dot{x}^2 + \dot{y}^2} - 0.5\omega \times s \tag{9}$$

$$\theta = \arctan\left(\frac{\dot{y}}{\dot{x}}\right) \tag{10}$$

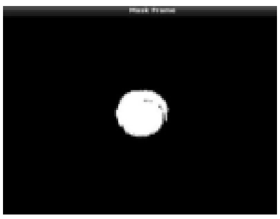
3. Product Implementation

The robot starts by checking for any obstacles around. If an obstacle is detected, the robot will call the corresponding obstacle avoidance function to circumvent it. If there is no obstacle, the program continues to check whether a ball is in the robot's field of vision. If no ball is detected, the robot will rotate to search for the ball. When the ball appears in the field of vision, the program checks the distance between the ball and the robot. If the ball is close, the robot will prioritize moving straight to the ball to pick it up. After picking up the ball, the robot returns to the original cycle to continue searching for and picking up other balls. If the ball is not close, the robot will move closer to the ball to pick it up. Figure 12 presents a flowchart that enables a successfully developed robot, as shown in Figure 13, to automatically detect, approach, and pick up the ball while effectively avoiding obstacles.

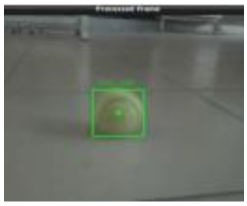
4. Results and Discussion

4.1. Image processing and obstacle avoidance

(a) Original image



(b) The processed image using HSV color space segmentation



(c) Result

Figure 14. *Image processing without object of the same color.*

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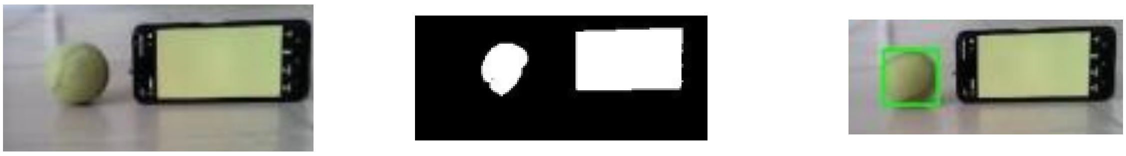
The robot successfully uses color segmentation techniques to locate tennis balls. Its recognition system demonstrates high accuracy in identifying the balls and returning their coordinates. The system's accuracy is impressive, and it also prioritizes recognizing closer balls by filtering out distant ones. The recognition algorithm ensures accurate and efficient operation by preventing objects of the same color from affecting the system.

The results are shown in Figure 14 and Figure 15.



(a) Original image. (b) The processed image using HSV color space segmentation. (c) Result.

Figure 15. *Image processing with object of the same color.*

4.2. Tennis Ball Pickup Ability Evaluation

This test is intended to determine how successfully the robot moves, picks up, and stores the tennis ball. This test determines the efficacy of the ball gathering system while the robot is moving.

Table 1. *Results of Testing the Robot's Autonomous Capability*

Trial	Number of successfully collected balls	Average time per ball (seconds)	Success rate (%)	Cause
1	23	15	92	Failed to detect the ball
2	24	14	96	Failed to detect the ball
3	22	14	98	Failed to detect the ball
4	23	13	92	Failed to detect the ball

The robot navigates a tennis court that is populated with balls, precisely counting the number of balls it successfully encounters. The results of testing are shown in the Table 1. The ability of ball collection is presented in the Table 2.

Table 2. *Results of Ball Collection Testing*

Trial	Result	Success rate (%)	Error
1	Ball successfully pushed into the box	86	No
2	Ball successfully pushed into the box	88	No
3	Ball successfully pushed into the box	89	No
4	Ball successfully pushed into the box	91	No

The automatic tennis ball picking robot has demonstrated good ball collection capabilities through real-world testing. It can effectively search for and collect balls, minimizing the number of missed balls. The system operates in two modes: manual and auto. The robot's operation speed is stable and fast, meeting the requirements for ball retrieval time and detection range. Additionally, the system has effective obstacle avoidance capabilities, allowing the robot to move flexibly and safely during operation, preventing collisions. However, during operation, the system encountered some errors in determining the ball's position, especially under excessively weak or strong lighting conditions. Furthermore, the system's obstacle-handling capability is still limited when dealing with low-height obstacles. Overall, the automatic tennis ball picking system has shown great potential in improving efficiency and automating the ball retrieval process. However, some limitations still need to be addressed to enhance accuracy and operational capability under different conditions.

5. Conclusions

This paper presents the development and testing of an autonomous tennis ball collecting robot. Although the system has demonstrated relatively high efficiency (>=86%), there is still room for improvement. Future research could focus on a more in-depth analysis of ball collection speed, manufacturing costs, and overall system performance. In order to enhance operational efficiency, necessary adjustments and optimizations should be made. One potential improvement is upgrading the path-tracking algorithm and refining the image processing method to increase accuracy in ball detection. Additionally, expanding the storage compartment would allow the robot to collect more balls per cycle, thereby improving overall performance.

The robot incorporates several key features. Firstly, its chassis motion control is highly flexible and precise. Secondly, the system separates chassis motion control from image recognition processing by utilizing STM32 and Raspberry Pi as independent control units for these functions. This separation of decision-making and control enhances system stability, reliability, and ease of development. Lastly, the tennis ball pickup mechanism is carefully designed for efficiency, ensuring that it meets the typical needs of users.

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Conflict of Interest

The authors declare no conflict of interest.

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