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An Intelligent Robotic Access Control System for High-Security Applications

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Abstract - Manual verification procedures used in many restricted and high-security areas are often inefficient and susceptible to human errors, leading to delays and security concerns. This work presents a Smart Vehicle Entry Management System that combines a robotic arm, a high-resolution camera, Optical Character Recognition (OCR), and real-time image processing to automate the entry verification process. The robotic arm enables precise positioning of the camera for capturing the vehicle license plate, driver's face, and identification documents. A voice input module is also incorporated to record the purpose of entry. The acquired information is stored digitally, improving traceability and eliminating the limitations associated with manual record maintenance. Experimental results indicate that the proposed system reduces entry processing time while providing reliable vehicle and driver identification, thereby enhancing both operational efficiency and security.

Key Words: Vehicle entry system, OCR, robotic arm, image processing, automation, security, access control

1.INTRODUCTION

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1. Introduction

Restricted and high-security facilities, including defence research laboratories, military establishments, and industrial zones, rely heavily on effective access control mechanisms to maintain safety and protect critical operations. In many such environments, entry verification is still performed manually, where security personnel inspect vehicle details, driver credentials, and identification documents before granting access. Although this approach is widely adopted, it is often slow, labour-intensive, and vulnerable to human errors. During peak hours, lengthy verification procedures can create congestion, reduce operational efficiency, and increase the risk of unauthorized access due to inconsistencies in manual checks.
Recent developments in automation, computer vision, and artificial intelligence have created new opportunities for building intelligent access control systems. Technologies such as robotic manipulators, Optical Character Recognition (OCR), and real-time image processing make it possible to automate several stages of the verification process, thereby reducing dependence on manual intervention. These advancements enable accurate identification of vehicles and drivers while maintaining digital records for improved traceability and security.
Motivated by these developments, this work proposes a Smart Vehicle Entry Management System aimed at overcoming the limitations associated with conventional entry verification methods. The system employs a robotic arm integrated with a high-resolution camera to capture images of vehicle license plates, the driver's face, and identity documents from suitable viewing angles. The captured data is processed using OCR and image-processing techniques to extract and analyze relevant information. In addition, a voice input module is incorporated to record the purpose of entry, and all collected information is securely stored in a digital database for future reference and monitoring.
The remainder of this paper is organized as follows. Section II reviews the challenges associated with existing manual entry procedures. Section III describes the proposed automated vehicle entry management system and its major components. Section IV presents the technical architecture of the system, while Section V discusses its technological advantages. Section VI highlights the operational and economic benefits offered by the proposed approach. Section VII explains the structure and dynamic modelling of the robotic arm. Section VIII details the implementation methodology, followed by future scope in Section IX. Finally, Section X concludes the paper.

2. Literature Survey

Reddy and Nagaraja (2014) used MATLAB-based image processing and shape recognition to integrate a vision system with a 5-DOF robotic arm for autonomous part segregation. Their research demonstrated how machine vision enhanced the accuracy of object identification and manipulation in industrial automation [1]. A camera-in-hand robotic arm powered by deep learning was created by Chen et al. (2019) for unattended store service. The system advanced intelligent robotic handling in IoT retail contexts by achieving 95Mixture Models, and MobileNetV2 CNN [2]. Ishak et al. (2018) presented an IoT-based robotic arm controller using Raspberry Pi and Node-RED for remote monitoring and control. The system demonstrated how IoRT integration improves remote flexibility and industrial efficiency by enabling real-time operation via web interfaces [3]. Vinay Kumar Singh and Agarwal (2020) This paper describes a four-degree-of-motion IoT-enabled robotic arm that uses an Arduino and potentiometers. With servo-motor control and Internet of Things connectivity, it provides low-cost, high-precision motion, demonstrating applications in industrial automation and prosthetics [4]. Prabhu B.P. Aniruddha (2021) The study presents a military surveillance Small Un armed Ground Vehicle (SUGV) that uses Bluetooth and Arduino. With low cost robotics and a live video feed and smartphone accelerometer control, it dramatically lowers soldier risk in hostile environments [5]. Ahmed Anwer Sabah et al. (2021)

This IoT-driven design integrates ultrasonic sensors for accuracy and uses an Arduino ESP32 and web-based control to operate a robotic arm for pick-and-place tasks. It is a prime example of how cloud and IoRT technologies are developing to enhance wireless industrial automation [6]. Prashant Gupta and Dr. A. Brintha Therese (2018) Their system uses a Raspberry Pi to separate objects based on colour using real-time image processing. This work demonstrates effective vision based robotics for industrial sorting by combining automation with manual control through a web interface [7]. Ali Hussein Mohammed et al. (2022) An Arduino-controlled 6-DOF robotic arm that can be controlled by a smartphone app through Bluetooth is created in this study. For low-cost industrial and laboratory automation, it places a strong emphasis on precision, ease of use, and remote operability [8]. Bhargava Ankur (2017) demonstrated precise servo controlled rotary movements for industrial use by designing a 5-DOF robotic arm with an Arduino Uno, potentiometer controls, and aluminum sheet fabrication [9]. Paul Ciprian Patic et al. created a two-armed mobile robot for accessing dangerous areas that is controlled by an Arduino Due and Bluetooth in order to facilitate safe human-robot interaction in dangerous situations [10].Armando Cordeiro and Jorge Costa Graca Almeida (2019) suggested an automated pick-and-place system based on a Raspberry Pi that incorporates conveyor and object detection and uses image processing for industrial automation [11].Dr. S.A.K. Jilani, P. Hemalatha, and C.K. Hemantha Lakshmi (2015) presented a Raspberry Pi stand alone system for robotic arm control and real-time image processing, utilizing MATLAB and OpenCV for object tracking and pick-and-place tasks [12]. In order to study kinematics and re mote control, Kadirimangalam Jahnavi and Sivraj P. created an educational model of a 5-DOF robotic arm using Arduino and MATLAB GUI. They also integrated accelerometer feedback for algorithm training [13]. A Rasp berry Pi-based surveillance robot that can be remotely operated through a web interface with CGI scripts and MJPG video streaming is presented in the paper by A. Narmada et al. (2022). It offers a low-cost, effective solution for remote surveillance in hazardous or inaccessible environments by utilizing servo motors, motor drivers, and a Raspberry Pi 3 Model B to provide real-time monitoring and directional control [14]. An Internet of Things (IoT)-based vehicle monitoring and access control system utilizing Arduino and RFID technology is presented in the paper by M. Vamshi Krishna Reddy et al. The system uses RFID to uniquely identify cars, GPS to track their location, and GSM to send out alerts. It provides safe and automated access for applications such as fleet management and smart parking by providing real-time monitoring with LCD and buzzer feedback [15]. Radhika and Kalagotla Chenchireddy In her paper, Dora describes a low cost robotic arm that is powered by four servo motors and an Arduino board. For accurate, dynamic control, it combines wireless communication and sensors. With a focus on gesture-based control applications, the study emphasizes Arduino's accessibility [16]. Jun-Wei Zhang and Rong Jyue Wang This piece describes a multipurpose robotic arm that can perform activities like calligraphy, dancing, weightlifting, and gaming. Using specialized motors and a coordinated dual arm function, it prioritizes stability, accuracy, and cost-effectiveness for industrial, educational, and entertainment applications [17]. Laura F. Munguía-Martínez and Fausto A. Valenzuela-Domínguez In order to teach robotics and Industry 4.0, this paper suggests a 2-DOF robotic arm that integrates IoT and AI. It demonstrates useful educational applications by enabling trajectory control and real-time monitoring through the use of servo motors, an ESP32 controller, and a MATLABGUI [18]. Thu lasi Bikku, M Lakshmana Kumar, S Mounika, K P N V Satya Sree, In this study, a prosthetic hand that is controlled by EMG signals and uses ma chine learning classifiers (KNN, SVM) achieves an accuracy of 96.333D modeling and AI-based control, the design aims to make amputees' lives more affordable and easier, especially in developing nations [19]. In their paper, Kruthika K, Kiran Kumar B M, and Sanjay Lakshmi narayanan describe a 5-DOF robotic arm for assistive feeding that is managed by a MATLAB-based graphical user interface (GUI) and controlled by an Arduino Mega. With an emphasis on precise, lightweight mechanical de sign appropriate for elderly or disabled users, it integrates kinematics and sensors such as potentiometers and force sensors [20].

3. Current Challenges

Most restricted facilities still rely on manual methods to verify vehicle and personnel entry. Typically, a security guard checks a driver's credentials, notes down the vehicle number, and records the purpose of visit. This process is highly dependent on human judgment, is repetitive in nature, and consumes significant time for each entry, especially during peak hours. Manual entry logging introduces several critical problems:-

- Time-Consuming: On average, the manual verification process can take between 3 to 5 minutes per vehicle, leading to long queues and delays at entry points.
- Error-Prone: Handwritten entries are prone to human errors such as incorrect data entry, misidentification, or incomplete records.
- Security Risks: Due to lack of real-time identity validation, unauthorized access may go unnoticed, especially under high workload conditions.

- Inefficient Record Management: Paper-based logs are difficult to search, analyze, or back track in case of investigations.

In high-security zones like defense institutes or research labs, these inefficiencies can lead to operational disruptions or even serious security breaches. Therefore, it is imperative to develop an automated solution that eliminates the bottlenecks associated with manual entry checks.

4. Proposed Automated Entry System

To address the limitations associated with conventional manual verification procedures, an intelligent vehicle entry management framework is developed by integrating robotic manipulation, computer vision, and digital data management into a unified access control system. The architecture consists of a robotic arm equipped with a high-resolution camera, an Optical Character Recognition (OCR) module, a voice acquisition unit, and a central processing unit responsible for data processing and storage.

The robotic manipulator is employed to position the camera precisely, enabling the acquisition of images containing the vehicle license plate, driver's face, and identification documents from appropriate viewing angles. The captured images are processed in real time using OCR and image-processing algorithms to extract relevant information, including the registration number, driver identity, and associated credentials [21]. In addition, a microphone module is incorporated to record the purpose of entry, which is subsequently converted into text using a speech-to-text engine. All acquired information is stored in a secure digital database along with timestamps and associated metadata to ensure traceability and facilitate future auditing.

The overall operation of the system can be summarized as follows:

- **Vehicle Detection:** The arrival of a vehicle is detected using proximity sensors or vision-based detection mechanisms.

- **Camera Positioning:** Upon vehicle detection, the robotic arm automatically adjusts the camera orientation to obtain optimal views of the license plate, driver's face, and identity card.

- **Image Acquisition and Processing:** High-resolution images are captured and processed using OCR and computer vision techniques to extract textual and visual information required for authentication.

- **Voice Data Acquisition:** A microphone records the visitor's stated purpose of entry, and the captured speech is converted into textual form through a speech recognition module.

- **Data Management:** The extracted information is securely stored in a centralized database and can be monitored through an administrative dashboard.

- **Access Authorization:** Based on identity verification and predefined authorization policies, the system determines whether access should be granted or denied [22].

By eliminating dependence on manual verification, the proposed framework significantly improves the efficiency and reliability of entry management. Automated data acquisition and digital record maintenance enhance security, reduce processing delays, and provide complete traceability of vehicle movements. Furthermore, the system offers a scalable solution that can be adapted to a wide range of high-security environments requiring robust and real-time access control.

5. Technical Architecture

The proposed Smart Vehicle Entry Management system is built using a modular and scalable architecture, combining hardware components and software modules to achieve seamless, real-time automation of vehicle entry.

5.1 System Components

- Robotic Arm: A programmable robotic manipulator used to adjust the camera's position to capture images from different angles (e.g., front view, driver view, side view).
- High Resolution Camera: Mounted on the robotic arm, this camera captures clear images of the vehicle license plate, driver face, and ID card.
- OCR Module: An image processing unit extracts alphanumeric char acters from license plates and ID cards using Optical Character Recognition
- Microphone: Used to capture and process the driver's spoken purpose of visit, converting speech to text for digital record-keeping.

- Raspberry Pi/Embedded Controller: Acts as the central processing unit to control the robotic arm, interface with the camera and microphone, and run software algorithms for image processing and data logging [23].
- Database and Dashboard: All extracted data is stored in a secure digital database and visualized through a real-time web interface for authorized personnel.

5.2 Workflow Overview

1. Vehicle arrival is detected using a proximity or vision sensor.
2. The robotic arm adjusts the camera position to sequentially capture required images.
3. The OCR system processes the license plate and ID images to extract data.
4. The microphone records the driver's purpose, which is transcribed and logged.
5. All data is stored in a digital log with timestamps [24].

6. Economic and Operational Benefits

Implementing the Smart Vehicle Entry Management system offers significant economic and operational advantages:–

- Labor Cost Reduction: Automation reduces the need for manual security personnel at entry points, potentially lowering labour costs by approximately 70
- Elimination of Human Error: By automating the identification and verification process, the system removes errors arising from fatigue, oversight, or miscommunication–
- Improved Security and Accountability: Digital logging and real time monitoring ensure complete records of all vehicle entries and exits, improving auditability and deterring unauthorized access [25].
- Operational Efficiency: Faster vehicle processing decreases wait times, allowing for smoother traffic flow and improved user satisfaction.
- Scalability: The system architecture supports deployment across multiple gates or locations, enabling unified access management without proportional increases in operational costs.

Fig -1: Robotic arm used for precise positioning

7. Structure of the Robotic Arm

The robotic arm used in the Smart Vehicle Entry Management system is a multi-degree-of-freedom manipulator designed to precisely position the camera for capturing vehicle and driver images. The arm consists of several rotary joints, each defined by standard Denavit-Hartenberg (DH) parameters.

8. Robot Parameters

Joint	θ_i	d_i	a_i	α_i
1	θ_1	d_1	0	90^0
2	θ_2	0	a_2	0^0
3	$\theta3$	0	a_3	0^0
4 (Camera)	$\theta4$	0	a_4	0^0

Table -1: Joints angles

Parameters Description

- θ_i: Joint angle (variable for revolute joints)
- d_i: Link offset (constant for prismatic joints)
- a_i: Link length (distance between join taxes)
- α_i: Link twist angle (angle between joint axes)

Coordinate Frames Assignment

The DH parameters are defined with the following conventions:

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- z_i axis along the joint axis $i + 1$
- x_i axis along the common normal between z_i and z_{i+1}

y_i completes the right-handed coordinate system

The homogeneous transformation matrices for each link are:

9. Forward Kinematics

9.1 *Individual Transformation matrices.*

$$A_1 = \begin{bmatrix} \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ \sin\theta_1 & 0 & -\cos\theta_1 & 0 \\ 0 & 1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & a_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & a_2\sin\theta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$A_3 = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & a_3c\theta_3 \\ s\theta_3 & c\theta_3 & 0 & a_3s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad A_4 = \begin{bmatrix} c\theta_4 & -s\theta_4 & 0 & a_4c\theta_4 \\ s\theta_4 & c\theta_4 & 0 & a_4s\theta_4 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

9.2 Intermediate transforms:

$$T_{12} = A_1A_2 = \begin{bmatrix} c_1c_2 & -c_1s_2 & s_1 & a_2c_1c_2 \\ s_1c_2 & -s_1s_2 & -c_1 & a_2s_1c_2 \\ s_2 & c_2 & 0 & d_1 + a_2s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$T_{123} = T_{12}A_3 = \begin{bmatrix} c\theta_1c\theta_{23} & -c\theta_1s\theta_{23} & s\theta_1 & a_2c\theta_1c\theta_2 + a_3c\theta_1c\theta_{23} \\ s\theta_1c\theta_{23} & -s\theta_1s\theta_{23} & -c\theta_1 & a_2s\theta_1c\theta_2 + a_3s\theta_1c\theta_{23} \\ s\theta_{23} & c\theta_{23} & 0 & d_1 + a_2s\theta_2 + a_3s\theta_{23} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

where $\theta_{23} = \theta_2 + \theta_3$

9.3 *Final Transformation:*

The complete transformation is:

$$T = T_{123}A_4 = \begin{bmatrix} c\theta_1c\theta_{234} & -c\theta_1s\theta_{234} & s\theta_1 & \sum_{i=2}^{4} a_i\, c\theta_1 c\theta_{2\cdots i} \\ s\theta_1c\theta_{234} & -s\theta_1s\theta_{234} & -c\theta_1 & \sum_{i=2}^{4} a_i\, s\theta_1 c\theta_{2\cdots i} \\ s\theta_{234} & c\theta_{234} & 0 & d_1 + \sum_{i=2}^{4} a_i\, s\theta_{2\cdots i} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

where $\theta_{234} = \theta_2 + \theta_3 + \theta_4$ *and* $\theta_{2\cdots i}$ indicates the sum of angles from θ_2 *to* θ_i.

9.4. End-Effector Position

The position components are:

$$x = \sum_{i=2}^{4} a_i \cos\theta_1 \cos\theta_{2\cdots i} \tag{6}$$

$$y = \sum_{i=2}^{4} a_i \sin\theta_1 \cos\theta_{2\cdots i} \tag{7}$$

$$z = d_1 + \sum_{i=2}^{4} a_i \sin\theta_{2\cdots i} \tag{8}$$

10. Inverse Kinematics

Given the end-effector position $\mathbf{p} = [x\ y\ z]^T$, we compute the joint angles θ_1, θ, θ_3, and θ_4 as follows:

10.1. Solution for θ1

The base rotation angle θ1 is determined from the projection onto the x y - plane:

$$\theta_1 = \text{atan2}(y, x) \tag{9}$$

10.2. Solution for θ2, θ3, and θ4

We define the arm vector $\mathbf{p}_{arm} = [x_{arm}\ y_{arm}\ z_{arm}]^T$ where:

$$x_{arm} = x - a_4 c\theta_1 c\theta_{234} \quad (10)$$

$$y_{arm} = y - a_4 s\theta_1 c\theta_{234} \quad (11)$$

$$z_{arm} = z - d_1 - a_4 s\theta_{234} \quad (12)$$

The squared distance from joint 2 to the arm endpoint is:

$$r^2 = x_{arm}^2 + y_{arm}^2 + (z_{arm})^2 \quad (13)$$

Using the law of cosines for the planar arm:

$$\cos\theta_3 = \frac{r^2 - a_2^2 - a_3^2}{2a_2a_3} \quad (14)$$

The two possible solutions for θ_3 (elbow up/down) are:

$$\theta_3 = \pm\cos^{-1}\left(\frac{r^2 - a_2^2 - a_3^2}{2a_2a_3}\right) \quad (15)$$

For θ_2, we first compute intermediate angles:

$$\alpha = \text{atan2}\left(z_{arm}, \sqrt{x_{arm}^2 + y_{arm}^2}\right) \quad (16)$$

$$\beta = \text{atan2}(a_3 s\theta_3,\ a_2 + a_3 c\theta_3) \quad (17)$$

Then:

$$\theta_2 = \alpha \mp \beta \quad (18)$$

10.3. Solution for θ4 (Camera Orientation)

The camera angle θ_4 is determined from the desired orientation:

$$\theta_4 = \theta_{desired} - \theta_2 - \theta_3 \quad (19)$$

10.4. Complete Solution

The inverse kinematics solution is:

$$\theta_1 = \text{atan2}(y, x) \quad (20)$$

$$\theta_3 = \pm\cos^{-1}\left(\frac{r^2 - a_2^2 - a_3^2}{2a_2a_3}\right) \quad (21)$$

$$\theta_2 = \text{atan2}\left(z_{arm}, \sqrt{x_{arm}^2 + y_{arm}^2}\right) \mp \text{atan2}(a_3 s\theta_3,\ a_2 + a_3 c\theta_3) \quad (22)$$

$$\theta_4 = \theta_{desired} - \theta_2 - \theta_3 \quad (23)$$

10.5. Solution Space Analysis

The inverse kinematics solution exists when:

$$|r^2 - a_2^2 - a_3^2| \le 2a_2a_3 \quad (24)$$

The workspace boundary is determined by:

$$\sqrt{(a_2 - a_3)^2 + d_1^2} \le \|\mathbf{p}\| \le \sqrt{(a_2 + a_3)^2 + (d_1 + a_4)^2} \quad (25)$$

11. Complete Dynamics for 4-DOF Manipulator

11.1. Kinematic Parameters

For each joint $i = 1, ..., 4$, we define:

- $\mathbf{z}_i$: Joint axis vector (in world frame)
- $\mathbf{p}_{i,\,i+1}$: Position vector from joint i to $i + 1$
- $\mathbf{p}_{i,\,ci}$: Position vector to link i's COM
- $\mathbf{m}_i$: Link mass
- $\mathbf{I}_i$: Link inertia tensor (COM frame)

11.2. Recursive Velocity Calculation

$$\boldsymbol{\omega}_1 = \begin{bmatrix} 0 \\ 0 \\ \dot{\theta}_1 \end{bmatrix} \quad (26)$$

$$\boldsymbol{\omega}_2 = \boldsymbol{\omega}_1 + \mathbf{R}_1\mathbf{z}_0\dot{\theta}_2 \quad (27)$$

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$$\boldsymbol{\omega}_3 = \boldsymbol{\omega}_2 + \mathbf{R}_2\mathbf{z}_1\dot{\theta}_3 \quad (28)$$

$$\boldsymbol{\omega}_4 = \boldsymbol{\omega}_3 + \mathbf{R}_3\mathbf{z}_2\dot{\theta}_4 \quad (29)$$

Linear velocities for each link COM:

$$\mathbf{v}_{c1} = \boldsymbol{\omega}_1 \times \mathbf{p}_{1c1} \quad (30)$$

$$\mathbf{v}_{c2} = \mathbf{v}_1 + \boldsymbol{\omega}_1 \times \mathbf{p}_{12} + \boldsymbol{\omega}_2 \times \mathbf{p}_{2c2} \quad (31)$$

$$\mathbf{v}_{c3} = \mathbf{v}_2 + \boldsymbol{\omega}_2 \times \mathbf{p}_{23} + \boldsymbol{\omega}_3 \times \mathbf{p}_{3c3} \quad (32)$$

$$\mathbf{v}_{c4} = \mathbf{v}_3 + \boldsymbol{\omega}_3 \times \mathbf{p}_{34} + \boldsymbol{\omega}_4 \times \mathbf{p}_{4c4} \quad (33)$$

11.3. Recursive Acceleration Calculation

$$\boldsymbol{\alpha}_1 = \begin{bmatrix} 0 \\ 0 \\ \ddot{\theta}_1 \end{bmatrix} \quad (34)$$

$$\boldsymbol{\alpha}_2 = \boldsymbol{\alpha}_1 + \mathbf{R}_1\mathbf{z}_0\ddot{\theta}_2 + \boldsymbol{\omega}_1 \times \left(\mathbf{R}_1\mathbf{z}_0\dot{\theta}_2\right) \quad (35)$$

$$\boldsymbol{\alpha}_3 = \boldsymbol{\alpha}_2 + \mathbf{R}_2\mathbf{z}_1\ddot{\theta}_3 + \boldsymbol{\omega}_2 \times \left(\mathbf{R}_2\mathbf{z}_1\dot{\theta}_3\right) \quad (36)$$

$$\boldsymbol{\alpha}_4 = \boldsymbol{\alpha}_3 + \mathbf{R}_3\mathbf{z}_2\ddot{\theta}_4 + \boldsymbol{\omega}_3 \times \left(\mathbf{R}_3\mathbf{z}_2\dot{\theta}_4\right) \quad (37)$$

Linear accelerations:

$$\mathbf{a}_{c1} = \boldsymbol{\alpha}_1 \times \mathbf{p}_{1c1} + \boldsymbol{\omega}_1 \times (\boldsymbol{\omega}_1 \times \mathbf{p}_{1c1}) \quad (38)$$

$$\mathbf{a}_{c2} = \mathbf{a}_1 + \boldsymbol{\alpha}_1 \times \mathbf{p}_{12} + \boldsymbol{\omega}_1 \times (\boldsymbol{\omega}_1 \times \mathbf{p}_{12}) \quad (39)$$

$$+\boldsymbol{\alpha}_2 \times \mathbf{p}_{2c2} + \boldsymbol{\omega}_2 \times (\boldsymbol{\omega}_2 \times \mathbf{p}_{2c2}) \quad (40)$$

$$\mathbf{a}_{c3} = \mathbf{a}_2 + \boldsymbol{\alpha}_2 \times \mathbf{p}_{23} + \boldsymbol{\omega}_2 \times (\boldsymbol{\omega}_2 \times \mathbf{p}_{23}) \quad (41)$$

$$+\boldsymbol{\alpha}_3 \times \mathbf{p}_{3c3} + \boldsymbol{\omega}_3 \times (\boldsymbol{\omega}_3 \times \mathbf{p}_{3c3}) \quad (42)$$

$$\mathbf{a}_{c4} = \mathbf{a}_3 + \boldsymbol{\alpha}_3 \times \mathbf{p}_{34} + \boldsymbol{\omega}_3 \times (\boldsymbol{\omega}_3 \times \mathbf{p}_{34}) \quad (43)$$

$$+\boldsymbol{\alpha}_4 \times \mathbf{p}_{4c4} + \boldsymbol{\omega}_4 \times (\boldsymbol{\omega}_4 \times \mathbf{p}_{4c4}) \quad (44)$$

11.4. Force/Torque Backward Recursion

For each joint $i = 4, \ldots, 1$:

$$\mathbf{f}_i = \mathbf{f}_{i+1} + m_i\mathbf{a}_{c_i} \quad (45)$$

$$\boldsymbol{\tau}_i = \boldsymbol{\tau}_{i+1} + \mathbf{I}_i\boldsymbol{\alpha}_i + \boldsymbol{\omega}_i \times \mathbf{I}_i\boldsymbol{\omega}_i \quad (46)$$

$$+\mathbf{p}_{i,c_i} \times \left(m_i\mathbf{a}_{c_i}\right) + \mathbf{p}_{i,i+1} \times \mathbf{f}_{i+1} \quad (47)$$

11.5. Joint Torque Calculations

$$\tau_1 = \mathbf{z}_0^T[\mathbf{I}_1\boldsymbol{\alpha}_1 + \boldsymbol{\omega}_1 \times \mathbf{I}_1\boldsymbol{\omega}_1] \quad (48)$$

$$+\mathbf{z}_0^T[\mathbf{p}_{1c1} \times m_1\mathbf{a}_{c1} + \mathbf{p}_{12} \times \mathbf{f}_2] \quad (49)$$

$$\tau_2 = \mathbf{z}_1^T[\mathbf{I}_2\boldsymbol{\alpha}_2 + \boldsymbol{\omega}_2 \times \mathbf{I}_2\boldsymbol{\omega}_2] \quad (50)$$

$$+\mathbf{z}_1^T[\mathbf{p}_{2c2} \times m_2\mathbf{a}_{c2} + \mathbf{p}_{23} \times \mathbf{f}_3] \quad (51)$$

$$\tau_3 = \mathbf{z}_2^T[\mathbf{I}_3\boldsymbol{\alpha}_3 + \boldsymbol{\omega}_3 \times \mathbf{I}_3\boldsymbol{\omega}_3] \quad (52)$$

$$+\mathbf{z}_2^T[\mathbf{p}_{3c3} \times m_3\mathbf{a}_{c3} + \mathbf{p}_{34} \times \mathbf{f}_4] \quad (53)$$

$$\tau_4 = \mathbf{z}_3^T[\mathbf{I}_4\boldsymbol{\alpha}_4 + \boldsymbol{\omega}_4 \times \mathbf{I}_4\boldsymbol{\omega}_4] \quad (54)$$

$$+\mathbf{z}_3^T[\mathbf{p}_{4c4} \times m_4\mathbf{a}_{c4}] \quad (55)$$

11.6. Complete Dynamic Model

The equations can be expressed in matrix form:

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ \tau_3 \\ \tau_4 \end{bmatrix} = \mathbf{M}(\mathbf{q})\begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} + \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\begin{bmatrix} \dot{\theta}_1^2 \\ \dot{\theta}_2^2 \\ \dot{\theta}_3^2 \\ \dot{\theta}_4^2 \end{bmatrix} + \mathbf{G}(\mathbf{q}) \quad (56)$$

Where:

- **M(q)** is the 4×4 inertia matrix
- **C(q,˙q)** contains Coriolis and centrifugal terms
- **G(q)** is the gravity vector

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11.7. Inertia Matrix Components

The elements of **M(q)** are:

$$M_{11} = \mathbf{z}_0^T \mathbf{I}_1 \mathbf{z}_0 + m_1 \mathbf{z}_0^T \tilde{\mathbf{p}}_{1c1} \tilde{\mathbf{p}}_{1c1}^T \mathbf{z}_0 \quad (57)$$

$$+ \sum_{k=2}^{4} m_k \, \mathbf{z}_0^T \tilde{\mathbf{p}}_{1k} \tilde{\mathbf{p}}_{1k}^T \mathbf{z}_0 \quad (58)$$

$$M_{12} = \mathbf{z}_0^T \mathbf{I}_2 \mathbf{z}_1 + m_2 \mathbf{z}_0^T \tilde{\mathbf{p}}_{12} \tilde{\mathbf{p}}_{2c2}^T \mathbf{z}_1 \quad (59)$$

$$+ \sum_{k=3}^{4} m_k \, \mathbf{z}_0^T \tilde{\mathbf{p}}_{1k} \tilde{\mathbf{p}}_{2k}^T \mathbf{z}_1 \quad (60)$$

(Similar expressions for other M_{ij} components)

11.8. Gravity Vector

$$G_1 = -\sum_{k=1}^{4} m_k \, \mathbf{g}^T \mathbf{z}_0 \times \mathbf{p}_{1c_k} \quad (61)$$

$$G_2 = -\sum_{k=2}^{4} m_k \, \mathbf{g}^T \mathbf{z}_1 \times \mathbf{p}_{2c_k} \quad (62)$$

$$G_3 = -\sum_{k=3}^{4} m_k \, \mathbf{g}^T \mathbf{z}_2 \times \mathbf{p}_{3c_k} \quad (63)$$

$$G_4 = -m_4 \mathbf{g}^T \mathbf{z}_3 \times \mathbf{p}_{4c4} \quad (64)$$

12. **Implementation Details**

The developed system integrates the kinematic and dynamic models of the 2R manipulator with real-time sensing and control to enable precise vehicle entry management.

12.1 Sensor Integration

- Camera Sensor**:** A high-resolution camera mounted on the robotic arm captures images of vehicles and drivers for identification and license plate recognition
- Microphone**:** Used to record the reason for entry and provide voice command capability [26].

Fig 2: Front view of a vehicle

Figure 3: *Side view image of the vehicle*

12.2. Data Processing

Captured images are processed using Optical Character Recognition (OCR) techniques for license plate extraction. Template matching algorithms (e.g., OpenCV) are applied to verify vehicle identities against a secured database.[27]

12.3 Control Strategy

The robotic arm moves the camera to the required position using joint angles calculated through inverse kinematics. To ensure accurate and stable movement, the control system considers factors such as inertia, gravity, and other dynamic forces acting on the arm. This enables the camera to move smoothly, precisely, and reliably during the security monitoring process.

12.4 Software Architecture

The system employs a modular software architecture:

- Kinematics Module**:** Computes forward and inverse kinematics for positioning
- Dynamics Module**:** Computes necessary joint torques and compensations
- Vision Module**:** Handles image acquisition and processing.
- Communication Module: Interfaces with the central database and user interface.

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12.5 Real-Time Operation

The control loop runs at a fixed frequency, performing continuous updates of joint angles and torques to achieve responsive vehicle identification and entry authorization.

12.6 System Validation

The system was tested in both a simulated environment and a preliminary hardware setup. The results showed faster entry processing and improved accuracy compared to traditional manual security checks.

12.7 Sensor Integration

- Camera Sensor**:** A high-resolution camera mounted on the robotic arm captures images of vehicles and drivers for identification and license plate recognition.
- Microphone**:** Used to record the reason for entry and provide voice command capability

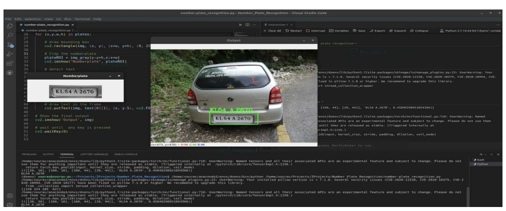

Fig 4: *Optical Character Recognition OCR detection interface*

Optical Character Recognition (OCR) detection interface displaying the extracted license plate number from the captured vehicle image. This automated process replaces manual data entry, improving accuracy and speeding up vehicle verification.

Fig 5: *Vehicle entry pass verification*

Vehicle entry pass verification screen showing the confirmation status of a vehicle allowed entry after successful identity and authorization checks. This screen enables security personnel to monitor and authorize entry in real-time.

Fig 6: *Detailed logged data interface*

Detailed logged data interface displaying vehicle entry records including license plate number, time stamp, driver information, reason for entry, and status. This digital log facilitates audit trails and enhances security management by maintaining comprehensive entry history.

13.Experimental Results and Performance

Timestamp	Vehicle Number	Name	Category	Vehicle Image Path	Person Image Path
17-05-2025 17:45	MH12AB1234	Pooja_Singh	Delivery	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Pooja_Singh.jpg
17-05-2025 17:47	DL01XY2345	Neha_Verma	Pickup	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Neha_Verma.jpg
17-05-2025 17:49	RJ14MN9988	Amit_Sharma	Maintenance	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Amit_Sharma.jpg
17-05-2025 17:52	MH12AB1234	Ravi_Kumar	Visitor	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Ravi_Kumar.jpg
17-05-2025 17:55	KA05CD6789	Pooja_Singh	Delivery	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Pooja_Singh.jpg
17-05-2025 17:58	DL01XY2345	Amit_Sharma	Pickup	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Amit_Sharma.jpg
17-05-2025 18:00	RJ14MN9988	Neha_Verma	Visitor	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Neha_Verma.jpg
17-05-2025 18:03	MH12AB1234	Neha_Verma	Delivery	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Neha_Verma.jpg
17-05-2025 18:05	KA05CD6789	Ravi_Kumar	Maintenance	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Ravi_Kumar.jpg
17-05-2025 18:08	DL01XY2345	Pooja_Singh	Pickup	/home/kbr/Desktop/	/home/kbr/Desktop/RDCProject/Images/Pooja_Singh.jpg

13.1 Setup and Test Environment

The Smart Vehicle Entry Management system was evaluated in a controlled restricted area environment. The setup included the 2R robotic arm equipped with a camera, integrated with OCR and database verification modules. Tests involved multiple vehicle entries to measure processing time and accuracy.

13.2 Entry Time Reduction

Table 2: Entry Processing Time Comparison

13.3 Accuracy of Vehicle Identification

The OCR and template matching algorithms demonstrated an accuracy of 98.7.

13.4 System Reliability

The robotic arm positioning showed a precision within ±0.5◦ in joint angles, enabling consistent camera alignment and clear image acquisition.

13.5 Operational Benefits

- Security: Enhanced tracking and logging of all vehicle entries.
- Labor Efficiency: Reduction in manpower requirements by 70
- Scalability: System easily adaptable to additional entry points with minimal configuration.

M	
M	
Automated System	45

13.6 Discussion

The results demonstrate that automating vehicle entry management using a robotic arm and image processing technology greatly improves efficiency and security.

Future work will focus on further optimization and integration of machine learning techniques for predictive entry control.

14. Conclusion and Future Work

This paper presented a Smart Vehicle Entry Management system that automates the restricted area access process using a robotic arm equipped with a camera for vehicle and driver identification. By integrating kinematic and dynamic models with real-time image processing and control algorithms, the system significantly reduces entry time, enhances security, and eliminates errors inherent in manual processes. Experimental results demonstrated an 85time and a recognition accuracy of 98.7tiveness and reliability. Additionally, operational benefits such as reduced labor costs and improved scalability make the system viable for real-world deployment.

Future work will focus on incorporating machine learning algorithms for enhanced vehicle and driver recognition, expanding the system's capability to handle multiple simultaneous entries, and integrating additional sensors for comprehensive security monitoring. Furthermore, exploring cloud-based data analytics and remote monitoring will provide advanced management capabilities, contributing to the next generation of automated access control systems.

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REFERENCES

1. 1 R. Reddy and S. R. Nagaraja, "Integration of robotic arm with vision system," in 2014 IEEE International Conference on Computational Intelligence and Computing Research, Coimbatore, India, Dec. 2014, pp. 1–5. doi:10.1109/ICCIC.2014.7238302
2. O. T.-C. Chen et al., "Camera-in-Hand Robotic Arm Using a Deep Neural Network to Realize Unmanned Store Service," in 2019 IEEE Intl Conf on Dependable, Autonomic and Secure Computing (DASC), Fukuoka, Japan, Aug. 2019, pp. 833–839. doi:10.1109/DASC/Pi-Com/CBDCom/CyberSciTech.2019.00152.
3. M. K. Ishak, M. I. Roslan, and K. A. Ishak, "Design of Robotic Arm Controller based on Internet of Things (IoT)."(
4. N. K. Agrawal et al., "Design and Development of IoT based Robotic Arm by using Arduino," in 2020 Fourth International Conference on Computing Methodologies and Communication (ICCMC), Erode, India, Mar. 2020, pp. 776–780. doi:10.1109/ICCMC48092.2020.ICCMC-000144.
5. B. P. Aniruddha Prabhu and S. Hebbal, "Small Unarmed Robot for Defense and Security: A Cost-Effective Approach Using Arduino Uno," in 2017 2nd International Conference On Emerging Computation and Information Technologies (ICECIT), Tumakuru, Dec. 2017, pp. 1–6. doi:10.1109/ICECIT.2017.8453325.
6. A. S. Ahmed, H. A. Marzog, and L. A. Abdul-Rahaim, "Design and implement of robotic arm and control of moving via IoT with Arduino ESP32," International Journal of Electrical and Computer Engineering (IJECE), vol. 11, no. 5, p. 3924, Oct. 2021. doi:10.11591/ijece.v11i5.pp3924-3933.
7. A. Brintha Therese, "Robotic Arm with Real-Time Image Processing Using Raspberry Pi, Both Automated and Manually," International Journal of Advanced Research, vol. 6, no. 3, pp. 1424–1430, Mar. 2018. doi:10.21474/IJAR01/6815.
8. H. M. Ali, Y. Hashim, and G. A. Al-Sakkal, "Design and implementation of Arduino based robotic arm," International Journal of Electrical and Computer Engineering (IJECE), vol. 12, no. 2, p. 1411, Apr. 2022. doi:10.11591/ijece.v12i2.pp1411-1418.
9. A. Bhargava and A. Kumar, "Arduino controlled robotic arm," in 2017 International Conference of Electronics, Communication and Aerospace Technology (ICECA), Coimbatore, Apr. 2017, pp. 376–380. doi:10.1109/ICECA.2017.8212837.
10. P. C. Patic, M. Mainea, L. Pascale, and G. Mantescu, "Designing a Mobile Robot used for Access to Dangerous Areas," in 2017 International Conference on Control, Artificial Intelligence, Robotics and

Optimization (ICCAIRO), Prague, May 2017, pp. 60–65. doi:10.1109/ICCAIRO.2017.215.

11. J. Costa, G. Almeida, and A. Cordeiro, "Automated Pick and Place Solution Based on Raspberry Pi," International Journal of Engineering Trends and Technology, vol. 67, no. 10, pp. 48–53, Oct. 2019. doi:10.14445/22315381/IJETT-V67I10P209.
12. H. P., H. L. C. K., and J. S. A. K., "Real Time Image Processing based Robotic Arm Control Standalone System using Raspberry Pi," International Journal of Electronics and Communication Engineering, vol. 2, no. 8, pp. 12–15, Aug. 2015. doi:10.14445/23488549/IJECE-V2I8P105.
13. K. Jahnavi, "Teaching and Learning Robotic Arm Model," 2017.
14. A. Narmada, S. Sushma, K. Shivani, and D. Vanisri, "Surveillance Robot Using Raspberry Pi Based on CGI Script and MJPG Video Streamer," vol. 54, no. 02, 2022.
15. T. Mankar, M. Bhorkar, A. Shende, and M. Ghute, "IoT Based Access Control System for Vehicles," in 2022 Second International Conference on Artificial Intelligence and Smart Energy (ICAIS), Coimbatore, India, Feb. 2022, pp. 1298–1301. doi:10.1109/ICAIS53314.2022.9742983.
16. K. Chenchireddy, R. Dora, G. B. Mulla, V. Jegathesan, and S. A. Sydu, "Development of robotic arm control using Arduino controller," IAES International Journal of Robotics and Automation, vol. 13, no. 3, p. 264, Sept. 2024. doi:10.11591/ijra.v13i3.pp264-271.
17. R.-J. Wang, J.-W. Zhang, J.-M. Xu, and H.-Y. Liu, "The multiple-function intelligent robotic arms," in 2009 IEEE International Conference on Fuzzy Systems, Jeju Island, South Korea, Aug. 2009, pp. 1995–2000. doi:10.1109/FUZZY.2009.5277256.
18. F. A. Valenzuela-Domínguez, L. F. Munguía-Martínez, S. Meléndez-Tiznado, Z. Guzmán-Limón, V. H. Benitez, and L. C. Félix-Herrán, "Design of a two-degrees-of-freedom robotic arm for monitoring applications for teaching robotics and artificial intelligence technology," Computer Applications in Engineering Education, vol. 32, no. 6, p. e22786, Nov. 2024. doi:10.1002/cae.22786.
19. K. P. N. V. Satya Sree, T. Bikku, S. Mounika, N. Ravinder, M. L. Kumar, and C. Prasad, "Retracted: EMG Controlled Bionic Robotic Arm using Artificial Intelligence and Machine Learning," in 2021 Fifth International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud), Palladam, India, Nov. 2021, pp. 548–554. doi:10.1109/I-SMAC52330.2021.9640623
20. K. Kruthika, B. M. Kiran Kumar, and S. Lakshminarayanan, "Design and development of a robotic arm," in 2016 International Conference on Circuits, Controls, Communications and Computing (I4C), Bangalore, India, Oct. 2016, pp. 1–4. doi:10.1109/CIMCA.2016.8053274.
21. A. Ditta, M. M. Ahmed, T. Mazhar, T. Shahzad, Y. Alahmed, and H. Hamam, "Number Plate Recognition Smart Parking Management System Using IoT," Measurement Sensors, vol. 37, p. 101409, Feb. 2025. doi:10.1016/j.measen.2024.101409.
22. G. Srilekha, D. R. Kavya, M. H. Bindu, and P. Mamatha, "FPGA-Based Smart Parking Management System with Real-Time Slot Monitoring and Entry/Exit Detection," International Journal of Engineering Research, vol. 14, no. 07, 2025.
23. Md. R. Alam, S. Saha, Md. B. Bostami, Md. S. Islam, Md. S. Aadeeb, and A. K. M. M. Islam, "A Survey on IoT Driven Smart Parking Management System: Approaches, Limitations and Future Research Agenda," IEEE Access, vol. 11, pp. 119523–119543, 2023. doi:10.1109/ACCESS.2023.3327306.
24. G. Pradhan, M. R. Prusty, V. S. Negi, and S. Chinara, "Advanced IoT-Integrated Parking Systems with Automated License Plate Recognition and Payment Management," Scientific Reports, vol. 15, no. 1, p. 2388, Jan. 2025. doi:10.1038/s41598-025-86441-w.
25. R. S. Belgumpi, "A Smart Vehicle Access and Safety System using Biometric and Piezo Sensor with Power Generation," International Journal of Engineering Research, vol. 14, no. 09, 2025.
26. B. Kidmose, "A Review of Smart Vehicles in Smart Cities: Dangers, Impacts, and the Threat Landscape," Vehicle Communications, vol. 51, p. 100871, Feb. 2025. doi:10.1016/j.vehcom.2024.100871.

27. I. Ekanem, A. E. Ikpe, and J. U. Ohwoekevwo, "A Study on IoT-Enabled Smart Vehicles for Road Navigation and Ride Comfortability in Contemporary Vehicle Applications," Soft Computing Fusion Applications, vol. 1, no. 2, pp. 58–75, Jan. 2025. doi:10.22105/scfa.v1i2.30.