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Modeling and Control of a Complicated Inverted Pendulum Cart System with a Camera to Detect Objects

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ABSTRACT: *This paper presents the design and implementation of a PID control system for an inverted pendulum model equipped with a camera for object observation and recognition. The paper encompasses system analysis, development of a mathematical model, and the application of PID control techniques to the inverted pendulum system using Matlab/Simulink. The outcome is a robust PID controller design that effectively maintains the balance of the inverted pendulum as it traverses the cart. An observation camera is integrated to provide visual information of the observed objects to the control and monitoring interface. Simulation and experimental results demonstrate the superior performance of the designed control system.*

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I. INTRODUCTION

While the inverted pendulum-cart system is a well-established benchmark in control engineering, its research significance extends beyond its 'classical' status [1-5]. The key aspects that continue to drive research interest include:

(i) Exploration of Novel Control Strategies: Due to the system's nonlinearity and instability, conventional control methods might not be sufficient. Research delves into advanced techniques like intelligent control (fuzzy logic, neural networks), optimal control, and robust control to achieve superior performance and handle uncertainties.

(ii) Real-World Applications: The inverted pendulum serves as a stepping stone for controlling more complex real-world systems. Research explores its application in balancing robots, Segway-like personal transporters, and even bipedal walking robots.

(iii) Disturbance Rejection and Robustness: Real-world environments introduce external disturbances that can destabilize the system. Research focuses on designing controllers that can not only stabilize the system but also reject these disturbances, ensuring robustness in practical applications.

(iv) Integration with Advanced Sensors and Actuators: Advancements in sensor and actuator technology create opportunities for more precise control of the inverted pendulum. Research explores incorporating state-of-the-art sensors (e.g., gyroscopes, accelerometers) and actuators to achieve higher performance and efficiency.

Considerable research endeavors have been devoted to designing and optimizing controllers for the inverted pendulum-cart system. Traditional control techniques, such as PID (Proportional-Integral-Derivative) [3] [4] [5] [6] [7], fuzzy logic [5] [8] [9], and LQR (Linear Quadratic Regulator) [6] [10] [11], have been thoroughly investigated, and their performances have been compared [7] [12]. Among these, the PID controller stands out as one of the most widely employed methods for the inverted pendulum-cart system due to its simplicity, effectiveness, and ease of parameter tuning [3] [4]. Nevertheless, the conventional PID controller encounters limitations in handling the system's nonlinearity, noise, and uncertainties [5] [13].

In response to these limitations, nonlinear control methods such as Lyapunov [14] and intelligent control techniques like fuzzy logic [8] [9] [15] and neural networks [9] have been proposed and refined. Research has demonstrated that fuzzy logic and neural networks exhibit superior capabilities in addressing the system's nonlinearity and uncertainties compared to traditional control methods [5] [8] [9]. Notably, the integration of fuzzy logic with the traditional PID controller (Fuzzy PID) has shown promising results in enhancing control performance and robustness against external disturbances [8] [9] [13].

Another crucial aspect of research on the inverted pendulum-cart system pertains to its ability for environmental observation and object recognition. The integration of cameras and image processing techniques represents a novel developmental direction, unlocking the extensive application potential of the system in domains such as service robotics, autonomous cargo transportation vehicles, and environmental security surveillance robots [16] [17] [18]. Recent studies have utilized camera modules like ESP32-CAM, coupled with image processing libraries such as OpenCV and object recognition algorithms like Yolo, to facilitate the observation and identification of various objects within the environment, including obstacles, individuals, and objects [18].

Nonetheless, the integration of control for the inverted pendulum-cart system with image processing and object recognition presents significant challenges necessitating resolution. This research endeavors to devise a PID control system for an inverted pendulum-cart apparatus equipped with an observation and object recognition camera. The envisioned outcome is a system capable of sustaining balance for the inverted pendulum's movement on the cart while concurrently observing and recognizing various objects within the surrounding environment. This initiative promises to stimulate the development of critical real-world applications, such as service robotics, autonomous cargo transportation vehicles, environmental security surveillance robots, and beyond.

To achieve the aforementioned objective, this research will undertake the following steps:

- System Analysis and Mathematical Modeling: A thorough analysis of the inverted pendulum-cart system will be conducted to identify its dynamic characteristics and governing equations. The Euler-Lagrange method will be employed to derive the mathematical model that accurately represents the system's behavior.
- PID Controller Design and Optimization: A PID controller will be designed for the inverted pendulum-cart system to regulate its angular position and achieve stable operation. The PID controller parameters will be optimized using Matlab/Simulink, a simulation environment, to ensure optimal performance.
- Real-Time Implementation: The control system will be implemented on a real-world platform using an Arduino microcontroller. The ESP32-CAM module will be integrated to capture visual data from the environment. The OpenCV library and the Yolo V3 object detection algorithm, implemented in Python, will be utilized to process and analyze the camera images.
- System Monitoring Interface: A graphical user interface (GUI) will be developed using the Winform framework to monitor the overall system operation. The GUI will display real-time information, including the pendulum's angular deviation, motor control pulses, and image processing and object detection results.

II. DESIGN OF THE INVERTED PENDULUM CART SYSTEM

2.1 Mathematical model of an inverted – pendulum cart – dynamic analysis

Consider the mathematical model of the inverted pendulum mounted on a cart undergoing rectilinear motion as depicted in Fig. 1. Frictional effects between the cart and the ground, as well as between the cart and the pendulum, are assumed to be neglected. The system parameters include: M - mass of the cart; m - mass of the pendulum; l - length of the rod; θ - angle between the rod and the vertical plane; F - control force; x - position of the pendulum; g - acceleration due to gravity.

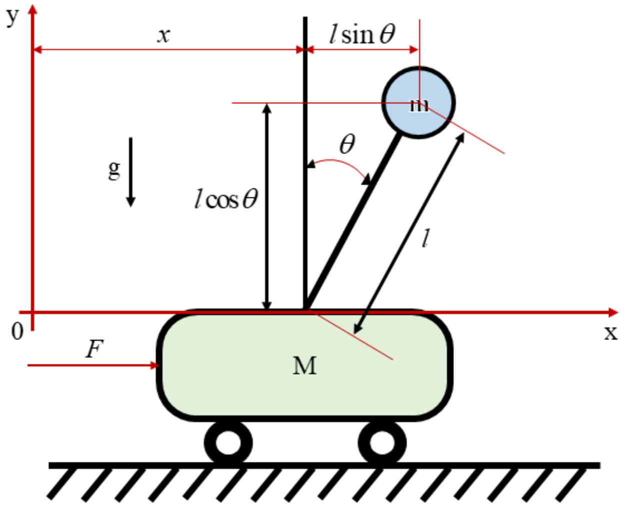

Fig. 1 Mathematical model of the inverted – pendulum cart

The system of equations describing the nonlinear dynamic characteristics of the pendulum system using the Euler-Lagrange method is depicted as follows:

$$\begin{cases} (\mathrm{m}+\mathrm{M})\ddot{x}+\mathrm{m}l\ddot{\theta}\cos(\theta)-\mathrm{m}l\dot{\theta}^2\sin(\theta)=F \\ \mathrm{m}l\ddot{x}\cos(\theta)+\mathrm{m}l^2\ddot{\theta}-\mathrm{mg}l\sin(\theta)=0 \end{cases} \tag{1}$$

From (1), it is straightforward to deduce the following:

$$\begin{cases} \ddot{x}=\dfrac{F+\mathrm{m}l\dot{\theta}\sin(\theta)-\mathrm{mg}\cos(\theta)\sin(\theta)}{\mathrm{m}+\mathrm{M}-\mathrm{m}\cos^2(\theta)} \\ \ddot{\theta}=\dfrac{F\cos(\theta)+\mathrm{m}l\dot{\theta}^2\cos(\theta)\sin(\theta)-(\mathrm{m}+\mathrm{M})\mathrm{g}\sin(\theta)}{l(\mathrm{m}+\mathrm{M}-\mathrm{m}\cos^2(\theta))} \end{cases} \tag{2}$$

The mathematical model presented in equation (2) can be fully utilized for simulation purposes to demonstrate the control strategies applied to the inverted pendulum system.

2.2 Mathematical model of the inverted – pendulum cart built in Matlab/Simulink

From (2), it is necessary to establish the Simulink model as shown in Fig. 2. This model is employed for the simulation execution in this work.

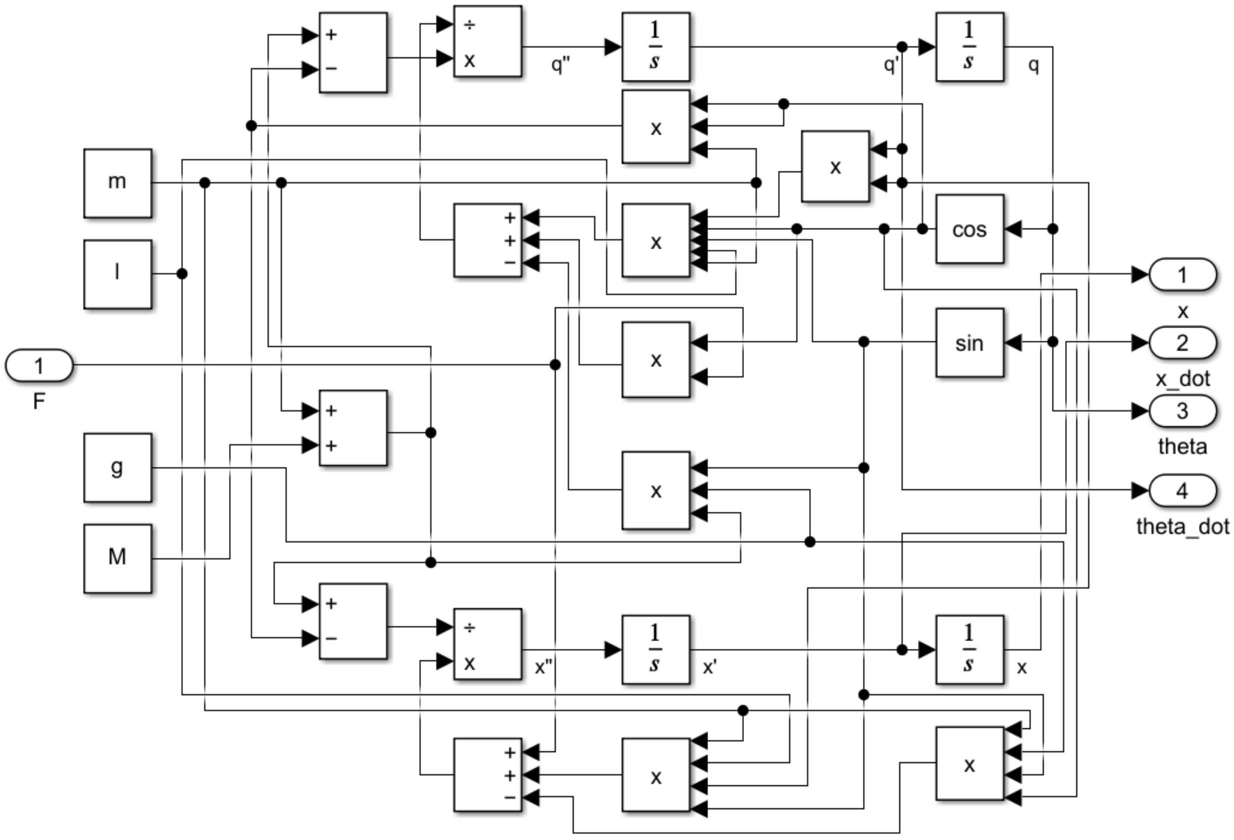

Fig. 2 Mathematical model of the inverted – pendulum cart built in Matlab/Simulink enviroment

The simulation parameters for the model used in this study provided in Appendix A.

2.3 Design of the control strategy for the inverted – pendulum cart

Using a PID controller, one of the most conventional and effecient regulators, for the inverted-pendulum system, the whole control system is presented in Fig. 3.

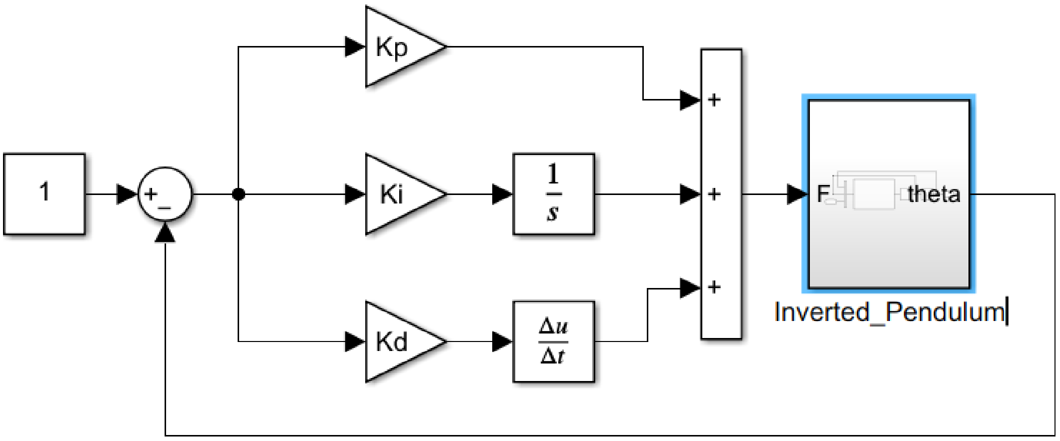

Fig. 3 PID-control for the inverted – pendulum cart system

The PID controller, depicted in Fig. 3, was constructed using the trial-and-error method, fine-tuning the parameters based on the system's actual response. The PID controller parameters include: K_p (Proportional gain), K_i (Integral gain), and K_d (Derivative gain). These parameters have distinct effects on the system's response:

- ✓ K_p (Proportional gain): This parameter influences the system's response magnitude. A higher K_p leads to a faster response but can also increase overshoot.
- ✓ K_i (Integral gain): This parameter addresses steady-state errors. A higher K_i reduces steady-state error but can slow down the response.
- ✓ K_d (Derivative gain): This parameter anticipates future changes and improves system stability. A higher K_d can reduce settling time but may also introduce noise sensitivity.

2.4 Using ESP32 CAM and Python OpenCV Yolo V3 to detect objects

To utilize the ESP32-CAM module, a static IP address configuration program must be uploaded to the module. In this research, the static IP address assigned to the ESP32-CAM is '192.168.0.106'. This IP address is then used to establish TCP/IP communication with Python, enabling the retrieval and processing of image data captured by the camera.

The next two steps need to be implemented:

(i) Establish a Directory for Object Detection with Yolo V3 in Python:

Create a dedicated directory to store the necessary files for object detection using Yolo V3 in Python.

(ii) Download and Place Yolo V3 Files:

Download the essential Yolo V3 files, including *coco.names*, *yolov3.cfg*, and *yolov3.weights*. Place these files within the same directory as the main Python script.

Develop a Python Script for Image Processing and Communication. Below are some explanations in detail.

(i) Image Processing:

Implement a Python script to process the image data received from the ESP32-CAM module. This may involve tasks such as image decoding, pre-processing, and feature extraction.

(ii) Communication with Control and Monitoring Interface:

Establish communication between the Python script and the control and monitoring interface. This may involve sending the processed image data or relevant information to the interface via a suitable communication protocol. The Appendix B presents the details of Python code for these goals.

2.5 Graphical User Interface for System Operation and Monitoring

The System Control and Monitoring Interface for the Inverted Pendulum Cart System enables users to monitor the pendulum's angular deviation, motor control pulses, and displays visual information from the ESP32 CAM, allowing users to observe the surrounding environment.

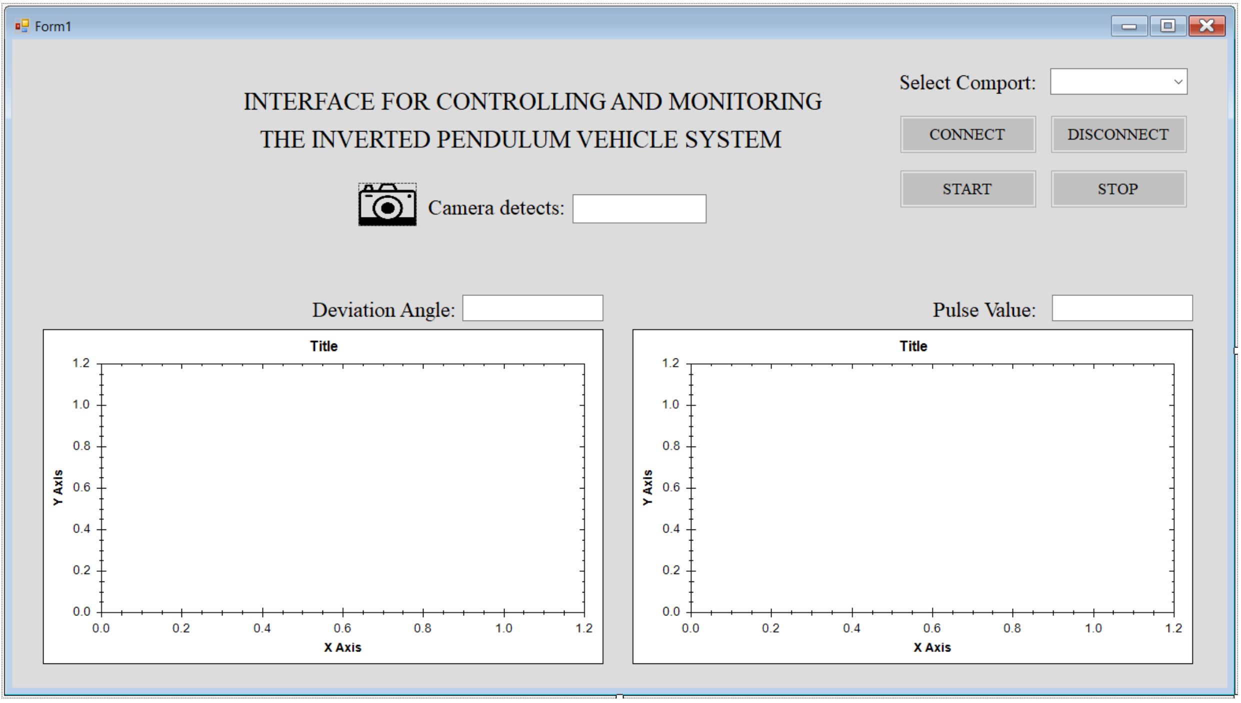

Fig. 4. Control and monitoring interface for the entire system

III. RESULTS AND DISCUSSION

With the parameters of the inverted pendulum-cart system defined as follows: M = 2kg; m = 0.5kg; l = 1m; g = 9.81m/s^2 (see Appendix), this work utilizes Matlab/Simulink to simulate the control results of the inverted pendulum-cart system using a PID controller. The obtained results are plotted in Fig. 5.

PID

	Time		Value
1	0.000e+00		0.000e+00
2	0.872		1.000e+00
ΔT	871.965 ms	ΔY	1.000e+00
	1 / ΔT		1.147 Hz
	ΔY / ΔT		1.147 (/s)

Fig. 5. Simulation results in Matlab/Simulink

Figure 5 illustrates that the settling time is 0.872s, with no overshoot and zero steady-state error. Once appropriate parameters are obtained through simulation, they will be implemented and tested again on the real system using Matlab/Simulink. Figure 6 describes the practical diagram for the inverted pendulum system implemented in Marlab/Simulink in well-connection with Arduino and encoders. Following the execution of the real model, the time response of the angular deviation is completely acceptable. In addition, the balance of the rod is maintained successfully. This demonstrates the feasibility of the control method proposed in this study.

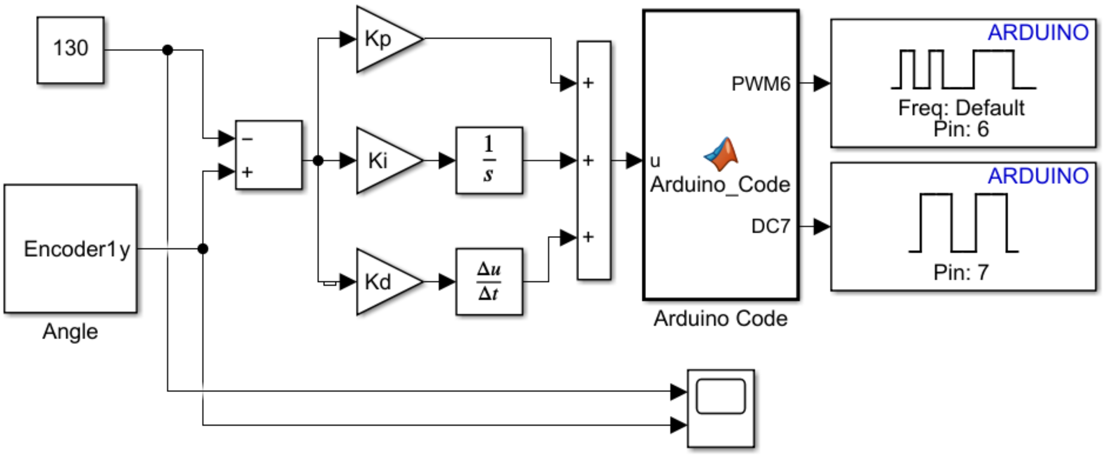

Fig. 6. Practical implementation of the inverted pendulum cart system integrated in MATLAB/Simulink package

IV. CONCLUSIONS AND DISCUSSIONS

This study has successfully designed a PID control system for an inverted pendulum model integrated with a camera for object observation and recognition. The entire research process includes: analysis of the inverted pendulum system, construction of a mathematical model using the Euler-Lagrange method, design and optimization of PID controllers using the Matlab/Simulink simulation software, programming of an Arduino microcontroller, utilization of the OpenCV image processing library with Python language to control and process image data from the ESP32-CAM camera, enabling real-time monitoring and identification of various objects, and finally, implementation of a monitoring interface for the entire system on the Winform platform. Simulation and experimental results demonstrate that the PID controller with optimized parameters can ensure the balance of the pendulum on the vehicle. Particularly, the integration of the observation camera ESP32-CAM provides the capability to monitor and identify various objects in the surrounding environment of the system such as obstacles, objects, humans, etc. Combined with an intuitive monitoring interface, this extends the potential applications of the inverted pendulum system in various important fields such as service robots, autonomous freight transportation vehicles, environmental security surveillance robots, and more.

APPENDICES

Appendix A: Simulation parameters

Symbol	***Description***	Value	***Unit***
M	Mass of the cart	2	kg
m	Pendulum mass	0.5	kg
l	Length of bar	1	m
g	Gravitaitonal acceleration	9.81	m/s^2

Appendix B: Python code

```
import cv2
import numpy as np
import urllib.request
import socket
HOST, PORT = "127.0.0.1", 65432  # IP loopback
sock = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
try:
    sock.connect((HOST, PORT))
    url = 'http://192.168.0.103/cam-hi.jpg'
    cap = cv2.VideoCapture(url)
    whT = 416
    confThreshold = 0.5
    nmsThreshold = 0.3
    classesfile = 'coco.names'
```

```
    classNames = []
    with open(classesfile, 'rt') as f:
        classNames = f.read().rstrip('\n').split('\n')
    modelConfig = 'yolov3.cfg'
    modelWeights = 'yolov3.weights'
    net = cv2.dnn.readNetFromDarknet(modelConfig, modelWeights)
    layernames = net.getLayerNames()
    outputNames = [layernames[i - 1] for i in net.getUnconnectedOutLayers().flatten()]
    def findObject(im):
        blob = cv2.dnn.blobFromImage(im, 1 / 255, (whT, whT), swapRB=True, crop=False)
        net.setInput(blob)
        outputs = net.forward(outputNames)
        bbox = []
        classIds = []
        confs = []
        for output in outputs:
            for det in output:
                scores = det[5:]
                classId = np.argmax(scores)
                confidence = scores[classId]
                if confidence > confThreshold:
                    box = det[0:4] * np.array([im.shape[1], im.shape[0], im.shape[1], im.shape[0]])
                    (centerX, centerY, width, height) = box.astype("int")
                    x = int(centerX - (width / 2))
                    y = int(centerY - (height / 2))
                    bbox.append([x, y, int(width), int(height)])
                    classIds.append(classId)
                    confs.append(float(confidence))
        indices = cv2.dnn.NMSBoxes(bbox, confs, confThreshold, nmsThreshold)
        if len(indices) > 0:
            for i in indices:
                x, y, w, h = bbox[i][0], bbox[i][1], bbox[i][2], bbox[i][3]
                cv2.rectangle(im, (x, y), (x + w, y + h), (255, 0, 255), 2)
                cv2.putText(im, f'{classNames[classIds[i]].upper()} {int(confs[i] * 100)}%', (x + 5, y + 20),
                            cv2.FONT_HERSHEY_SIMPLEX, 0.5, (255, 0, 255), 2)
                data = classNames[classIds[i]] + "\n"
                print(data)
                sock.sendall(data.encode("UTF-8"))
        return im
    while True:
        img_resp = urllib.request.urlopen(url)
        imgnp = np.array(bytearray(img_resp.read()), dtype=np.uint8)
        im = cv2.imdecode(imgnp, -1)
        img = findObject(im)
        cv2.imshow('ESP32 CAM', im)
        if cv2.waitKey(1) == ord('q'):
            break
finally:
    sock.close()
cv2.destroyAllWindows()
```

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